INSTITUT DE RECHERCHE SUR L'HYDROGÈNE
UQTR

Hydrogen Research Institute
University of Québec at Trois-Rivières
819-376-5011
3351 Des Forges Blvd., P.O. Box 500, Trois-Rivières, Québec G9A 5H7 | 2481 L.-P.
irh@uqtr.ca

Guide to the Integration, Management, and Operation of a Hydrogen Train in North America

Date: February, 9 2026

Version: 2.0

Photographs: © **Alstom / C. Fleury**

To cite this report:

Baudy M, Gervais-Lavoie R, Mohammadmirzaeibafghi M, Hourri A, Bareha Y, Marchand-Lamarche M, Giroux F, Almheiri Z, Boulon L, Barnabé S, Pollet B. Guide to the integration, management, and operation of a hydrogen train in North America. Hydrogen Research Institute, Université du Québec à Trois-Rivières, 2026.

Foreword

Alstom, a world leader in green and smart mobility, has been developing a portfolio of zero-emission mobility solutions for several years and has launched an ambitious innovation program to bring new technologies to market. The first two Coradia iLint™ 100% H_2 trains powered by a fuel cell system entered commercial service in Germany in 2018. To date, 41 hydrogen trains have been ordered by two German regions, and successful trials have taken place in Austria, the Netherlands, Sweden, and France. In Italy, operator FNM confirmed an order for 14 hydrogen trains at the end of 2020. In 2021, France also joined the circle of participating countries with an order from SNCF for 12 Coradia Polyvalent dual-mode trains (electric/catenary and hydrogen/fuel cell traction) for four French regions (Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté, Grand Est, and Occitanie).

The use of hydrogen in the rail sector would reduce GHG emissions by 80% to 95% compared to conventional trains. To achieve this, the hydrogen must be low carbon, such as when produced by water electrolysis, a process that breaks down water into oxygen and hydrogen gas using an electric current. In addition, local pollution is also reduced in terms of noise and fine particle emissions, as there is no combustion in a fuel cell.

Hydrogen trains are a relevant solution compared to full or partial electrification of tracks (with the use of battery-powered trains) on lines with lower traffic and little or no electrification. They are characterized by a potentially lower investment cost than track electrification, depending on the distance to be electrified, but by a higher energy cost.

Today, Alstom aims are to accelerate its hydrogen strategy and continue to offer and develop innovative and clean solutions. The company want to provide public authorities and operators with relevant technical and economic solutions as part of the energy transition. In doing so, Alstom aim to contribute to the influence of Québec and Canada in this technology of the future and break into the U.S. market. To this end, Alstom has launched a demonstration project for a hydrogen-powered passenger train between Québec City and Charlevoix, operated by Train de Charlevoix. The train arrived from Europe in the spring of 2023 and was in service during the tourist season (summer 2023). The hydrogen supplier is the Québec-based company Harnois Énergies. It should be noted that this project is in line with the activities of Alstom's innovation center dedicated to green rail mobility solutions in St-Bruno-de-Montarville, Québec, announced in July 2022.

In order to prepare for its entry into the US market, Alstom has undertaken, with the Hydrogen Research Institute (IRH) at the University of Québec at Trois-Rivières (UQTR), Harnois Énergies, and Train de Charlevoix, to study the conditions for the success of the refuelling and operating ecosystem for a hydrogen train in Québec, based on its implementation in Charlevoix.

Acknowledgements

Through this message, the authors wish to thank everyone we met during the project, both via videoconference and in the field, and recognize all the teams who made the train's operations possible in the summer of 2023. We warmly thank all the employees and passengers who participated in the interviews and surveys. We are happy and proud to have contributed to this wonderful project and would like to express our sincere thanks to all our partners, Alstom, Harnois Énergies, Réseau Charlevoix, MITACS, and MEIE. The authors would also like to express their sincere thanks to Erman Eloge Nzaba Madila, Ph.D., Research Officer at IRH, UQTR, Andrew Diamond, Ph.D., Postdoctoral Researcher at I2E3, UQTR and Sadesh Kumar Natarajan, Ph.D., Research Officer at IRH, UQTR for their involvement in verifying references and translating this report.

About the authors

This guide was made possible by the collaboration of the Hydrogen Research Institute (IRH) with the Institute for Innovation in Biomass-Based Eco-Materials, Eco-Products, and Eco-Energies (I2E3), two research institutes at the University of Québec at Trois-Rivières (UQTR). Information about the project was collected in the field and provided by partners during various visits and interviews. The passenger experience study was conducted in collaboration with Félix Giroux of the University of British Columbia (UBC), and the well-to-wheel emissions analysis was performed by Zainab Almheiri of McGill University (McGill).

- Mathieu Baudy[1–5], Ph.D., Postdoctoral Researcher at IRH, UQTR
- Raphaël Gervais-Lavoie[1–5], Research Assistant at IRH, UQTR
- Mohammadali Mohammadmirzaeibafghi[1–5], Ph.D., Postdoctoral Researcher at I2E3, UQTR
- Ahmed Hourri, Ph.D.[1,3], Research Officer at IRH, UQTR
- Younès Bareha, Ph.D.[2], Postdoctoral Researcher at I2E3, UQTR
- Marie-Ève Marchand-Lamarche[5], Laboratory Technician at IRH, UQTR
- Félix Giroux[4], Doctoral candidate in Anthropology, UBC
- Zainab Almheiri[4], Ph.D., Postdoctoral Researcher, McGill
- Loïc Boulon, Ph.D.[s], Professor, UQTR
- Simon Barnabé, Ph.D.[s], Professor, UQTR
- Bruno Pollet, Ph.D.[s], Professor, UQTR

Contributions: [1]=Section 1; [2]=Section 2; [3]=Section 3; [4]=Section 4; [5]=Section 5; [1–5]=all sections ; [s]=supervisor

Note: The first version, dated 10 September 2024, was written in French and made available upon request.

Acronyms and abbreviations

- CO_2e: Carbon dioxide equivalent
- GHG: GreenHouse Gas
- H_2: Dihydrogen molecule, commonly known as hydrogen
- LH_2: Liquid Hydrogen
- PEMFC: Proton Exchange Membrane Fuel Cell
- ERAP: Emergency Response Assistance Plan

Summary

List of tables

List of figures

Executive summary

Alstom, a global leader in sustainable and smart mobility, in partnership with the Government of Québec, Réseau Charlevoix, Train de Charlevoix, Harnois Énergies, HTEC, and Accelera by Cummins, has launched commercial service for its Coradia iLint BR654 hydrogen train, the first commercial operation in North America located on the Québec City-Charlevoix railway and tourist route in 2023. The Coradia iLint's first commercial trip took place on June 17. At the end of the demonstration, the Coradia iLint had carried more than 10,000 passengers on its 117 trips between the Chute-Montmorency and Baie-Saint-Paul stations. A record number of passengers was recorded for the summer season by the Train de Charlevoix company, which doubled its ridership commercial operation known as "the hydrogen experience," which consisted of replacing one of the diesel trains in its fleet with the Coradia iLint. Manufactured by Alstom in Germany, this demonstration train made the journey from Europe to be put on the rails, thanks to $3 million in financial support from the Québec government through its Technoclimat program, with the overall project budget amounting to $8 million. A fully functional hydrogen ecosystem has thus emerged over the past few months of activity, with many questions raised and/or answered by the project team and the Hydrogen Research Institute (IRH) at the University of Québec at Trois-Rivières (UQTR). The IRH was commissioned to implement the refuelling module, provide training, and study the refuelling, operation, and maintenance ecosystem of the Coradia iLint in this context. The study has been completed and a report has been written on the observations, information, responses, and prospects.

In summary, passengers showed a genuine interest in the technology; however, their primary focus was comfort and design of the train that were appreciated. "How does a hydrogen train work? How is hydrogen produced?" These are not the safety issues that passengers are concerned about. They consider that these aspects have already been taken into account in the train's design and that it has already proven itself, having been in service in Europe since 2018.

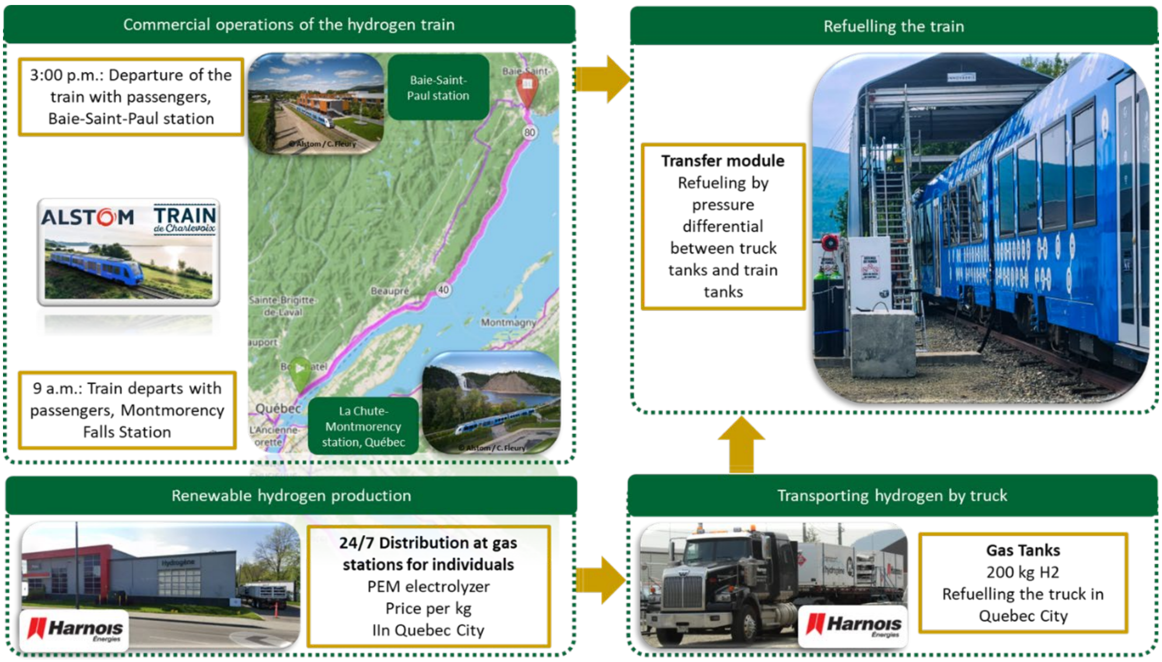
Hydrogen adoption in the rail sector is generating a lot of interest, but also raises a number of technical, practical, and regulatory questions. According to this study, the specific characteristics of hydrogen have little impact on how a train is designed and operated. The hydrogen tanks and fuel cells that produce electricity are installed on the roof of the train so that hydrogen can be vented and diluted in the outside air in the event of a leak. This prevents any potential accumulation of hydrogen in a retention area, thereby mitigating risks. It should be noted, however, that train traffic in a tunnel would be a special case that must be considered, as tunnel ventilation must be adapted to the operation of vehicles transporting gas. Therefore, the specific nature of hydrogen train operation lies in its refuelling and the relevant regulations.

Several solutions are possible for refuelling a train's hydrogen tanks. For this demonstration, the Canadian company HTEC designed a transfer module in conjunction with Harnois Énergies and Alstom. The commissioning and all refuelling operations took place without any particular problems,

demonstrating that the technical solution used is functional, simple to implement, and safe for this application. However, it should be noted that a specific safety analysis must be carried out for any new system or when connecting several systems in order to mitigate risks as much as possible, regardless of the technology and energy used.

This study focused on several regulatory aspects. Regarding the requirements for the installation of hydrogen production, distribution, and storage equipment, the Bureau de Normalisation du Québec (BNQ) has published the CAN/BNQ 1784-000/2022 standard to be taken into consideration. This is a revision of the Canadian Hydrogen Installation Code. The latest revision of the standard aims to harmonize certain requirements with the American NFPA2 code, "Hydrogen Technologies Code," in order to ensure continuity in practices between Canada and the United States for the safe use of hydrogen.

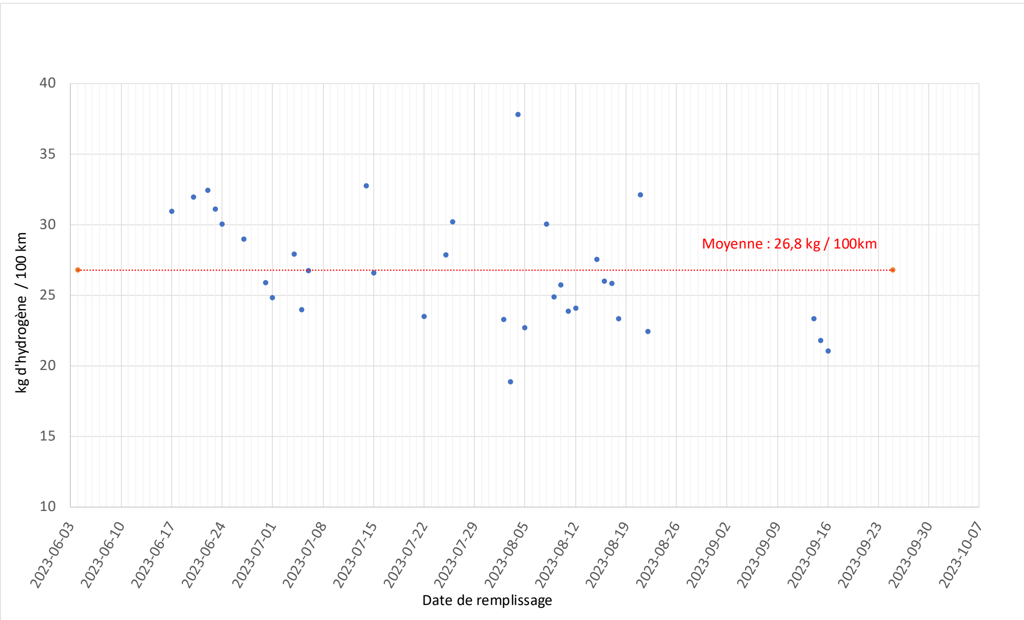
The hydrogen used in this demonstration is produced by Harnois Énergies through water electrolysis at its refuelling station on Boulevard Wilfred-Hamel in Québec City. The green hydrogen is transported by truck to Baie Saint Paul at the Train de Charlevoix maintenance site in an area specially designated for the hydrogen train. To store and transport the hydrogen, Harnois Énergies used PC-45 hydrogen storage units from HTEC. These storage units consist of five 315-liter tanks that can each hold 9 kg of hydrogen at a pressure of 450 bar. With four PC-45 units per trailer, 180 kg of hydrogen can be transported at a pressure of 450 bar. The transfer module is used in accordance with HTEC's procedures for refuelling the train. This module connects the train's tanks to those transported by the truck using fluidic hoses (mechanically secured). All equipment and the operator must be at the same electrical potential. The module monitors pressure changes and has a safety system in case of problems. Refuelling was carried out by the train technician (Alstom) with the train manager (Alstom), the truck driver (Harnois Énergies), and the train driver (Train de Charlevoix).



The refuelling process relies on a pressure differential. The technician opens the truck's hydrogen tanks in pairs. The truck contains a total of twenty tanks. When the valves are opened, the hydrogen gas flows until the tanks reach equilibrium pressure, at which point the technician closes the valves. He can then open the valves of two other tanks on the truck. This procedure is repeated until the desired pressure is reached in the train's hydrogen tanks.

The safety measures are relatively standard for refuelling a train: cell phones are prohibited and the use of antistatic personal protective equipment is mandatory. In addition, the use of gas requires leak tests to be carried out to ensure the system is airtight before refuelling can begin. The personnel involved in these operations have received adequate training on the associated risks and on the use of the systems they operate. Although experience with other fuels may provide some familiarity with the handling of hazardous materials, remains essential given its unique properties (as with any fuel). Once the checks and refuelling have been completed, the train is then ready to depart for the Baie-Saint Paul and Chute-Montmorency stations for a round trip before returning to park overnight in its maintenance area.

The quantities of hydrogen delivered were monitored throughout the project. Refuelling data was used to calculate an average hydrogen consumption of 26.8 kg/100 km during this demonstration. The trips were made under normal operating conditions, with passengers on board and all train systems running, including air conditioning, and maintaining a cruising speed below 50 km/h.



In contrast to diesel engines, which emits various greenhouse gases and harmful emissions (NOx, fine particles, etc.), the Coradia iLint's fuel cells emit only water and are silent. In addition, during normal operation, a train also emits particulate matter through the use of its mechanical brakes. As mechanical braking is not the main braking mode of the Coradia iLint, it necessarily produces fewer emissions in this regard. By conducting an in-depth life cycle analysis of the two systems, it would be possible to compare the ecological footprint of each energy ecosystem used to operate these two trains. The commercial operation of the Coradia iLint is thus the first concrete example of the implementation of a hydrogen ecosystem to run a passenger train on the continent.

In North America, it should be noted that the rail network covers over 300,000 kilometers, with less than 1% currently electrified. Diesel is still widely used for passenger travel and freight transport. It was in this market context that the hydrogen train ran in Québec during the summer of 2023. Various mature electric technologies (catenary, battery, and hydrogen) are already commercially available around the world and adapted to multiple railways uses, whether for passenger or freight transport. The renewal of train fleets that are reaching the end of their life cycle provides an ideal opportunity to consider the most appropriate technology for the application, considering the economic and environmental context. The judicious deployment of new energy and rail ecosystems, in a context adapted to the public transport needs of the population (and freight transport), can ultimately be considered as an attractive alternative to private cars (and heavy trucks for freight) in terms of cost, availability, and frequency, while offering a unique experience to users (in terms of comfort and even tourism) and thus contributing further to the sustainable future of our societies.

For the optimal integration of hydrogen technologies, a comprehensive energy ecosystem is therefore essential to ensure the production, distribution, storage, and use of energy. The first, historical method of hydrogen production was based on centralized production. This type of model supports large-scale production but requires a hydrogen transportation network to serve all consumers. A company or industry consuming low volumes could be penalized by the cost of compression, transport, and storage. However, technical advances in new decentralized production methods suggest that new organizational approaches closer to users will eventually emerge. New business models would enable stakeholders to control production and transportation costs, use local resources, and optimize carbon impact. In 2019, Québec's first hydrogen station open to the public refueled 50 Toyota Mirai vehicles. That number has risen to 75 in 2023, and the station can produce 200 kg oh H_2 per day, consuming 55 kWh and 10 L of water for every 1 kg of H_2. The availability of surplus hydrogen production has made it possible to consider refuelling the Coradia iLint train in Québec.

In decentralized production, it may be advantageous to expand the electrolyzer to accomodate new players to enter the ecosystem and develop the distribution network to serve local customers. A second advantage could be the ability to benefit from more cost-effective production by maximizing production when electricity is cheapest. However, it is important to consider the initial purchase cost of the electrolyzer, taking into account existing subsidies, to ensure a reasonable return on investment from an economic standpoint. Finally, there is the question of electricity pricing to promote the installation and sustainability of decentralized production. Whether centralized or decentralized, each ecosystem is different and must be adapted to the needs!

In addition, regulatory issues associated with the various activities surrounding the refuelling, operation, and maintenance of hydrogen trains in Québec and Canada raised questions. Through close collaboration between Québec's Ministry of Transport and Sustainable Mobility and Alstom, hydrogen train operations commenced in the summer of 2023. Since the beginning of the project, the Québec Ministry of Transport and Sustainable Mobility has supported the various stakeholders to ensure the monitoring and acceptance of the safety file required for any railway product. Working together, additions and modifications were made to the Coradia iLint to ensure its compliance with current regulations. Transport Canada is currently working to establish federal regulations to allow hydrogen trains to operate throughout the country, as is the case in Europe.

General introduction

Hydrogen for storing renewable energy

Global energy demand grew by 114% between 1978 and 2018 [1], with fossil fuels mainly meeting this growth. Fossil fuels still account for more than 80% of global energy demand [2] and their widespread use contributes significantly to greenhouse gas emissions, thereby accelerating climate change. This situation calls for a profound transformation of our energy systems, transitioning to cleaner, more sustainable energy sources.

Renewable energy, such as wind and solar power, is central to the energy transition. They offer solutions for producing low-carbon electricity, but their intermittent production is not always aligned with consumption needs. Periods of overproduction can therefore occur, for example on particularly sunny or windy days, when the amount of electricity produced can exceed demand.

Various solutions can be implemented to manage the excess energy produced by an electricity grid. First, the export of electricity to other grids via interconnections should be considered. This solution allows the energy to be used directly, with losses only related to the transmission of electricity. If the electricity cannot be consumed directly, storage solutions can then be considered. For example, the use of pumped storage hydroelectric dams allows energy to be stored seasonally so that it is available during periods of high consumption. Another solution is to artificially increase consumption, for example by charging electric vehicles or bringing certain industries, such as hydrogen production, into service. If none of these solutions are possible, producers may be forced to reduce their production or, as a last resort, dissipate the energy in the form of heat (in a railway, for example), which results in energy loss.

The development of efficient interconnections and storage systems is therefore essential, as they provide flexibility and optimize the use of surplus energy. For daily storage, batteries are an excellent storage medium. Storage in the form of hydrogen or other conversion processes (Power-to-X) has lower energy efficiency but offers a long-term storage solution that allows energy to be used for specific industrial and residential purposes, as well as for certain heavy and intensive mobility applications where direct electrification is not possible.

Promoting hydrogen for rail transport

In North America, less than 1% of all rail systems run on electricity. Currently, diesel trains are widely used, particularly for long-distance journeys and in rural areas where electrical infrastructure is lacking or too costly to install. Although electric trains with overhead lines are a sustainable and effective solution for reducing CO_2 emissions, installing electrical infrastructure on railways remains very expensive, which limits their deployment in certain regions. In this context, trains using hybrid technologies (diesel-overhead power lines, battery-overhead power lines, hydrogen-battery) are alternatives to consider for freight and passenger transport.

Hydrogen can be utilized in rail transport in two ways: through internal combustion engine via hydrogen fuel cells. In the first case, the internal combustion engine burns hydrogen to produce mechanical energy but also generates polluting particles from the combustion process. In the second case, the fuel cell converts hydrogen into electricity on board, powering a battery and electric motors, with water vapor as the only emission. These technologies represent an attractive alternative for journeys requiring long ranges on non-electrified railways. However, the use of hydrogen in the railway sector requires the establishment of an appropriate infrastructure for its production and distribution. All of these elements—production, distribution, and use of hydrogen—together form a hydrogen energy ecosystem.

Québec's hydrogen strategy

Québec has set ambitious climate targets for 2030: to reduce greenhouse gas emissions by 37.5% compared to 1990 levels and oil consumption by 40% compared to 2013 levels. The ultimate goal is to achieve carbon neutrality by 2050. To achieve these goals, Québec is pursuing electrification initiatives and energy efficiency projects and is considering renewable, low-carbon hydrogen as a solution to meet the energy needs of certain applications. The province is already actively advancing hydrogen technologies and seeks to increase bioenergy production by 50% by 2030. Québec intends to leverage these strengths to be a leader in the energy transition [1].

In January 2021, Air Liquide, a French company, completed construction of the world's largest Proton Exchange Membrane (PEM) electrolyzer in Bécancour[1]. Completed in less than two years, this project doubled the site's hydrogen production capacity by installing a 20 MW electrolyzer that can produce 8.2 tons of green hydrogen per day. Depending on how the hydrogen is transported and used, this production unit can reduce CO_2 emissions by nearly 27,000 tons per year (equivalent to the annual emissions of nearly 8,000 gasoline-powered cars) [1]. This electrolyzer complements the offering of Air Liquide Canada, which also operates natural gas reformers at this site.

In addition, TES Canada, a Canadian pioneer in advancing projects to accelerate the energy transition, is preparing a project in Québec. This initiative involves a total investment of $4 billion in the region, including the commissioning of an electrolyzer and renewable energy production facilities. Once launched in 2028, the project aims to produce 70,000 tons of renewable hydrogen per year exclusively for end consumers in Québec.

[1] This record has since been broken in Shanghai, China, with the installation of a plant comprising 52.5 MW alkaline electrolyzers, with a total capacity of 260 MW and an announced production of 10,000 tons per year [2].

This is one of the largest decarbonization projects announced in Québec, with a goal of reducing annual CO_2 emissions by 800,000 tons [3]. Other projects are also being studied in Baie-Comeau and Sorel-Tracy. It should be noted that in 2023, the largest producers of hydrogen in Québec for their own consumption were the Suncor (176 tons/day) and Valero (96 tons/day) refineries, as well as the steelmaker ArcelorMittal (160 tons/day).

In 2023, Québec has only one hydrogen refuelling station, used mainly for private cars. It is operated by Harnois Énergies. The station is capable of producing approximately 200 kg of hydrogen per day through electrolysis, with electricity supplied by Hydro-Québec [4,5]. This station enabled the government to launch a test bed for fuel cell electric vehicles (FCEVs) in April 2019 to evaluate the performance of FCEVs and the associated production and distribution infrastructure in a northern climate, thereby enriching knowledge about hydrogen-based electric mobility. Until the end of the study period in June 2023, 46 FCEVs (45 Toyota Mirai and 1 Hyundai Nexo) were operated by staff from various government departments in the greater Québec City area. The test bench results revealed variable energy efficiency of FCEVs depending on the outside temperature, with optimal performance in summer and a relative decline in winter ([6]), similar to that of thermal and electric vehicles. The report thus demonstrates the value of these vehicles for northern climatic conditions by highlighting the challenges associated with the implementation of decentralized hydrogen production and distribution. Put into perspective with advances in light battery vehicle technologies, these results support Québec's 2022 Green Hydrogen and Bioenergy Strategy, which confirms the benefits of using primarily carbon-free hydrogen for industries that already consume it (steel, chemicals, etc.) and validates the benefits for heavy-duty transport applications as a complement to electrification (trucks, planes, boats, trains, etc.). It is within this framework that a new demonstration is being carried out in Québec.

In the summer of 2023, a hydrogen train began commercial operation between the stations of Montmorency Falls, near Québec City, and Baie Saint-Paul. The Harnois station supplied hydrogen for this Coradia iLint demonstration train imported from Europe. The main objective was to conduct a concrete demonstration to showcase the technology and show that it, already proven in Europe, could also work in other geographical contexts. In 2023, hydrogen trains have also been tested and deployed on a small scale in North America, in Alberta, Canada (freight transport) and California, United States (passenger transport).

Purpose and scope of the guide

This guide aims to assist rail sector stakeholders in the rail sector (operators, decision-makers, engineers, etc.) in the integration, management, and operation of hydrogen trains in North America. It draws on field experience gained during the commercial operation of Alstom's Coradia iLint train in Québec in 2023 to offer practical and operational recommendations. This guide follows on from the economic and environmental analyses that must be carried out prior to any project. These analyses include:

- Total cost of ownership (TCO[2]): to assess economic viability;
- The cost of CO_2 reduction, to quantify the environmental impact of a technology compared to existing alternatives.

[2] Total Cost of Ownership.

The purpose of this report is to document and analyze the experience gained in Québec in 2023, and to use these findings to support the integration, management, and operation of hydrogen trains in North America. Integration refers to the process of introducing a hydrogen train into an existing rail system and includes analyzing the measures necessary to ensure its compatibility with existing rail infrastructure. This involves addressing technical, logistical, and regulatory challenges to ensure a smooth transition. Management, on the other hand, concerns the organization and coordination of the resources necessary to operate a hydrogen train. This includes maintenance activities, hydrogen supply, route planning, and crew training. Finally, operations cover all practices and procedures related to the daily use of hydrogen trains, including safety, equipment performance, collaboration between stakeholders, and social acceptability. The comprehensive approach presented in this guide, based on feedback, offers advice and recommendations for decision-makers, operators, and engineers involved in current and future hydrogen rail ecosystem projects.

Section 1: Hydrogen ecosystem for railway applications

1. *Electrification of railway applications*

1.1. Background

Rail transport offers significant economic advantages including superior energy efficiency, and increased capacity while requiring less land space than road transport. In addition, rail transport is less dependent on weather conditions and allows for more reliable planning. It plays a crucial role in sustainable development by reducing greenhouse gas (GHG) emissions [7]. Although it accounts for 9% of global freight transport and 8% of passenger transport, railways account for only 3% of the total energy used for transport. Trains are remarkably efficient, eight times more so for freight and twelve times more so for passengers than other modes of transport. However, in the net-zero emissions scenario, all necessary measures must be taken to limit GHG emissions [8–10].

Rail freight transport has grown significantly over the past two decades, particularly in North America, China, Russia, and India, due to the extent of their rail networks and their significant bulk material transport needs. In regions such as Canada, Mexico, and the United States, freight trains are preferred over passenger trains to meet long-distance freight transport demands. Conversely, the European Union (EU), Japan, and Korea prioritize passenger rail services [11]. Rail freight transport is essential to global logistics and the supply chain. It uses technologies such as diesel-electric and electric catenary-battery locomotives to transport different types of goods, which are the result of decades of innovation (see Figure 1).

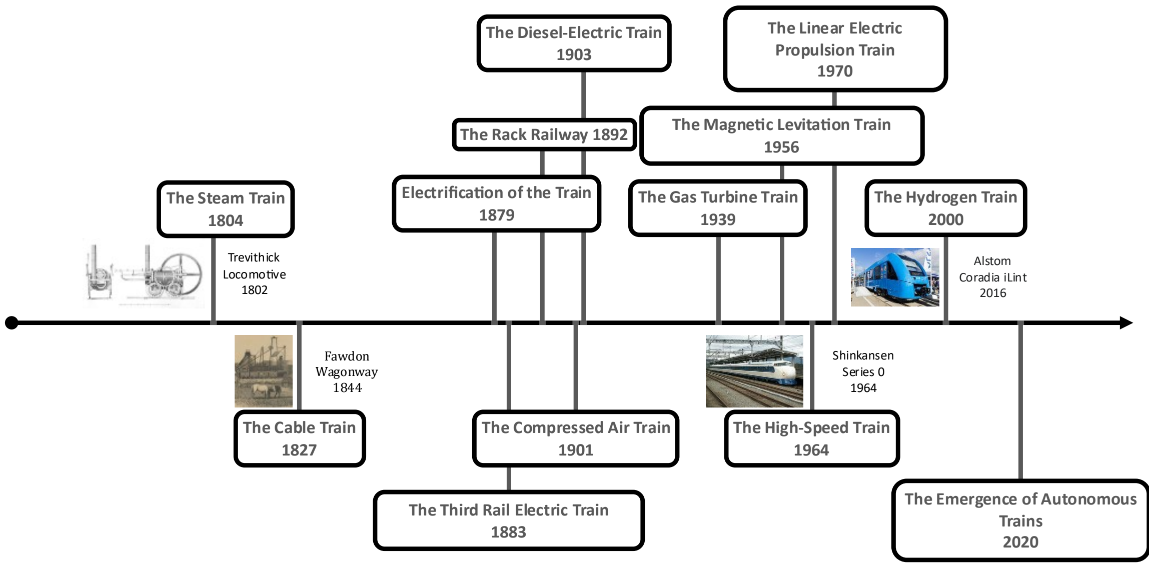


Figure 1 : Chronological emergence of new train technologies, source: IRH-ALSTOM.

The rail traction sector remains largely dependent on diesel, leaving it vulnerable to fluctuating oil supplies and increasing environmental regulations. Globally, electric locomotives account for only about 30% of the fleet in service. Electrification of lines eliminates direct emissions during operation, but its high initial investment cost is a major obstacle, particularly for private operators. The determinants of operating costs differ from region to region. In Europe, the price of diesel is strongly influenced by taxation, while in the United

States it mainly reflects the volatility of the crude oil market. Additionally, installing electrification infrastructure (overhead contact lines/catenaries, substations, control systems) requires significant capital expenditure and long payback periods, which limits the attractiveness of this option despite its potential long-term environmental and economic benefits. Globally, only a quarter of the rail network is electrified; however, these lines account for a significant share of traffic. Electrification rates vary greatly between regions and countries: 99% in Switzerland, 62% in the European Union, and around 1% in North America [12].

It is in this context that alternative solutions that do not depend on electrification infrastructure, such as hydrogen-based energy generation systems (internal combustion engines and fuel cells), are being considered. Depending on how it is produced, hydrogen can contribute to a significant reduction in GHG emissions. An internal combustion engine (ICE) burns hydrogen to produce heat that directly powers the train's traction system or generates electricity for a battery using a generator, emitting water, but also NOx and particulates from combustion. Fuel cells (PACs), on the other hand, produce electricity through the redox reaction of hydrogen with oxygen, emitting only water and heat, to power an electric motor, making the traction system more efficient than one based on combustion. However, the higher cost of energy conversion systems and the challenges associated with storing gas, particularly hydrogen, compared to liquid fuels can be major challenges depending on the application [7]. In recent years, hydrogen fuel cell trains have been tested around the world (see Appendix A2: Summary of international trials and progress of hydrogen trains), as illustrated by the map at Figure 2.

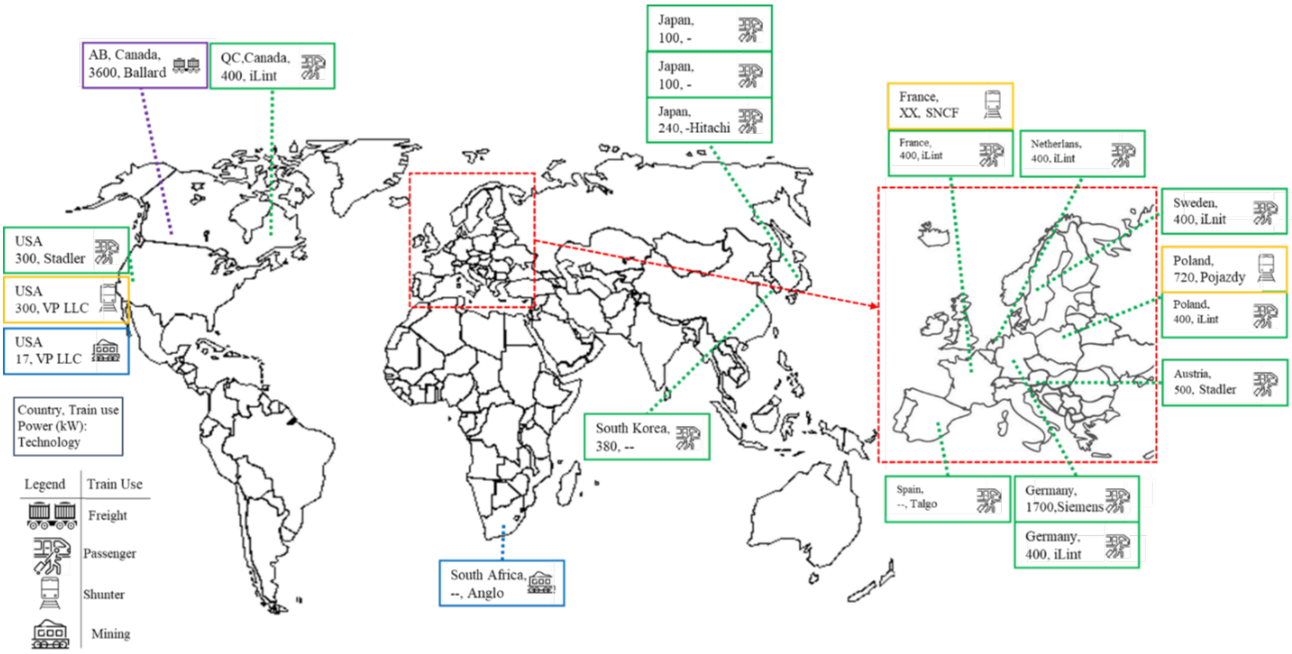
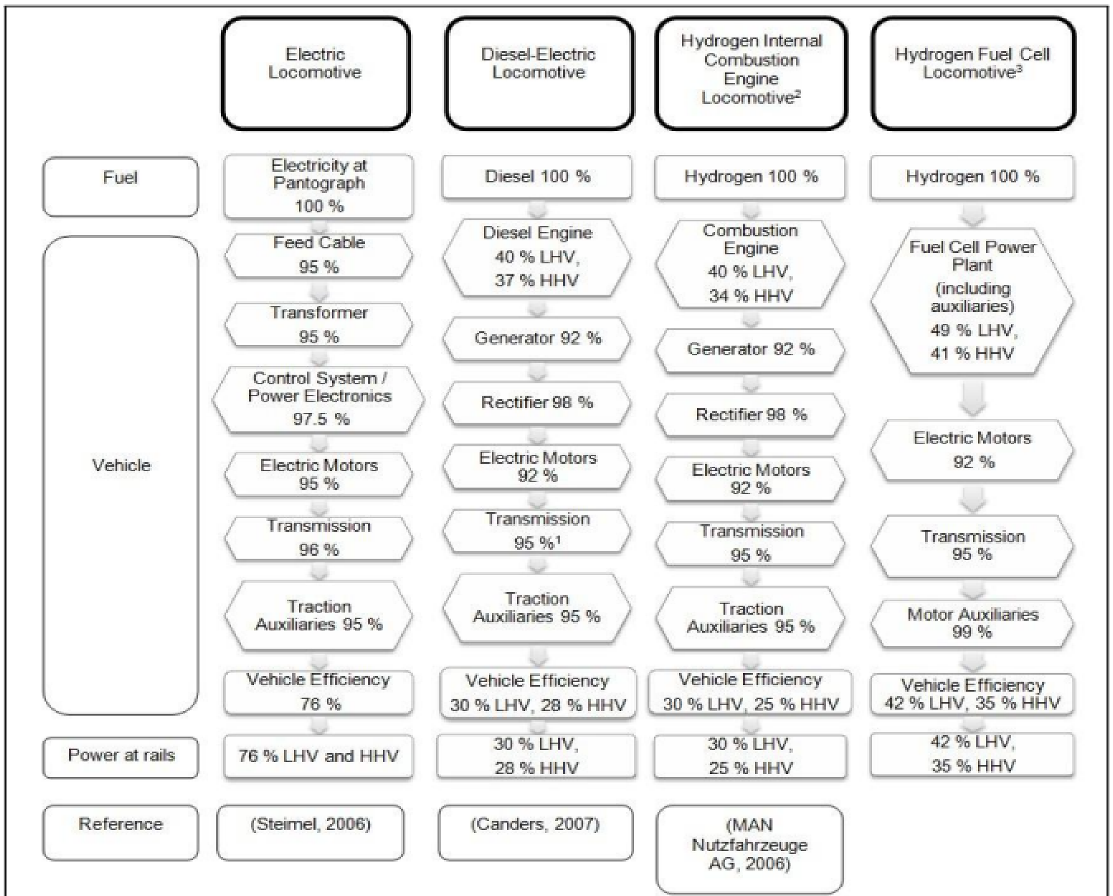


Figure 2 : Demonstrations of fuel cell and hydrogen use in the railway environment before 2024 [13].

1.2. Rail traction systems

The hydrogen train (sometimes referred to as "hydrail") is the generic name for trains whose traction motors are powered by electricity generated from hydrogen. Two technologies can harness the energy contained in hydrogen: the internal combustion engine and the fuel cell. In both cases, the energy system can incorporate a battery to support the train's power demands and recover energy during braking using a power converter. The energy system is considered hybrid as it utilizes multiple energy sources.

Just as an internal combustion engine requires auxiliary equipment such as a battery (for starting and operating accessories) or a cooling system, a fuel cell needs a battery, thermal (or water) regulation, and an energy control and distribution system. All this equipment together makes up the fuel cell system. A comparison of the traction chains of these four locomotive technologies (electric with catenary, diesel-electric, hydrogen internal combustion engine, and hydrogen fuel cell) shows that the electric locomotive has the best energy efficiency. The two technologies involving combustion are the least efficient, while the fuel cell technology has a slightly higher efficiency (see Figure 3). In this analysis, only the efficiency of energy use from the tank to the wheel is compared, based on the different equipment that makes up the traction chain.



Notes:
[1]Canders (2007) does not consider auxiliaries; the auxiliary value from Steimel (2006) of 95 % has been added.
[2]The Hydrogen ICE Locomotive does not exist. MAN produced hydrogen internal combustion engines for buses. In this comparison this engine substituted the diesel engine.
[3]For the fuel cell locomotive, only the fuel cell power-plant efficiency was determined. It is built from a diesel-electric locomotive, therefore, the efficiency chain from a diesel has been used. Auxiliaries, such as ventilation and cooling of the fuel cell stack, are already included in the power-plant efficiency, so the auxiliary value at the end of the chain is motor-specific and accounts, for example, for traction motor cooling.

Figure 3 : Comparison of efficiencies, from tank to wheel, for an electric locomotive (catenary), diesel with electric motor, hydrogen combustion engine, hydrogen fuel cell (from [14]).

1.3. The Coradia iLint Passenger Train

The Coradia iLint is an electric passenger train powered by hydrogen fuel cells, developed by the multinational rail transport company Alstom. It is designed to offer an environmentally friendly and efficient alternative to traditional diesel-powered trains. Alstom developed its first hydrogen train in 2016 by adapting the design of a diesel-powered train. These trains use an electric motor powered by a hydrogen fuel cell, which uses hydrogen stored on the roof of the train with oxygen from the air to generate electricity. Onboard batteries also store braking energy and support high power demands.

The main feature of the Coradia iLint is the use of hydrogen fuel cells combined with a battery to generate electricity for the motor. The commercial version of the Coradia iLint has a range of up to 1,000 kilometers on a full hydrogen tank, allowing it to operate on non-electrified railways without modifying the track, but requiring hydrogen production and distribution along its route. It can reach a maximum speed of 140 kilometers per hour, making it suitable for regional and suburban rail services. The Coradia iLint, in its series version, can carry up to 153 seated passengers and 150 standing passengers. By using renewable or low-carbon hydrogen, the Coradia iLint is a train that helps reduce greenhouse gas emissions compared to an equivalent diesel train, while also reducing particulate emissions and noise.

The first tests of the Coradia iLint were carried out in Germany. They began in 2018, when two Coradia iLint demonstration trains were put into service in the Lower Saxony region. These tests aimed to demonstrate the feasibility and technological viability of the hydrogen train, as well as to evaluate its performance and suitability for commercial use. The Coradia iLint was tested under real operating conditions, carrying passengers on regular lines. One of these two demonstration trains was deployed in Québec in 2023.

2. *Integrating hydrogen into a rail ecosystem.*

2.1. What is hydrogen?

Hydrogen is the simplest of all chemical elements. The hydrogen atom consists of a single proton around which a single electron orbits. It is the lightest and most abundant element in the universe, accounting for approximately 75% of all baryonic mass in the universe [15]. However, it exists only in very small quantities in the Earth's atmosphere and is virtually non-existent in its pure form. On Earth, hydrogen is chemically bound to other elements such as water, biomass, and fossil fuels [15]. However, it is possible to isolate it to obtain pure molecular hydrogen in the form of a gas whose molecules are composed of two atoms, hence its chemical formula H_2. This is referred to as an energy carrier. Like all gases, hydrogen liquefies when cooled sufficiently to reach a temperature of -253°C at ambient pressure [16]. Finally, hydrogen is also found in the Earth's crust as a gas. This natural hydrogen may be generated by water/rock interaction (diagenesis)[3] and by the natural radioactivity of the Earth's crust (radiolysis) [17].

[3]Diagenesis releases hydrogen from water during oxidation processes, which occur in various geological contexts.

2.2. How is it used?

Hydrogen can be used in many applications. It is used as a raw material in various industrial processes, including ammonia production for fertilizers, oil refining, and chemical manufacturing. In addition, hydrogen can be used directly as fuel in a gas turbine or internal combustion engine. It can also be injected in small quantities into natural gas networks (to reduce the carbon footprint of natural gas). It can also be used as a reactant in fuel cells for residential applications (electricity and heating) and for transportation.

2.3. How is it produced?

Hydrogen can be produced from various sources, for example by steam reforming natural gas or by using electricity from renewable energy sources for water electrolysis. Steam reforming of natural gas is currently the most common method for producing hydrogen. During this process, water vapor reacts with natural gas at high temperatures (840 to 950°C) and moderate pressure (approximately 20 to 30 bar) in the presence of a catalyst (usually nickel) to produce hydrogen and carbon dioxide. However, this method has the disadvantage of releasing carbon dioxide (CO_2) into the atmosphere as a b-product. CO_2 capture and storage (CCUS) technologies are being studied to minimize this impact, but issues involving methane leaks associated with these systems have so far prevented any significant improvement in the environmental benefits of producing hydrogen from natural gas [18].

Water electrolysis breaks down water molecules into hydrogen and oxygen by passing an electric current between two electrodes immersed in water. This production method does not emit greenhouse gases or pollutants during operation. However, its impact is directly linked to that of the electricity used and is therefore minimal when produced from renewable energy sources, such as solar or wind power (see Appendix A1: GHG emissions from different types of hydrogen production). Finally, there are a multitude of processes using various raw materials for hydrogen production. An overview of these processes is summarized in the Table 1.

With the multiplicity of processes and raw materials used to produce hydrogen, a classification of hydrogen types has emerged. Based on a color code, it attempts to identify the origin of hydrogen according to its production method [19]. Subject to debate and not standardized, it has many limitations and causes confusion, particularly regarding the carbon intensity of the hydrogen produced. However, for information purposes, we present here a color palette that is often used to represent hydrogen according to different production methods based on their raw materials/inputs and estimated carbon intensity. Among the most common are: (i) Grey hydrogen, which is produced from fossil fuels and whose carbon dioxide emissions are not captured; (ii) Blue hydrogen, which is produced in a similar way to gray hydrogen, with the only difference being that carbon dioxide emissions are captured and stored; and finally (iii) Green hydrogen, which uses renewable energy sources that minimize emissions. It should also be noted that several sources of native hydrogen (white hydrogen) have been identified in recent years in various locations around the world, and extraction projects are under consideration [20]. To date, only one project is commercially active, in Mali. To avoid confusion that may arise from this classification, hydrogen production methods should be classified according to their carbon intensity [21]. Thus, hydrogen produced using renewable energies is called renewable hydrogen, and hydrogen produced with low carbon intensity, regardless of the method, is called low-carbon hydrogen.

2.1. How should it be stored?

As with any other fuel, the safe and efficient storage of hydrogen is crucial to its use as an energy carrier. According to the US Department of Energy (DoE), the main technical challenge for hydrogen storage in transportation has been identified as the ability to store enough hydrogen to meet range requirements (> 480 km) while meeting cost, safety, and performance requirements [33]. Before hydrogen can be used as an energy carrier, it must be transported and stored. Various methods are available for storing hydrogen, each with its own specific advantages and limitations, making them suitable for different applications. Figure 4 illustrates the different methods for storing hydrogen. In this section, we will briefly describe compression storage, which is the most widely used option today, as well as liquid storage and cryogenic compression storage. Other methods, based on materials, are still in the research and development stage or are only just beginning to be commercialized.

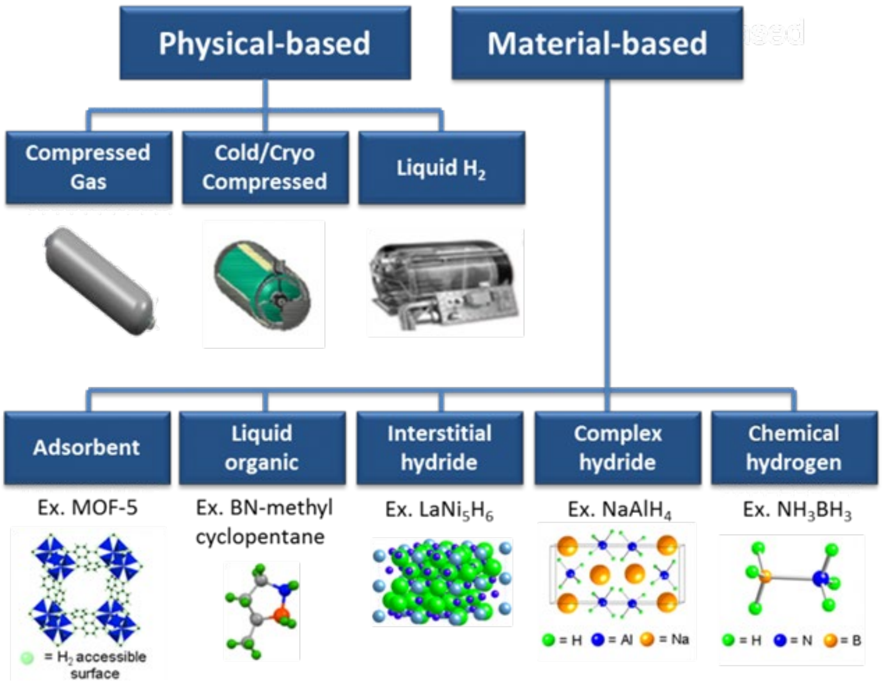


Figure 4 : Different methods for hydrogen storage [33].

Table 1 : Overview of hydrogen production methods, their degree of maturity, their share in production, and their carbon intensity.

Production method	Process	Raw material	Maturity	Share of production	Carbon intensity $kgCO_2e$[4] $/kgH_2$ (without carbon capture)	Source
Thermochemical	Steam reforming	Natural gas, petroleum by-products (distillates, etc.)	Commercial	78	10-13	[22–24]
	Gasification	Coal	Commercial	21	22-26	[22,24]
	Gasification Pyrolysis	Biomass	Commercial	< 2%	6-11	[24–26]
Electrochemical	Electrolysis	Raw material: Water Electricity from: Biomass; Wind; Hydro; Nuclear; Natural gas; Coal; Oil	Commercial	< 2%	0-57	[22,24,25,27,28]
Biological	Microbial electrolysis	Raw material: Biomass Electricity from: Biomass; Wind; Hydro; Nuclear; Natural gas; Coal; Oil	R&D	-	-	[29,30]
	Fermentation Photofermentation	Biomass	R&D	-	-	[31,32]

[4] The CO_2 equivalent (CO_2e) of a greenhouse gas emission is the amount of carbon dioxide CO_2 that would cause the same cumulative radiative forcing over a given period, i.e., that would have the same capacity to retain solar radiation. It depends on the gas and the period considered.

Compression storage

Hydrogen storage by compression has now established itself as the most mature on-board storage method due to its high performance and practicality. It involves physically storing hydrogen gas in high-pressure tanks, which are commonly classified into four standard types: Type I, II, III, and IV. These standards depend on the lightness and cost of the tank material capable of withstanding high pressure requirements, the material's resistance to hydrogen diffusion, and the damage that may be caused by the stored hydrogen [34]. For hydrogen storage by compression, it is essential to consider several important factors. First, the tank material must be lightweight, inexpensive, and strong enough to meet the required stress, deformation, and safety specifications. In addition to the material composition, the geometry of the tank is also a crucial consideration.

In vehicle applications, hydrogen should be stored in cylindrical tanks, as spherical tanks can be difficult to integrate on board. Finally, the thermal conductivity of the material must be high enough to handle the exothermic heat during tank filling (compressed storage offers high rates of hydrogen filling and release) [35]. TheTable 2 : Some properties of tanks for on-board storage of high-pressure hydrogen.illustrates some properties of hydrogen tanks [36]. Commercially, hydrogen fuel cell vehicles are increasingly using high-pressure tanks for compressed hydrogen storage. Notably, the Toyota Mirai and Hyundai Nexo vehicles use compressed hydrogen at a pressure of 700 bar, equipped with three type IV cylinders, and can travel more than 600 km on a single charge [34].

Table 2 : Some properties of tanks for on-board storage of high-pressure hydrogen.

Type	Materials	Typical pressure (bar)	Gravimetric density (%)*
I	All-metal construction	300	1.7
II	Mostly metal, wrapped in composite in the circumferential direction.	200	2.1
III	Metal coating, completely wrapped in composite material.	700	4.2
IV	Entirely constructed of composite material	700	5.7 (Toyota Mirai)

*Percentage by weight (weight of H_2 stored / weight of tank)

Liquid storage

Hydrogen liquefies at -253°C, reaching a density of 70.8 kg/m³ [3], which is 68% higher than that of hydrogen gas compressed to 700 bar (42 kg/m³) under normal temperature and pressure conditions, hence the interest in storing hydrogen in liquid form. Liquid hydrogen is currently a common storage method for large quantities for possible transfer by tanker truck, train, or ship to the place of use. The aerospace and nuclear industries were among the first to adopt liquid hydrogen because of its high energy density and purity. The development of liquid hydrogen production and storage systems was accelerated by research and production of liquid hydrogen-based rocket propulsion during the early decades of the last century. Although liquid hydrogen can only exist at low temperatures and low pressures, the corresponding tanks can be lighter because they operate at lower pressures. Nevertheless, to store hydrogen in liquid form, it is essential to keep the temperature of the hydrogen below its boiling point of -253°C to prevent overpressure in the storage container. This requires precise temperature control and the installation of cooling systems. Effective insulation of storage tanks is also crucial to minimize hydrogen loss through evaporation.

Liquid hydrogen is housed in double-walled cryogenic tanks, which can be cylindrical or spherical double-walled containers, where the inner and outer walls are separated by several layers of vacuum to ensure thermal insulation. The construction of these tanks involves the use of specific materials to minimize energy transfer by conduction or radiation from the environment to the tank. These materials must be able to withstand the low temperatures of liquid hydrogen, prevent gas permeation, and resist the effects of hydrogen embrittlement[5]. However, the greatest energy loss in this form of storage is due to the high costs of the existing liquefaction process, which consumes between 11.9 and 15 kWh/kg CHECK of H_2, corresponding to 35 to 45% of the lower calorific value of hydrogen [6] [37].

Cryogenic compression storage

Cryogenic compression storage combines aspects of both compressed hydrogen gas and cryogenic hydrogen. Hydrogen is stored at cryogenic temperatures and under a minimum hydrogen pressure of 250 to 350 bar and at temperatures between -150°C and -240°C. Compared to liquefied hydrogen, cryo-compressed hydrogen offers higher densities of around 80 kg/m³ (which is 13% higher than the density of liquefied hydrogen and 90% higher than that of compressed hydrogen gas at 700 bar ([38,39]). However, this storage method presents additional challenges related to pressure management, low temperatures, and liquefaction, as with liquid hydrogen.

2.2. How can it be transported?

Hydrogen can be produced locally (decentralized) or centrally. Decentralized hydrogen production means that the molecule is produced close to where it is used, while in centralized production, the molecule is produced in large plants and transported over long distances. Localized production may produce less hydrogen and be more expensive, but transportation is less costly. On the other hand, centralized production allows more hydrogen to be produced efficiently and at lower cost, but transportation is more expensive [40]. This process involves the safe and efficient movement of hydrogen gas or other forms of hydrogen from production facilities to end users, such as industrial consumers, refuelling stations, or other applications (see Figure 5 and Table 3). The most common options for hydrogen transport are by truck and pipeline (between two plants, for example) [42,43].

Transport by pipeline.

Pipelines are commonly used in the chemical industry to transport large quantities of hydrogen in a continuous flow. Pipelines dedicated to hydrogen are used to transport hydrogen from production sites to distribution points. These pipelines are designed to minimize the effects of hydrogen embrittlement, which can affect the integrity of pipeline materials. This means of transport requires the use of compressors.

Transportation of liquid hydrogen.

It can be transported in cryogenic tanks. Liquid hydrogen is stored at extremely low temperatures (-253°C) and transported in specially designed cryogenic tank trucks or by ship.

[5] This phenomenon occurs due to the diffusion and dissolution of hydrogen in the microstructure of pipes or metal infrastructure. Combined with mechanical stresses, hydrogen creates capillary cracks that gradually grow over time.

[6] The lower heating value (LHV) is the amount of heat released by the complete combustion of a unit of fuel, assuming that the water vapor is not condensed and the heat is not recovered.

Hydrogen tube trailers.

These are specialized transport vehicles that carry compressed hydrogen in a series of interconnected high-pressure tubes (delivered by truck).

Bulk transport in compressed gas cylinders.

For smaller quantities of hydrogen, hydrogen can be transported in compressed gas cylinders. These cylinders are typically made of high-strength materials and are pressurized to safely store and transport hydrogen.

Transport of hydrogen via ammonia.

Since ammonia is easier to transport and store than hydrogen, it can be cracked to release hydrogen at the destination, either through catalytic processes or other methods.

Transporting hydrogen using liquid organic hydrogen carriers.

Liquid organic hydrogen carriers are chemical compounds capable of absorbing and releasing hydrogen. They are used to transport and store hydrogen at ambient temperatures and pressures, making them more convenient for certain applications.

Table 3 : Comparison of different means of transporting hydrogen (source: IRH)

Means of transport	Pipeline (H2 gas)	LH_2truck (liquid hydrogen)	Tube trailer (200–500 bar)	Ammonia (NH_3) carrier	LOHC (organic carrier)
Energy efficiency	Highest for continuous flows over long distances (excluding compression) ; best relative efficiency	Medium, with losses from liquefaction and boil-off ; higher losses due to cooling	Good for short distances ; efficient short-term	Lower chain efficiency (hydrogenation /dehydrogenation) ; mature for maritime	Similar to NH_3, leverages waste heat ; good for ambient conditions
Impacts (climate, environment…)	Low operational impacts ; monitor H_2 leaks and material embrittlement	Footprint tied to electricity source ; fewer trips per ton ; higher if gray energy used	Road traffic, noise, transfer leaks ; medium impact	NH3 toxicity, NOx risks ; mature logistics ; higher risks than pure gas	Ambient conditions ; solvent risks ; safer than NH_3
Optimal use cases	Large volumes, fixed permanent connections; ideal for stable industrial corridors	Medium/high volumes, medium distances without pipelines ; flexible alternative	Small/medium volumes, short distances, rapid deployment ; ideal local/flexible	Long distances (especially maritime), direct NH_3 use ; best international	Decentralized supply via existing liquid logistics, waste heat available

Selecting a hydrogen transportation method depends on variables such as hydrogen volume, distance, infrastructure availability, safety considerations, and economic efficiency. For stable corridors and high flow rates, pipelines are the most efficient and economical in the long term. For low/medium volumes and short distances, tube trailers are flexible and fast. For higher volumes and medium distances without pipelines, liquid hydrogen becomes competitive despite the decrease in efficiency due to liquefaction. Over long international distances, ammonia may be the best carrier, especially if the end use can consume it directly (otherwise, the user will have to factor in the energy cost of cracking). Finally, liquid organic hydrogen carriers are attractive for exploiting liquid fuel infrastructure and waste heat, with good solvent management. The actual environmental footprint depends heavily on electricity and thermal integration; controlling leaks (H_2, NH_3, solvents, etc.) remains crucial to avoid climate and/or environmental impact.

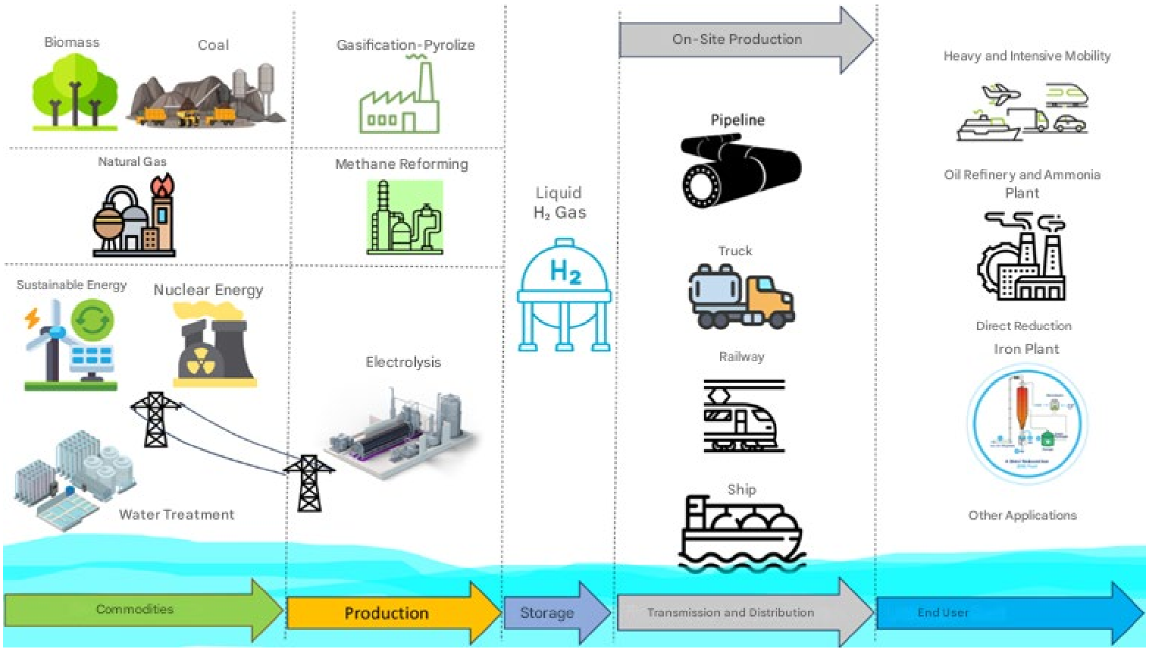


Figure 5 : Hydrogen production, storage, transport, and use, adapted from [41].

3. *Global overview*

3.1. Supply and demand in 2023

Demand for hydrogen in 2023 is primarily driven by traditional applications such as oil refining, which peaked at 40 Mt of H_2 in 2018 before falling by around 2 Mt of H_2 in 2020 due to the economic slowdown caused by Covid (estimates for 2021 are around 41 Mt of H_2 in 2020 due to the economic slowdown caused by Covid (usage estimates for 2021 are around 41 Mt of H_2), ammonia synthesis with 34 Mt of H_2, and methanol production with 5 Mt of H_2 (see Figure 6).

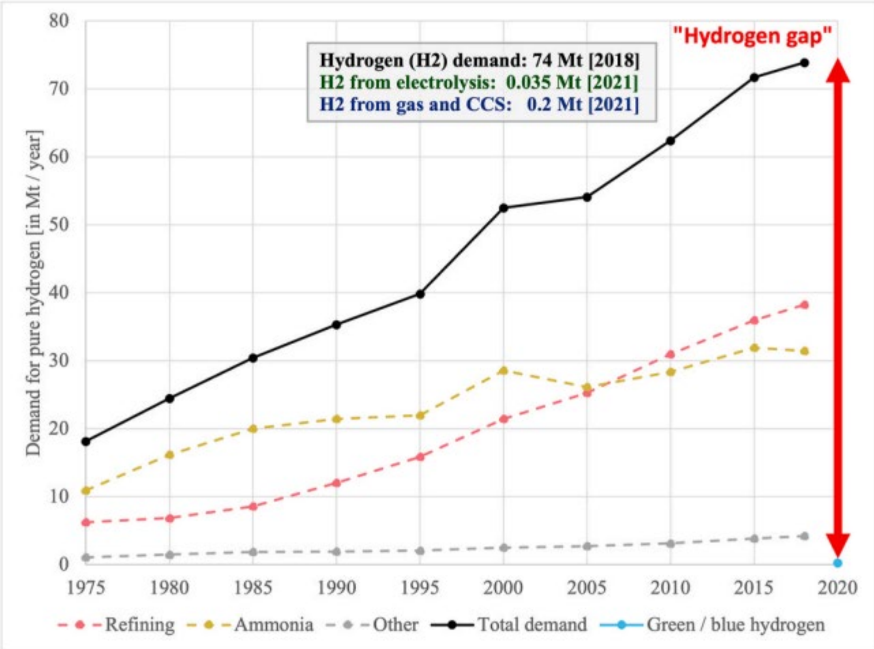


Figure 6 : Global hydrogen demand trends through 2020 for oil refining, ammonia, and other activities (steel, methanol, heat, chemicals, cement, pulp and paper, glass, aluminum, ceramics, transportation, etc.) compared to renewable and low-carbon hydrogen production [44].

All hydrogen applications can be classified into four main categories: chemical uses, energy uses, physical uses, and medical and scientific uses [45]. The penetration of renewable and low-carbon hydrogen remains very limited in heavy industry applications, reaching only around 40 kt of H_2 , which represents just 0.04% of total global hydrogen demand in 2021 [22]. Most of this demand is concentrated in road transport, which has seen a significant 60% increase due to the accelerated deployment of hydrogen fuel cell electric vehicles, particularly heavy-duty vehicles, in China [22].

According to the *Global Hydrogen Review 2023* report published by the International Energy Agency (IEA), hydrogen production comes mainly from fossil fuels [22]. In 2022, total global production amounted to 95 million tonnes of hydrogen (Mt of H_2), resulting in associated emissions of more than 900 Mt of CO_2 (Figure 7) As in 2021, the main production method, accounting for 62% of total production, was the use of natural gas without carbon capture and storage. Hydrogen produced from coal, mainly in China, accounted for 21%. Hydrogen obtained as a by-product of catalytic reforming of naphtha[7] in oil refineries accounted for 16% of global production [22]. Meanwhile, the use of oil, in limited quantities, contributed less than 1% [22].

The production of renewable hydrogen by electrolysis (from renewable energy sources) increased between 2021 and 2023. Although this proportion is very low, hydrogen production by water electrolysis increased by around 20% compared to 2020, reflecting the growing deployment of electrolyzers. China has the largest share of the renewable hydrogen production market, followed by Australia, Germany, the United States, and finally Saudi Arabia (see Figure 8).

[7] Naphtha is a transparent liquid produced by the distillation of petroleum.

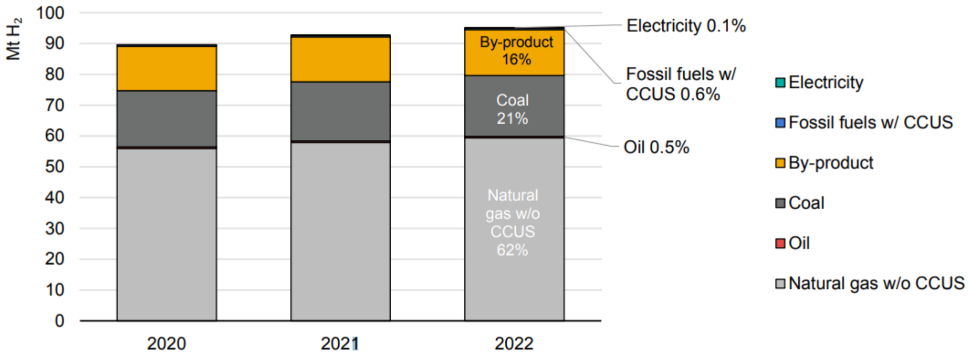


Figure 7 : Global hydrogen production between 2020 and 2022 [24] (CCUS = carbon capture, utilization, and storage)

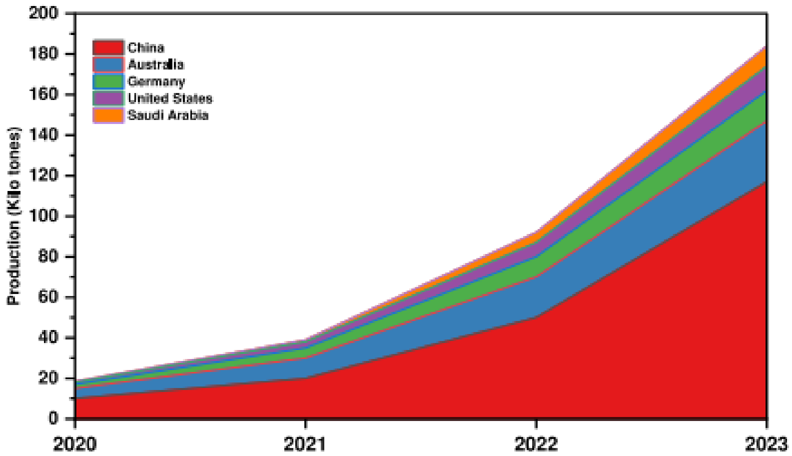


Figure 8 : Global market share of renewable and low-carbon hydrogen (from [46])

3.1.1.Hydrogen production in Europe

In 2021, the largest producers of hydrogen were Germany (2⸱398 million m³), the Netherlands (2⸱015 million m³), France (1,163 million m³) and Spain (1⸱316 million m³), which also have the highest consumption. The Netherlands is the largest exporter of hydrogen, while Belgium imports the largest quantities of hydrogen [47].

European Union (EU) countries consume around 9.7 million tons of hydrogen per year [47]. Demand for hydrogen varies across economic sectors. In 2019, the highest demand for hydrogen was in Germany (1.68 million tons), the Netherlands (1.28 million tons), Poland (0.77 million tons), Spain (0.60 million tons), and Italy (0.55 million tons) (see Figure 9).

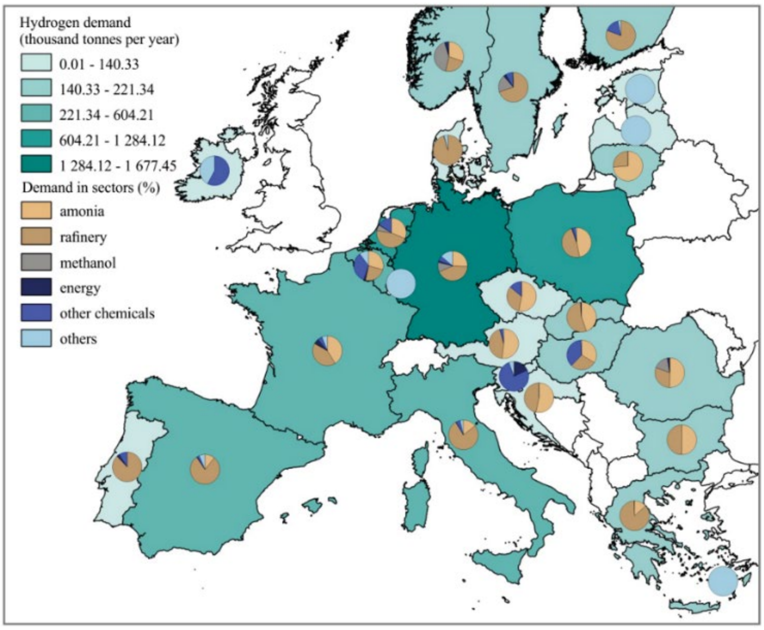


Figure 9 : Demand for hydrogen by sector in tons per year, data as of the end of 2019[8] (from [47]).

An interactive map allows users to track the specific deployment of hydrogen infrastructure in Europe at [48], and a map of renewable and low-carbon hydrogen production projects worldwide is updated annually on the International Energy Agency website [49].

3.1.2. Hydrogen production in North America

Maps of hydrogen production in Canada and the United States at the end of 2023 are available at Figure 10 and Figure 11, respectively.

[8] The "Other" category covers demand from small- and medium-scale hydrogen users, including the food industry, glass manufacturing, automotive, and transportation.

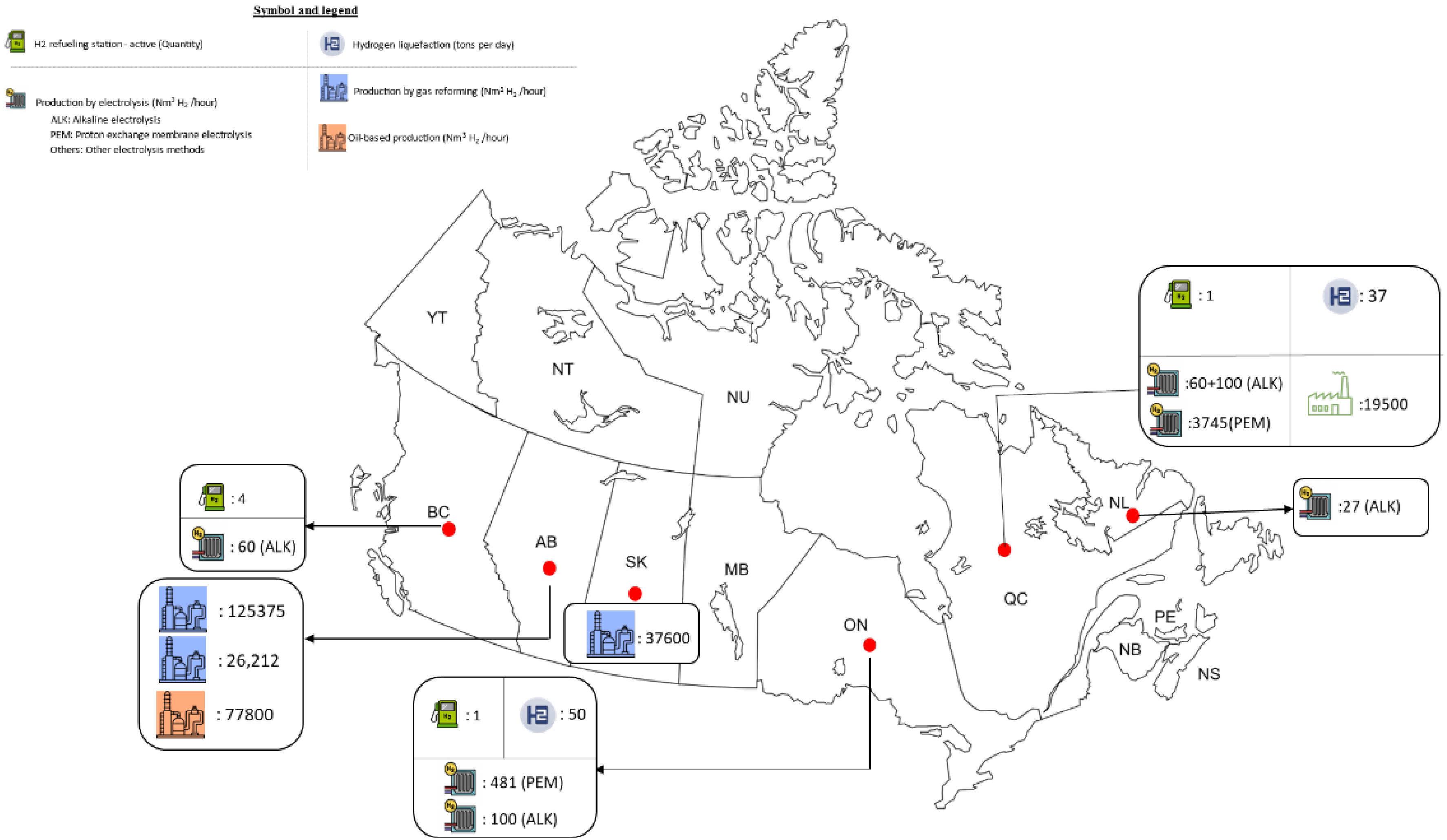


Figure 10 : Hydrogen infrastructure in Canada in 2023, map based on data from [4,50–52] , source: IRH-UQTR.

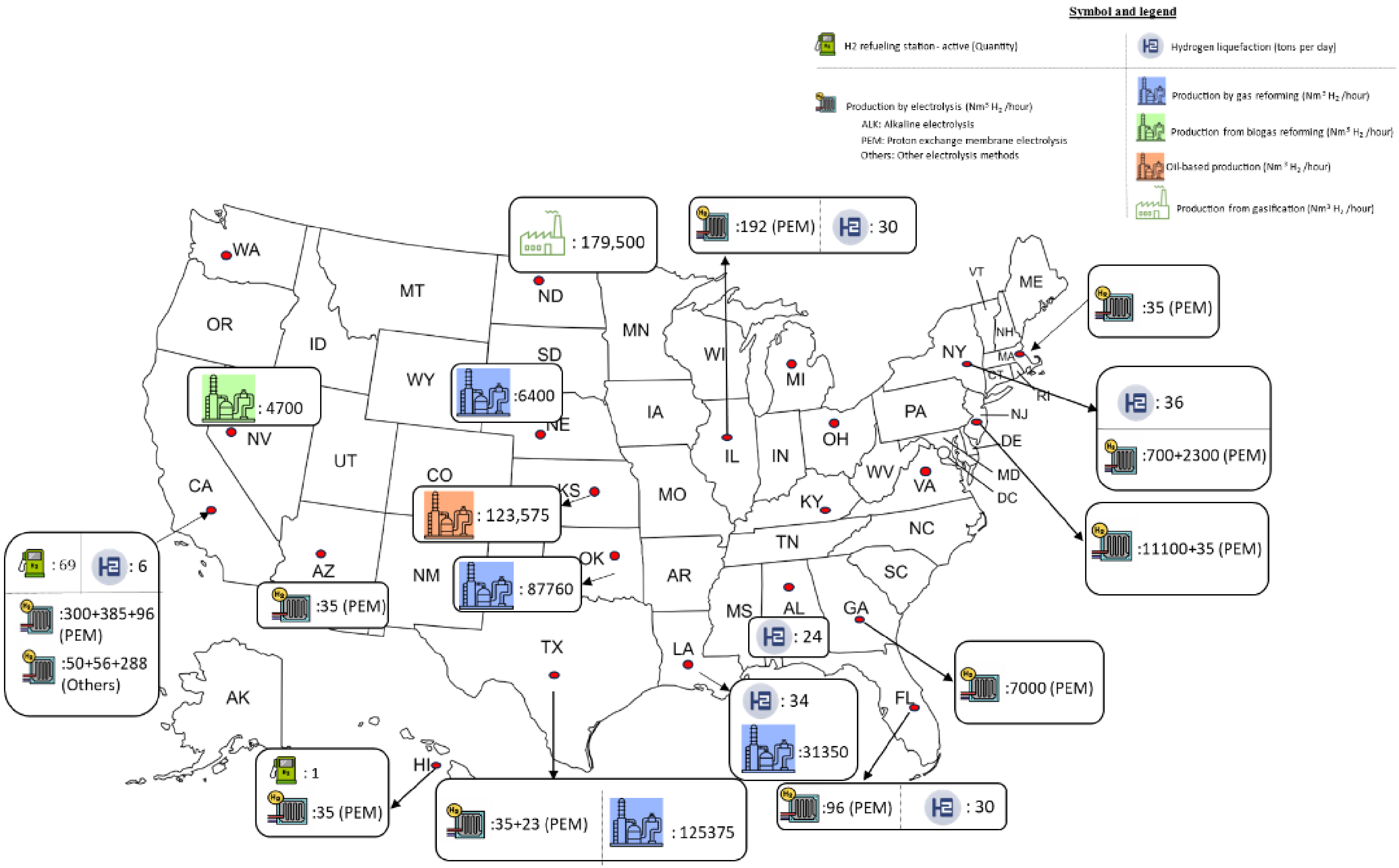


Figure 11 : Hydrogen infrastructure in the United States in 2023, map based on data from [4,50–52] , source: IRH-UQTR.

3.2. Example of creating hydrogen ecosystems for transportation

Let's start with an innovative example from across the Atlantic: an airport environment in Toulouse, in southwestern France, hosted the Hyport project [53]. This project led to the installation of the first electrolyzer in an airport zone in Europe, inaugurated in December 2023. It was financed to the tune of €5.2 million out of a total project cost of €7.2 million, including €1.9 million for hydrogen production and distribution alone. With a capacity of 1 MW, it uses electricity and 9 tons of water to produce 430 kg of hydrogen per day to power twenty hydrogen buses. These buses operate at very high frequency at all times and require rapid refuelling. One station is installed in the airport and a second outside (see Figure 12 : Example of the Hyport project, France [53].Figure 12). The surplus hydrogen generated is expected to be used for future applications that will be implemented at the airport: powering shuttles and trolleys, initially for baggage and eventually for towing aircraft arriving on the Toulouse runways or leaving the Airbus factories, generators that supply electricity to aircraft when they are on the runways, and trucks and buses.

The site also includes an export area that allows for the potential surplus of renewable hydrogen to be used for events (generators), to decarbonize industrial processes and produce e-kerosene. This area can also be used to import hydrogen during possible consumption peaks.

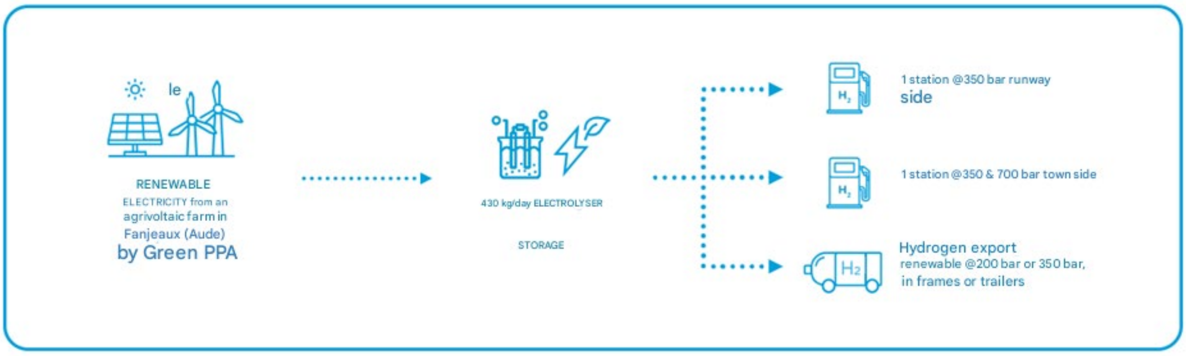


Figure 12 : Example of the Hyport project, France [53].

This project is part of a larger project led by the Occitanie region called Corridor H2, which is part of a Europe-wide initiative to develop a series of hydrogen production and distribution capacities for mobility from the Iberian Peninsula to northern Europe, coupled with the deployment of numerous heavy-duty vehicles using hydrogen.

The first building block of this European project has therefore been launched with the aim of deploying the following in Occitanie by the end of 2023: 2 renewable hydrogen production units representing 6 tons/day of cumulative production, 7 hydrogen distribution stations (from 600 to 1,200 kg/day), 40 hydrogen-powered trucks, 62 trailers/refrigeration units, and 15 retrofitted regional intercity coaches. With support from the European Investment Bank (€40 million) and the European Commission (€14.6 million), and a total budget of €110 million in investments. In France, the Occitanie region is the first to have launched a hydrogen corridor project on its territory.

4. *Comparisons of energy ecosystems for railway applications*

4.1. Energy comparison

Energy comparisons with other molecules show that hydrogen is the fuel with the highest energy content per unit mass. The chemical energy in 1 kg of hydrogen, 120 megajoules (MJ), is equivalent to that in 2.6 kg of natural gas, 2.8 kg of gasoline, or 5.2 kg of coal (see Table 4).

Table 4 : Comparison of the energy properties of H_2 with other fuels under standard conditions[9] [54-56].

	Density (kg/m³)	**Lower heating value[10]**	
		Specific (MJ/kg)	**Volumetric (MJ/liter)**
H_2 (gas)	0.071	120	0.008
H_2 (liquid)	70.798	120	8.501
Natural gas[11]	0.777	47	0.037
Conventional gasoline	744.701	43	32.356
Gasoline/Diesel[12]	846,936	43	36,090
Fuel oil/Heating oil[13]	840	42.69	35,850
Methanol	794.101	20	15,956
Propane (gas)	2,009	46	0.0373
Propane (liquid)	507.210	46	23.482

On the other hand, unlike other fuels such as gasoline, which are liquids at ambient conditions, hydrogen is a very light gas. Although its energy content per unit of mass is high, its energy content per unit of volume is very low. Thus, its density at 0°C and ambient pressure is only 71 grams per cubic meter (0.071 kg/m³), which is about eleven times lower than that of natural gas. Therefore, to obtain the same amount of energy, a volume of hydrogen approximately two and a half times greater than that of natural gas must be burned. Similarly, the density of one liter of liquid hydrogen is low (70.8 kg/m³). Therefore, the energy content of one liter of liquid hydrogen corresponds to that of 0.27 L of gasoline, whose density is 10.5 times higher (see Figure 13). This comparison is valid for an application where the fuel would be burned directly. However, in the case of a vehicle with an internal combustion engine, all vehicles would have to be compared in order to conclude on the efficiency of one fuel over another. This is because the systems that make up the engine and fuel tank will not necessarily be identical, which will have an impact on the vehicle's efficiency and therefore its range.

[9] 1.013 bar, 25°C.
[10] Does not take into account the condensation energy of the water vapor produced.
[11] Natural gas is a gaseous mixture extracted from the ground, composed mainly of methane (generally 85 to 98%), but it also contains other gases in small quantities, such as ethane, propane, butane, carbon dioxide (CO_2), nitrogen (N_2), and sometimes traces of sulfur or other impurities.
[12] Low-sulfur diesel.
[13] A fossil fuel, fuel oil is a petroleum-derived fuel used mainly in boilers. The only notable difference between fuel oil and diesel is its lower cetane number.

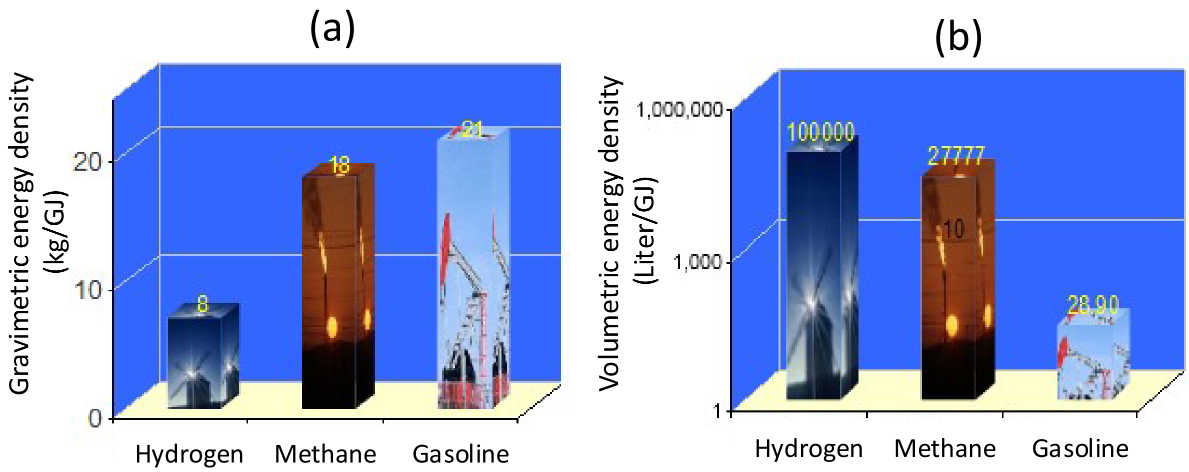


Figure 13 : Comparison between the gravimetric (a) and volumetric (b) energy densities of hydrogen, methane, and gasoline at ambient conditions. Source: IRH-UQTR.

To compare energy storage technologies in electric vehicles, a system-level analysis of the complete powertrain is essential[14] (see Figure 3). Battery electric vehicles store energy directly within the battery pack, whereas hydrogen fuel cell electric vehicles require an integrated system comprising high-pressure tanks, the fuel cell stack, and typically a small auxiliary battery. Gravimetric energy density analysis reveals hydrogen's theoretical superiority by two orders of magnitude over current lithium-ion batteries.

However, complete fuel cell systems achieve substantially higher effective density for light-duty vehicles and even greater advantages for heavy-duty applications where payload constraints dominate. Considering this theoretical advantage, manufacturers prioritize batteries for light vehicles due to rapidly declining costs, mature charging infrastructure, and supportive government policies, whereas fuel cells are better suited for heavy transport where rapid refueling (15 minutes versus hours for batteries) and superior range without weight penalties are critical operational requirements.

Battery technology continues rapid evolution, with emerging chemistries progressively closing the performance gap for light-duty applications while fuel cell vehicles maintain dominance in weight-critical heavy transport.

4.2. Technical Feasibility

While diesel locomotives have been the industry standard for over a century, mounting environmental concerns and emission regulations are driving a shift toward cleaner alternatives. Electric locomotives, on the other hand, transmit approximately 85% of their energy to the wheels (95% considering the efficiency of the traction motor alone), making them more efficient than diesel-powered trains (efficiency below 30%). The global market also favors electric locomotives due to lower costs and maintenance expenses. However, the infrastructure required for catenary electrification poses a problem, particularly on long-distance, low-traffic

[14] All of the components of a vehicle that enable it to move are referred to as the "powertrain." Simply put, this powertrain consists of the engine, clutch, transmission, and wheels.

transport corridors [9]. In addition, they require additional land for catenaries, substations, and safety measures, which has an impact on overall project costs [59].

Currently, diesel trains can run on existing non-electrified rail networks and can be refueled by truck at intersections with road connections, such as train stations. To run on non-electrified sections of track, batteries and hydrogen trains are viable options for trains. Batteries have a limited range and can only be used for journeys of around 100 kilometers. The use of dual-mode battery and catenary trains is one solution for optimizing battery range if the electrical infrastructure to power the catenaries is available [57]. A hydrogen train's operational range is determined by its onboard storage capacity and the availability of regional refuelling infrastructure, with refuelling times similar to those of diesel locomotives [58]. This technology may therefore be of interest for decarbonizing railways that are difficult to electrify over distances of several hundred kilometers. The production of renewable, low-carbon hydrogen and the development of refuelling infrastructure are the main challenges that will need to be addressed in the train ecosystem.

4.3. Advantages and disadvantages (hydrogen, battery, and diesel)

From a rail operator's perspective, for short, non-electrified lines, battery trains offer the best efficiency and lowest operating costs, at the expense of more limited range and network charging planning. For longer journeys or in areas where electrification or charging is difficult, hydrogen provides a range close to that of diesel while eliminating local emissions, but with reduced efficiency and higher energy infrastructure costs (in 2023). Diesel remains the simplest solution to implement and offers the most infrastructure flexibility, but it is penalized by emissions, noise, and operating costs that are sensitive to fuel and regulations. The optimal selection depends primarily on the distance between energy nodes, the electrical power available at terminals, the local price of electricity and hydrogen, and climate objectives. Depending on needs and routes, it is possible to integrate several technologies operating on the same rail network.

From an electrical grid perspective, trains powered by overhead lines and batteries are the most efficient option in terms of electricity consumption, provided that the grid can absorb peak loads during periods of high consumption. However, these local peaks can be mitigated by installing stationary energy storage systems, for example. In contrast, the use of hydrogen decouples rail traction from peak demand: controllable electrolyzers can operate during off-peak hours and when renewable energy production peaks, playing a seasonal storage role while providing flexibility to the grid. On the other hand, total electricity consumption will be higher than with batteries (due to losses from electrolysis, compression, and fuel cell system efficiency), and connection constraints will shift to the electrolysis site (for example, 2 tons of hydrogen per day require energy consumption of around 110 MWh per day, or 7 MW of installed power if operated for 16 hours a day). If hydrogen is imported (LH_2 trucks/pipes), the local impact on the railway power grid is low but is transferred to another grid. Diesel, on the other hand, avoids any need for electrical reinforcement but externalizes the impacts (CO_2, NOx, noise) and does not contribute to the flexibility of the electrical system. In summary, when the network can accommodate moderate peaks and the primary objective is energy efficiency, battery trains are preferable; when connection constraints are high and/or the use of renewable surpluses is strategic, hydrogen offers decisive flexibility for the energy system. Hybrid architectures (charging stations for battery-powered trains, flexible electrolyzers, local storage, etc.) make it possible to optimize both rail operations and grid integration.

5. *Conclusion of Section 1*

This project is in line with major initiatives by the Québec government to accelerate the energy transition, through support for the development of renewable and low-carbon hydrogen initiatives to decarbonize heavy transport. It also extends the efforts made under the Québec Strategy on Green Hydrogen and Bioenergy, which encourages the use of hydrogen mainly for industrial consumer sectors and the validation of its potential for heavy transport applications, such as rail, as a complement to electrification.

In this context, Alstom's development in Québec appears to be a fundamental strategic lever. Between 2021 and 2023, Alstom consolidated its presence in Québec by acquiring Bombardier's rail division, enabling the Caisse de dépôt et placement du Québec to become its main shareholder. This merger led to the transfer of the head office to Montreal, the creation of local jobs, and the opening of a mobility innovation center, thereby strengthening Québec's role in the North American rail sector.

It is in this context that the first commercial operation of a hydrogen train under real operating conditions on the North American continent was launched, supported by the Government of Québec‘s Technoclimat funding program. This major project was made possible thanks to close collaboration between several key partners: Alstom, as the manufacturer of the hydrogen train and project leader; Harnois Énergies, responsible for hydrogen production and delivery; and Réseau Charlevoix and Train de Charlevoix, the owner and operator of the railway line. HTEC also played a key role by supplying the transfer module for refuelling, the transport truck tanks, and the filling interface at the Harnois Énergies hydrogen station. In addition, the electrolyzer and fuel cells used in this project were supplied by Accelera by Cummins (formerly Hydrogenics).

Section 2: Regulations

1. *Legislative framework for the railway sector in North America and Europe in 2023*

➔ **As a university research laboratory focus on technologies, the Hydrogen Research Institute provides this section for informational purposes only. The information presented and its interpretation date from 2023 and cannot replace the legal texts and their analysis by qualified personnel. We recommend consulting legal professionals and the competent authorities.**

1.1. Legislative framework for the railway sector in North America and Europe

For this section, the sources consulted include information from Canada, the United States, and the European Union, available exclusively in English and French. This section addresses the legislative and regulatory framework governing the rail transport sector, identifying the government actors involved and analyzing their influence on this sector.

1.1.1. Laws and regulations in Canada

In Canada, railway jurisdiction is split between federal and provincial levels. The Government of Canada, through Transport Canada, regulates and supervises rail transportation on railways under federal jurisdiction. The main statutes from which the regulations for the railway sector are derived are listed below:

- Canada Transportation Act (S.C. 1996, c. 10) [63] : This Act is the primary federal legislation governing transportation in Canada, including rail transportation. It contains provisions on rail rate regulation, accessibility, safety standards, rolling stock certification, and many other aspects of rail transportation.
- Railway Safety Act (R.S.C. (1985), c. 32 (4th Supp.)) [64] : This Act establishes the regulatory framework for railway safety in Canada. It grants regulatory powers to the Minister of Transport to ensure this mission.
- Canadian Environmental Protection Act (S.C. 1999, c. 33) [65] : This Act deals with the management of hazardous substances, including fuels, and may apply to the storage, handling, and management of petroleum products used to refuel locomotives.

Under these acts, regulations based on the interpretation of the acts are approved by the government and/or Transport Canada. The industry may also propose rules for approval by Transport Canada and are designed to adapt quickly to realities and technological advances. These texts are adopted to ensure various safety objectives for users, residents, the environment, and others. These laws remain broad and do not prevent the deployment of new rail technologies, provided they are safe and regulated.

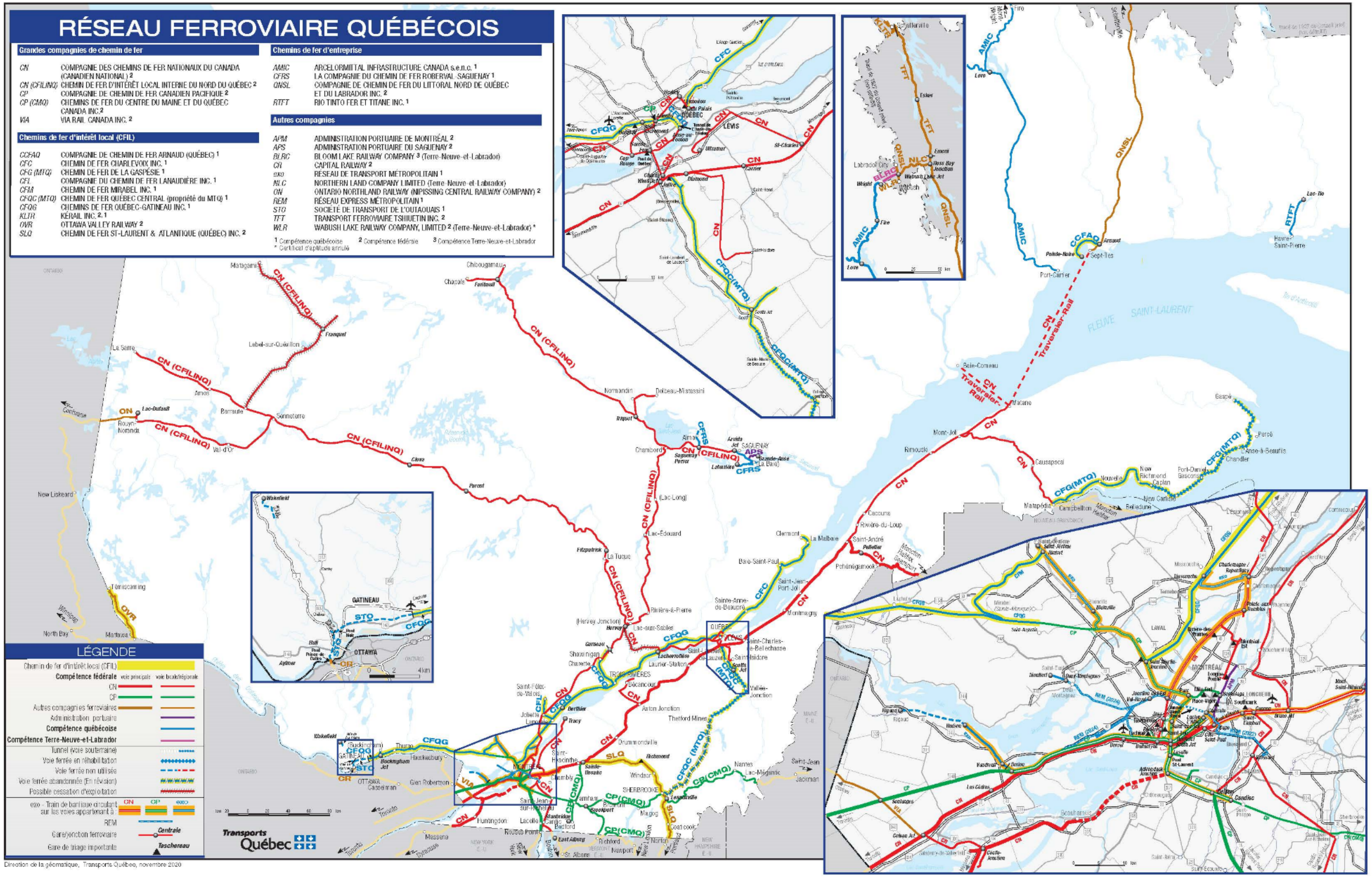
Regulations and rules specify what is required (standards, norms, etc.) to design and operate a train. In the case of hydrogen, no mention is made of this type of energy for train design in the *Railway Locomotive Inspection and Safety Regulations* [66]. In addition to these regulations, other texts may need to be clarified to consider the specific nature of adopting hydrogen as a motive power source. The Table 5 provides a non-exhaustive list of regulations that could potentially limit the deployment of hydrogen technologies for rail.

Table 5 : Regulatory texts that could potentially limit hydrogen trains in Canada (non-exhaustive list).

Text	Type	Applicability	Limitations to be assessed
Rules for the Inspection and Safety of Railroad Locomotives [63]	Rule	For locomotives operating on the federal network	Inspection adapted to diesel and steam locomotives.
Rules concerning periods of extreme heat and fire risk mitigation on the rail network [64]	Rule	For locomotives and infrastructure operating on the federal network	Amendment to take into account the risks associated with hydrogen?
Regulations on Locomotive Emissions (SOR/2017-121) [68]	Regulations	For locomotives operating on the federal network	Based on the Environmental Protection Agency (EPA) [69], there is no mention of a method for measuring emissions from hydrogen trains
Regulations concerning the installation, inspection, and verification of air tanks (other than those on locomotives) [67]	Rule	Pressure tanks in stations (fixed or transportable)	Possibility of amending this text to extend it to all gases used by locomotives that refer to applicable standards
Regulations respecting the bulk storage of liquefied petroleum gases (C.R.C., c. 1152) [68]	Regulations	Pressure tanks at stations	Possibility of amending this text to extend it to all gases used by locomotives that refer to applicable standards

On railway tracks under provincial jurisdiction, laws and regulations are issued by provincial governments. In the case of Québec, the *Guided Land Transportation Safety Act* [72], from the Ministry of Transport and Sustainable Mobility, applies to railways under provincial jurisdiction. This network is significant, representing 27% of the 6,278 km of rail network in Québec [73] (see Figure 14).

This Act allows Québec legislators to ensure the safety of infrastructure and vehicles by adopting regulations. The regulation resulting from this Act is the *Railway Safety Regulation* [74]. This regulation is less specific than the federal regulation regarding the design of rolling stock, and no direct mention is made of the type of fuel that can be used, leaving open the possibility of using trains powered by alternative energy sources. However, according to Appendix V of the regulations (Appendix V - Traffic Report), the unit used for fuel is the liter. This unit is not compatible with the measurement systems of hydrogen trains such as the Coradia iLint, whose fuel measurement unit is expressed in kilograms.



Direction de la géomatique, Transports Québec, novembre 2020

Figure 14 : Map of railway lines in Québec (source: Ministry of Transport and Sustainable Mobility [75]).

1.1.2. Laws and regulations in the United States

Railway regulations in the United States are mainly governed by the federal government, specifically by the Federal Railroad Administration (FRA), the rail branch of the U.S. Department of Transportation (DOT). Their jurisdiction extends to all public and intercity railways. Rail lines disconnected from this network, as well as metropolitan railways, are excluded. Similar to Canada, there are several laws that govern regulations for the railway sector.

The main law that defines the regulatory framework for railways in the United States is the Federal Railroad Safety Act [76]. This law gives the Secretary of Transportation the power to regulate railway safety through the FRA, including passenger and employee safety, signaling standards, braking systems, etc. These rules are recorded in the Federal Register and apply throughout the United States. These rules may also be enhanced at the state level.

The Federal Railroad Administration (FRA), like Transport Canada, is the federal agency responsible for regulating and supervising railways in the United States. The FRA develops regulations and safety standards for the entire railroad industry, including track design, train safety, maintenance, signaling, passenger and employee safety, and more. In the FRA's Federal Register (Title 49, Subtitle B, Chapter II [77]), Part 229 of the code contains no provisions regarding hydrogen as a locomotive fuel. However, diesel, steam, and magnetic levitation locomotives are mentioned in Title 49, Subtitle B, Chapter II of the FRA Code of Regulations.

Other laws, such as the Clean Air Act [78], which gives regulatory power to the Environmental Protection Agency (EPA), will have an impact on the introduction of hydrogen trains into the railway landscape. Indeed, the Code of Federal Regulations, Title 40, Part 1033 [69] regulates atmospheric emissions from locomotives. As previously seen with the Canadian Locomotive Emissions Regulations (SOR/2017-121) [68], this regulation is not suitable for hydrogen-powered trains. It should be noted that electric locomotives powered by external sources of electricity are exempt.

1.1.3. Directives and regulations in the European Union

The rail sector in Europe is regulated at the European Union level, but the legislative structure differs from that of the United States and Canada. Directives are adopted and then transposed by member states. These directives therefore have the force of law in member states and may be amended. The directives issued aim to promote the interoperability of the rail system, open up the market and facilitate access to it, improve safety, etc. These directives include (non-exhaustive list):

- Interoperability Directive (2008/57/EC) [79] ;
- Railway Safety Directive (2004/49/EC) [80] ;
- Railway Infrastructure Management Directive (2012/34/EU) [81].

European regulations stemming from these directives are also formulated by the European Commission and the European Parliament and enforced under the auspices of the European Railway Agency (ERA). These regulations are binding legislative acts issued to govern various aspects of the railway sector within the EU. Here are some of the main European railway regulations in force:

- Railway Rolling Stock Regulation (Regulation (EU) No. 1302/2014) [82] : This regulation establishes specific requirements for the placing on the market and operation of railway vehicles, covering aspects such as design, construction, approval, certification, maintenance, and operation.
- Railway Safety Regulation (Regulation (EU) No. 2018/545) [83] : This regulation establishes common rules for railway safety, including the certification of train drivers, investigations into railway accidents, and railway safety management.
- Regulation on the interoperability of the rail system within the Community (Regulation (EU) No. 1316/2013) [84] : This regulation establishes the principles and objectives of rail interoperability, including technical specifications for various rail subsystems.
- Regulation on pollutant gas emissions (Regulation (EU) No. 2016/1628) [85] : regulates pollutant gas and particulate emissions from internal combustion engines for non-road mobile machinery.

National railway regulations supplement these regulations, which may vary from one country to another. It is also the role of national regulatory bodies to oversee the application of European and national regulations. Local initiatives by local authorities are reported to improve railway regulations and enable better inclusion of hydrogen trains. Indeed, the German Federal Railway Authority (Eisenbahn-Bundesamt or EBA) has mandated TÜV Rheinland to prepare regulations and standards specific to railway applications of hydrogen [86].

1.2. Applicable standards and codes for hydrogen trains

As previously noted, there are no regulations specific to hydrogen trains and their ecosystem. The regulatory framework needs to be adapted in Canada, the United States, and Europe. In this section, we will explore the maturity level of existing standards for applications in the hydrogen train ecosystem. For clarity, the scope will be the same as that defined in the NRC study [87], with support from the Metrolinx study [88], and will summarize the main conclusions of this working group.

In their report "Risk Assessment of Hydrogen and Battery Power in Locomotives – Part 3 – Codes and Standards," the system under consideration includes six classes of standards:

- general standards (see below);
- standards for ground equipment (storage and refuelling);
- standards for locomotives (train tank, fuel cell module and associated traction system, ventilation, heat exchangers, water treatment);
- standards for lithium batteries;
- standards for natural gas transport;
- standards for bulk rail transport.

General standards are defined as those applicable to hydrogen and equipment that uses/stores this product. In particular, they address hydrogen purity standards and equipment construction to ensure the safe use of this gas. The NRC has identified 20 general standards ranging from the design of pressure vessels containing hydrogen to risk assessment standards.

While the review primarily focused on Canadian standards, relevant American and international codes were also evaluated. Their analysis shows that the general standards are well established and suitable for the implementation of a hydrogen train ecosystem. Even though some standards may only be applicable in one country or one field, they are easy to transcribe because they are well defined by the standards development organization. This can be illustrated for static electricity management with the NFPA 77 standard, which is used in Canada when no specific American or Canadian standard exists. Nevertheless, for certain specific standards, applicability checks are necessary for international standards on hydrogen detectors, fire alarm systems, and mechanical components of compressors. Finally, there are no standards specific to rail applications for decompression devices and hydrogen compressors.

With regard to equipment specific to hydrogen trains and their refuelling systems, it is reported that standards exist, but that they are not specific to railway applications. In fact, with the exception of fuel cells and hydrogen storage systems in stations, whose design is not necessarily linked to their use, the standards for fuel cell ancillary systems are new for rail applications. IEC (International Electrotechnical Commission) standards are also being developed for locomotive storage, traction systems, and lithium-ion batteries.

All these changes could subsequently be incorporated into the Association of American Railroads' *Manual of Standards and Recommended Practices*, which addresses locomotive design. These standards are widely applied to locomotives operating in North America and are currently more suited to the design of electric (catenary), diesel-electric, diesel, and steam locomotives.

1.3. Policy overview to encourage the deployment of hydrogen trains

The adoption of hydrogen for rail applications is a recent development. As noted in the previous sections, railway legislation and, to a lesser extent, the codes and standards applied to the railway sector are not yet up to date. Indeed:

- No existing legislation explicitly addresses the operation of hydrogen trains;
- Standards exist for most hydrogen-related components, but are not defined for the railway context. Adaptations specific to the rail ecosystem may be necessary;
- Extreme cold and heat are not taken into account in current standards.

Nevertheless, as hydrogen trains are still trains, the only new developments to be introduced at the legislative and code level concern the use of hydrogen in railways.

To address the regulatory gap for hydrogen, policies and plans to support its development have been introduced. These texts, which are primarily intended to guide investment and economic development, have no legal value. However, it is expected that recommendations will emerge from these initiatives to legislate and create or adapt standards in this field.

For example, regulations in Canada (Clean Fuel Regulations - SOR/2022-140) [89] and the United States (Renewable Fuel Standard - 40 CFR parts 80 and 1090) [90,91] have already been introduced to support hydrogen production for the decarbonization of mobility applications. The Canadian regulation includes vehicles using fuel cells, including trains, as technologies that can generate compliance units for hydrogen producers. In the US regulation, the rail sector is excluded from this regulation. European regulations have also evolved to take into account the use of alternative fuels, including hydrogen, for mobility applications. Thus, Regulation (EU) 2023/1804 [92] for the deployment of alternative fuels infrastructure aims to set targets for Member States for the deployment of hydrogen distribution infrastructure. Furthermore, Article 13 of this regulation requires action plans to be put in place for the use of hydrogen to power non-electrified trains.

According to the IEA, 22 governments had adopted hydrogen development strategies by 2023 [93]. In these strategies, rail is generally mentioned but is not the focus of the project. The Table 6 presents the main strategies adopted in Canada, the United States, and Europe.

Table 6 : Hydrogen strategies in Canada, the United States, and the European Union (EU).

Geographic area	Comprehensive hydrogen strategy	Local hydrogen strategies mentioning rail
United States	U.S. National Clean Hydrogen Strategy and Roadmap [94]	Few local strategies specific to hydrogen, even fewer for rail.
EU	REPowerEU Plan [95]	Specific strategies for member countries alongside the European strategy (e.g., in France, the national strategy for the development of carbon-free hydrogen (SNH)).
Canada	Hydrogen strategy [96]	Specific strategies exist in parallel in Québec (Green Hydrogen and Bioenergy Strategy [1]), Ontario (Ontario's Low-Carbon Hydrogen Strategy [97]), British Columbia (B.C. Hydrogen Strategy [98]) and Alberta (Alberta Hydrogen Roadmap [99]). There are no specific hydrogen plans in the other provinces and territories.

The adoption of these strategies enables the implementation of programs that fund research and development, demonstration, and deployment of hydrogen-related technologies, including hydrogen-powered rail applications.

2. *Driving cycles (Europe vs. North America)*

2.1. Driving cycles for fuel consumption and emissions

Driving cycles are defined as a standardized sequence of maneuvers performed during certification tests on a type of vehicle, designed to consistently reproduce the driving conditions observed on relevant tracks and roads. Closely linked to the certification of automobiles, these standardized test procedures are used to measure fuel consumption, the range of electric vehicles, and greenhouse gas (GHG) and pollutant emissions. The internationally used standard for automobiles is the Worldwide Harmonized Light Vehicles Test Procedures (WLTP). This has been applied in Europe since 2019 and in China. In North America, the standards used for driving cycles are imposed by the U.S. Environmental Protection Agency (EPA) and, generally, Canada complies with them for the sake of consistency [100].

For example, fuel cell vehicles are subject to EPA certification, particularly for GHGs, in the United States [101] and Canada, and are subject to Regulation (EU) 2023/851 [102] (on CO_2 emissions from passenger cars) in Europe. The aim is to promote the adoption of this technology by taking into account low emissions in the overall GHG balance of a company, region, or country. With this mechanism, the use of low-emission technology can then lead to carbon credits.

In the railway sector, there are no driving cycles applied to trains as such. However, as shown in the first part of this section, trains operating in Europe and North America are required to comply with air quality standards. These standards are imposed in Canada by the Locomotive Emissions Regulations (SOR/2017-121) [68] , in the

United States by the Code of Federal Regulations, Title 40, Part 1033 [69] , and in Europe by the Regulation on pollutant gas emissions (Regulation (EU) No. 2016/1628) [85].

These regulations are geared toward emissions from internal combustion engines and impose atmospheric emission limits on carbon monoxide (CO), total hydrocarbons (HC), nitrogen oxides (NOx), total particulate matter (PM), and fine particulate matter (PN, European Union only).

In the case of a train powered by hydrogen via a fuel cell, such as the Coradia iLint, a potential adaptation, similar to that for electric trains (catenary or battery), could be evaluated (see 4.3GHG emissions). For a locomotive equipped with an internal combustion engine using hydrogen, this type of fuel is not specified in the regulations specific to trains. Since the combustion of hydrogen in air leads to the production of $NO_{(x)}$ [103] , hydrogen-powered trains could be subject to these regulations on atmospheric emissions.

2.2. Rail vehicle certification

Operating locomotives requires compliance with international, regional, and national standards set by governing railway authorities, as well as those imposed by the line operator.

These norms and standards include provisions concerning various aspects of locomotives, such as interoperability, safety, reliability, and technical compatibility. It is important to note that these approval standards cannot be uniform for all networks and may vary depending on the situation. European standards, for example, take precedence over national standards, but they can be adapted by countries or network operators.

In order to obtain approval for a locomotive, it is necessary to carry out simulations and dynamic tests on the rolling stock, which may differ depending on the country or railway operator. These tests and simulations cover aspects such as braking systems, on-board safety devices, maintenance, reliability, weight, etc. [104]. Their purpose is to ensure the safe operation of trains on the railway tracks.

Numerical simulations can be combined with real-world tests to validate the behavior of the various components of the locomotive. These dynamic tests on rolling stock are standardized by the standards in force in the countries listed below (non-exhaustive list):

- EN 14363+A2 [105] : Tests and simulations for the approval of the dynamic characteristics of railway vehicles – Dynamic behavior and stationary tests (European standard adapted to the French standard);
- EN 15734-2:2013 [106] : Railway applications – Braking systems of high-speed trains – Part 2: Test methods (European);
- NF EN 16185-2+A1 [107] : Railway applications – Braking systems of multiple unit trains – Part 2: Test methods (European standard adapted to French standards);
- Standards compiled in the *Manual of Standards and Recommended Practices* [108] of the Association of American Railroads for the United States, Mexico, and Canada.

It should be noted that hydrogen trains must meet the same dynamic performance requirements as electric and diesel vehicles. However, differences in the approval process may also result from technical constraints related to a country's infrastructure. The example of the approval of Alstom's hydrogen train, the Coradia iLint, in France is an illustration of this. According to an article in Usine Nouvelle, the model approved in Germany may not be approved in France due to factors such as signaling incompatibilities[15].

2.3. Winter and summer conditions

In North America ambient temperatures can fluctuate by more than 60°C between summer and winter seasons. For example, in Québec City, the extreme temperatures recorded in the last decade are -36.7°C and 38.6°C. This wide temperature range places considerable constraints on the operating conditions of various systems. Winter conditions can have a significant impact on transportation in Québec, which faces snowstorms, freezing rain, and extremely cold temperatures. Equipment may therefore require specific heating systems for lithium batteries and fuel cell systems, both for storage and operation, in order to operate these systems within the recommended temperature ranges. Fuel cells are subject to ambient temperature limits for storage and operation. For example, the Ballard FCmove™-HD fuel cell power module [7] has a minimum start-up temperature of -25°C, a short-term storage temperature range of -40°C to +80°C, and an operating temperature range of -30°C to +40°C. The start-up temperature could be an issue (if not controlled), as the fuel cell system may require pre-purge of the fuel cell stack area to remove hydrogen residues before certain components are powered up, and ambient air may be drawn into the system for this purpose. The introduction of very cold air in sub-zero conditions can produce ice during start-up.

The main risks in the event of water freezing inside the fuel cell are the obstruction (partial or complete) of the fluid distribution and extraction channels (mainly at the cathode), which then leads to a slowdown in chemical reactions and a loss of power that can lead to the fuel cell shutting down. Repeated freezing and thawing cycles can accelerate damage to the fuel cell, particularly due to the expansion caused by ice in the channels. Cold starting of the fuel cell also requires special attention. Various starting strategies have been studied for light vehicles [110,111], and performance has been monitored on a fleet of light vehicles in the United States and Québec, Canada, which showed a decrease in efficiency in winter. It should be noted that this decrease is also observed in thermal and electric vehicles.

Very hot summer temperatures can also be a challenge for fuel cell cooling. A proton exchange membrane fuel cell (PEMFC) operating at 80°C will require more energy to maintain its temperature through forced convection as the outside air gets hotter. As the redox reaction in the fuel cell is exothermic (it produces heat), the operating temperature must be regulated to prevent material degradation. The choice of cooling system and suitable heat transfer fluid will therefore be influenced by external operating conditions.

2.4. Offshore

Fuel cells operated offshore face a different environment than those on land. Weather conditions can be more unpredictable, and the presence of salt in the water and air can lead to greater corrosion [112]. Although there are many projects underway, more long-term testing in the marine environment is needed to obtain results on the durability of fuel cells at sea [113].

[15] For trains with a cross-border profile (high-speed trains or long-distance locomotives), the European Interoperability Directive (2008/57/EC) aims to establish a single, interconnected European railway area [79,109]. This directive does not apply to the Coradia iLint, which is a non-cross-border regional train.

3. *Conclusion of Section 2*

The regulatory aspects associated with the various activities surrounding the refuelling, operation, and maintenance of hydrogen trains in Québec and Canada raise questions. Work to establish federal regulations is underway by Transport Canada to allow, as in Europe, the circulation of hydrogen trains throughout the country. Hydrogen trains will then be able to gradually replace those running on diesel.

Thanks to close collaboration between Québec's Ministry of Transport and Sustainable Mobility, Alstom, and Réseau Charlevoix, the hydrogen train has been approved for use on the Charlevoix railway in the summer of 2023. Since the beginning of the project, the Ministry of Transport and Sustainable Mobility has supported the various stakeholders, particularly Alstom, to ensure compliance with the safety requirements for all railway products. Working together, additions and modifications have been made to the Coradia iLint prototype to ensure its compliance with current regulations.

Regarding the requirements for the installation of hydrogen production, distribution, and storage equipment, the Bureau de normalisation du Québec (BNQ) has published standard CAN/BNQ 1784-000/2022, which is a revision of the Canadian Hydrogen Installation Code. The latest revision of the standard aims to harmonize certain requirements with the American NFPA2 code, "Hydrogen Technologies Code," in order to ensure continuity in practices between Canada and the United States for the safe use of hydrogen.

Finally, regulations and standards are adapting quickly, and it is expected that most revisions will be completed by the time the next hydrogen trains, whether passenger or freight trains, are put into service.

Section 3: Health and Safety s of Hydrogen for Transportation

1. *Introduction*

For decades, before hydrogen's emergence as a viable energy carrier, industries used hydrogen in large quantities as a chemical product and developed significant expertise in the production, storage, transport, and safe use of hydrogen. Space agencies were undoubtedly the first to take an interest in hydrogen as an energy carrier, recognizing its high potential in terms of energy density. In fact, with the exception of nuclear fuels, hydrogen is the molecule that can store the greatest amount of energy per unit of mass [114]. Space agencies have therefore used hydrogen to power shuttles, rockets, and other vehicles for space exploration.

As with any fuel, proper handling is critical to ensure operational safety. Like gasoline and natural gas, hydrogen is flammable and can behave dangerously under certain conditions. In this regard, several properties make hydrogen attractive compared to other fuels when it comes to safety. However, in order to successfully deploy hydrogen technologies, awareness of safety issues and best practices is essential.

Achieving this requires rigorous safety protocols, employee training, and preventive equipment to mitigate hydrogen-related risks and ensure the protection of people and property. The stakeholders involved must conduct an individual risk assessment[16]. This allows facility and operations managers to plan for safety and establish best practices for the safe use of hydrogen. There is no standard risk profile, and risks manifest themselves differently depending on the infrastructure. Therefore, a risk assessment consists first of acquiring a fundamental understanding of what hydrogen use entails, identifying specific safety issues, defining safety indicators, quantifying the risk, and reducing it to an acceptable level [115].

This section will present the properties of hydrogen, the associated risks, and best practices. It should be noted that these properties are inherent to the use of hydrogen in any ecosystem, including the Coradia iLint demonstration project on the Charlevoix railway. Issues related to regulations, codes, and standards surrounding hydrogen are addressed and referenced at Section 2: Regulations.

2. *The properties and risks associated with the use of hydrogen*

2.1. Hydrogen gas

Whether hydrogen is used in stationary or mobile applications, the most critical safety issues under normal operating conditions relate to leak prevention and detection. Safety considerations therefore vary depending on the potential effects of a leak and the risks posed to health and safety during operations. The properties of hydrogen, such as its wide flammability range across a broad concentration range, low minimum ignition energy, high buoyancy (very low density compared to air under ambient conditions), and propensity for leakage and permeability, present challenges for its safe use. Hydrogen is an odorless gas and burns with an almost invisible flame. These unique properties of hydrogen require safety guidelines that are different from those for conventional gases.

The primary concern with hydrogen utilization is uncontrolled leakage. An accidental leak will generally result from the failure of a component (e.g., a valve, flange, fitting, pipe, seal, etc.). The resulting jet, which has the

[16] The concept of "risk," as commonly defined in a safety analysis of an industrial facility, is a combination of two factors: the probability of a dangerous event occurring and the severity of that event.

potential to ignite, could cause harm to personnel, equipment, and property. It is therefore crucial to understand the dissipation of hydrogen during leaks and the consequences of accidental ignition.

In the event of an outdoor leak, hydrogen rises rapidly due to its high buoyancy and diffuses quickly, allowing for very rapid dispersion that limits the risk of a flammable cloud forming [116]. The only exception is cryogenic hydrogen leaks, where the initially formed cloud of very cold vapor can be denser than the surrounding air, causing it to settle on the ground before warming up, becoming lighter than air, and eventually rising. In the event of a hydrogen leak in an enclosed environment, such as a garage or warehouse, a gas cloud may accumulate inside the enclosure, leading to the formation of flammable or explosive air-hydrogen mixtures [113].

Hydrogen has inherent risks, like any other flammable gas or liquid. These risks are directly related to its physical and chemical properties, which are summarized in the Table 7. Below, the behavior of gas jets and the important safety-related properties of hydrogen are detailed.

Buoyancy

The density of hydrogen is considerably lower than that of air. In the event of a leak, it spreads rapidly upwards at a speed of approximately 20 meters per second, which is twice as fast as helium and six times faster than natural gas. As a result, it dilutes quickly to reach a non-flammable concentration in a short period of time. Unlike heavier hydrocarbons, this property gives it the ability to escape quickly into an open atmosphere and mix with ambient air at concentrations below the flammability threshold.

While buoyancy greatly reduces the undesirable consequences of hydrogen releases into the outside atmosphere, in the event of accidental release in a confined space, hydrogen can disperse rapidly upward, potentially forming a flammable mixture and leading to a deflagration [118–121].

Table 7 : Physicochemical properties of hydrogen [118,122,123].

Physicochemical property	Value
Chemical formula	H_2
CAS No 2F[17]	1333-74-0
Physical state	Colorless and odorless, compressed or liquefied gas
Fire	Extremely flammable
Explosion	Explosive air-gas mixture
Molecular weight	2.016 g/mol
Stoichiometric mixture in air (by volume)	29.53% vol
Relative density in air[18]	0.07
Gas density	0.08342 kg/Nm^3 (20 °C/1 atm)
Solubility in water	0.019 (vol/vol at 15.6 °C)
Minimum ignition energy	0.017 mJ in air and 0.0012 mJ in oxygen

[17] This is a numerical designation assigned to chemical substances by the American Chemical Society (CAS).
[18] The density (or relative density) of a body is the ratio of its mass per unit volume to the mass per unit volume of another body taken as a reference (air = 1).

Flammability range in air	4 to 75% (in air at TPN[19]) and 4 to 94% (in oxygen at TPN)
Auto-ignition temperature	585 °C/858 K
Fundamental combustion velocity in air at _	2.65 to 3.25 m/s
Flame temperature in air	2045 °C
Theoretical explosion energy	2.02 kg TNT/m^3 gas
Diffusion coefficient in air	0.61 cm^2 /s

The effect of hydrogen buoyancy is less significant for gas leaks with high momentum, i.e., when the leak velocity is high. In this case, the direction of the escaping gas jet is critical, as a flammable cloud forms downstream of the leak opening, in the direction of the jet. It is important to note here that the extent of the flammable cloud for these high momentum gas leaks is influenced by the presence of winds and immediate obstacles around the leak, whether these are contact surfaces or structures that induce turbulence, i.e., obstructions [117].

Flammability limits

An air-fuel mixture will only burn if the fuel concentration is between the lower flammability limit (LFL) and upper flammability limit (UFL). The terms "explosive limits" are also used incorrectly in the literature to describe flammability limits. These flammability limits in air depend on temperature and pressure. The values given here are based on standard test conditions at ambient conditions of 25°C and 1 atm.

- **Lower flammability limit (LFL)**

The percentage by volume of fuel in the air below which combustion is not possible because the mixture is too lean. The units correspond to the percentage by volume of fuel in the air.

- **Upper flammability limit (UFL)**

The volume percentage of fuel in the air above which combustion is not possible because the mixture is too rich.

Compared to other fuels, hydrogen has a wider flammability range. The Table 8 compares, under standard conditions, the LEL and UEL of hydrogen with those of methane, gasoline, and propane, which have much narrower flammability ranges.

Table 8 : Flammability limits (hydrogen, gasoline, propane, and methane) [118].

	LEL	LEL
Gasoline	1.0	7.6
Methane	5.3	15.0
Hydrogen	4.0	75.0
Propane	2.2	9.6

Flammability limits exhibit a non-linear relationship with pressure. Between 1 and 150 bar, the UFL increases with pressure from 4.0% to 5.6%. The LEL varies between 71.0% and 76.6% [124].

[19] Normal temperature and pressure conditions.

Turbulent gas jets and plumes

Turbulent jets in a calm environment are generally classified according to the relative importance of the initial momentum flux compared to the initial specific buoyancy flux. The jet is a regular plume when the momentum flux is low compared to buoyancy, while it is a pure jet when the initial buoyancy flux is negligible compared to momentum. It is a floating jet when buoyancy and momentum are of comparable magnitude. As a steady plume, hydrogen is much lighter than air and dissipates and rises rapidly as explained above. When released, hydrogen rises rapidly and dilutes to a non-flammable concentration [125].

However, when the jet has a large initial momentum, the hydrogen cloud will spread in the direction of the leak. Figure 15 gives an example of the three possible types of jets. The top jet represents a plume and is essentially controlled by buoyancy. The bottom jet represents a pure jet controlled solely by momentum. One of the peculiarities of a pure jet is that the upward trajectory of the jet occurs beyond the dilution point of the hydrogen cloud below its LII. Finally, the middle jet represents the intermediate case where the leak is initially controlled by momentum, then buoyancy eventually takes over to inflict an upward trajectory on the cloud.

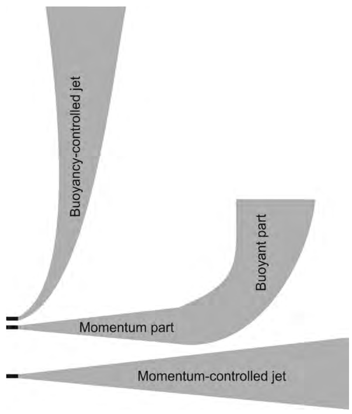


Figure 15 : Example of hydrogen jet behavior as a function of momentum [124].

Sonic and subsonic jets

Gas leaks through an orifice occurs due to a positive pressure difference differential between a container and its surroundings. Depending on the storage pressure, gas flow or leakage through an outlet hole at atmospheric pressure can be either critical (or sonic; *choked flow*) or subsonic for hydrogen. Sonic emissions occur when the storage pressure is 1.9 times higher than atmospheric pressure, so most hydrogen leaks are sonic. The flow rate of a critical or sonic flow depends only on the storage pressure, while the flow rate of a subsonic flow will depend on the difference between the storage pressure and atmospheric pressure. A flow/leak from a compressed gas storage system into the ambient environment will therefore be sonic as long as the storage pressure remains above 1.865 atm. For subsonic flows, the exit velocity is less than the speed of sound, while for sonic flows, the exit velocity becomes locally sonic (Mach 1). It should be noted that the ultrasound generated by the sonic gas jet has led to the emergence of a new gas leak detection technology called ultrasonic gas leak detection[20].

[20] This technology does not use gas concentration as a relevant measure, but rather uses the ultrasonic noise produced by the escaping gas to detect the leak and generate an alarm. The sensors react to the noise generated by the escaping gas at ultrasonic frequencies. The rate of gas leakage depends mainly on the size of the leak and the pressure of the gas. In most installations, the majority of process noises are in the audible range, while normal operation generates only limited ultrasonic noise. High-pressure gas emissions produce ultrasonic waves (25-100 kHz) that ultrasonic sensors can detect despite the presence of audible noise [126].

Hydrogen ignition

The energy required to ignite hydrogen combustion is significantly lower than that required for other common fuels such as natural gas or gasoline. The ignition energy varies depending on the composition and reaches a minimum value when the mixture approaches stoichiometry[21] (i.e., for a hydrogen-air mixture at 29.59% by volume). Within the flammability range of hydrogen-air mixtures, the minimum ignition energy varies by almost three orders of magnitude and can drop to 0.017 mJ, which is much lower than that of hydrocarbon-air mixtures (0.27 mJ for natural gas). The auto-ignition temperature of hydrogen, i.e., the minimum temperature of a hot surface that can ignite a flammable mixture, is 585°C.

Typical sources of hydrogen ignition [16,127]

- **Static electricity**

Due to hydrogen's exceptionally low minimum ignition energy (0.017 mJ), flammable mixtures are highly susceptible to electrostatic ignition by an electrostatic discharge. It is therefore critical that all components of a hydrogen system be grounded, and the use of antistatic equipment to reduce the risk of electrostatic discharge is recommended for workers.

- **Hot surfaces**

Ignition by a hot surface occurs as a result of local heating of the hydrogen-oxidizer mixture until a sufficiently large volume reaches the auto-ignition temperature and the combustion reaction is triggered. This requires the surface to be at a temperature above the auto-ignition temperature, which is 585°C for hydrogen.

- **Open flame**

Flammable hydrogen-air mixtures within the flammability limits will inevitably ignite on contact with open flames.

- **Electric sparks**

Hydrogen-air mixtures are known to be sensitive to ignition by electrical sparks. Electrical sparks are defined as discontinuous electrical discharges across a gap in a complete electrical circuit between at least two electrodes. This includes sparking from electrical switches, electric motors, generators, or other electrical equipment.

- **Other ignition sources**

Friction and mechanical sparks (occurring in cases of excessive friction between metals or extremely hard substances), mechanical impact, electrostatic discharge by corona effect, ignition by hydrogen diffusion (adiabatic compression) [124,128,129].

Hydrogen detonation

Hydrogen combustion can occur through two distinct processes: deflagration and detonation.

- **Hydrogen deflagration**

Hydrogen deflagration represents "normal" combustion. Deflagration can occur in a hydrogen-air mixture when the mixture ratio is between the lower flammability limit and upper flammability limit of 4% and 75%,

[21] In a stoichiometric composition (here: hydrogen and oxygen present in the air), hydrogen, which is the reactant, is used optimally, allowing a complete reaction without residues. The hydrogen-air mixture is stoichiometric when it contains twice as much hydrogen as oxygen by volume.

respectively. The deflagration of a hydrogen cloud is characterized by a combustion propagation speed of up to 100 m/s [130].

- **Hydrogen detonation**

Hydrogen detonation constitutes the worst-case combustion scenario. Detonation of a hydrogen-air mixture requires that the mixture ratio be between the lower and upper detonation limits of 11% and 59%. This range is narrower than that allowing hydrogen combustion by deflagration. When a hydrogen-air mixture detonates, combustion is accompanied by a supersonic shock wave. The propagation speed of combustion, as well as the propagation speed of the shock wave, is 1,500 to 3,000 m/s during detonation [130].

Specific conditions are normally required to trigger a hydrogen detonation, such as special confinement or violent ignition from explosives. Thus, hydrogen detonation in open air is unlikely due to its tendency to disperse rapidly upward (high buoyancy). This contrasts with heavier fuels, such as propane or gasoline vapors, which tend to remain close to the ground, creating a greater risk of detonation [118,131–133].

It should be noted that a deflagration or detonation cannot occur in a tank or confined space containing only hydrogen. For such an event to occur, the presence of an oxidizer, such as oxygen, is required at a concentration of at least 5% [124].

Other properties of hydrogen [16,127,134]

- **A greater propensity to leak.**

Hydrogen molecules are very small, with a low molecular weight and low viscosity. As a result, hydrogen can escape at a higher molecular flow rate and easily permeate materials compared to other fuels.

- **Hydrogen is odorless, colorless, tasteless, and non-toxic.**

It is therefore undetectable by human senses. Industries that produce and use hydrogen have sensors to detect hydrogen leaks. The addition of odorant gas (such as mercaptan) is generally not possible with hydrogen given the purity required.

- **Risk of asphyxiation.**

Hydrogen is a simple asphyxiant, just like helium and argon. In the event of a significant leak in a confined space, hydrogen can lead to a reduction in the oxygen level in the air by displacement. A decrease in the oxygen content of the air below 19% is considered dangerous. As hydrogen rises quickly, the risk of asphyxiation is particularly high for workers at height in confined spaces in the event of a hydrogen leak.

- **Absence of flame color**.

Hydrogen-oxygen and hydrogen-pure air flames are colorless. (Any visible flame is due to impurities.) This limits the visual detection of hydrogen flames and thus increases the risk of burns under these conditions. Specialized cameras that can detect hydrogen flames are often used in high-risk facilities. Hydrogen refuelling stations are usually equipped with this type of camera, which triggers an emergency shutdown of the station if a hydrogen flame is detected.

Finally, the Table 9 compares several properties of different fuels with hydrogen.

Table 9 : Comparison of the properties of several fuels [123,135].

Properties	Gasoline	Methane	Propane	Hydrogen
Density (kg/m³)	677—798	0.65	1.880	0.084
Diffusion coefficient in air (cm²/s)	0.050	0.160	0.098	0.610
Specific heat capacity, constant pressure (kJ/(kg.K))	1.20	2.22	1.68	14.89
Flammability limits in air (vol%)	1.0—7.6	5.3—15.0	2.2—9.6	4.0—75.0
Detonation limits in air (vol%)	1.1–3.3	6.3—14.0	---	13.0—59.0
Flammable energy in air (mJ)	0.24	0.29	0.25	0.017
Auto-ignition temperature (°C)	227-470	539	470	585
Flame temperature in air (°C)	2197	1875	1480	2045

2.2. Liquid hydrogen

Liquid hydrogen carries all the hazards of gaseous hydrogen, compounded by rapid evaporation rates. However, there are additional risks due to the properties of liquid hydrogen itself [136].

Low boiling point

Liquid hydrogen has a normal boiling point of -252.9°C at atmospheric pressure. Any contact of liquid hydrogen with the skin or eyes can cause severe "burns" due to frostbite.

Therefore, cryogenic storage tanks must be maintained under positive hydrogen pressure to prevent air infiltration. With the exception of helium, any gas that comes into contact with liquid hydrogen will condense or solidify. This is true, among other things, for oxygen in the air, which can then accumulate in the liquid hydrogen to form an explosive mixture that is sensitive to shock. Consequently, liquid hydrogen tanks must be periodically heated and purged to maintain the oxygen level below 2% (ISO/TR 15916:2004 standard) [124].

Ice formation

Cryogenic vents and valves are susceptible to ice plug formation caused by atmospheric moisture. This can cause excessive pressure, leading to the rupture of the container and the release of a potentially dangerous amount of hydrogen.

Trapped liquid

When hydrogen changes from a liquid to a gas at normal temperature and pressure, the expansion coefficient is 847, which means that one liter of liquid hydrogen will yield 847 liters of hydrogen gas under standard conditions (NTP). If liquid hydrogen is confined, for example in a pipe between two valves, it will eventually warm up to ambient temperature, causing a significant increase in pressure. This pressure increase can reach 1,770 bar for a volume of trapped liquid hydrogen going from -253°C to room temperature. The presence of pressure relief valves is therefore critical when there is a risk of trapping liquid hydrogen in a system.

Continuous evaporation

The continuous evaporation of liquid hydrogen (LH_2) in a tank produces hydrogen gas, which must be vented to a safe location or temporarily confined in a safe manner to prevent a significant increase in tank pressure. This continuous evaporation of liquid hydrogen is due to the imperfect thermal insulation of cryogenic liquid hydrogen tanks.

Cold gas leak

At temperatures above -250°C, hydrogen gas is lighter than air at standard temperature and pressure and tends to rise. At temperatures reached immediately after the liquid evaporates, the vapor is heavier than air and will remain close to the ground until the gas temperature rises.

3. *Maintenance and repair*

In this section, "equipment" refers to the integrated system of piping, instrumentation and control mechanism of the hydrogen system. Inspection and maintenance of this equipment may consist of repairs to existing equipment or its replacement. Any changes made to the original installation during maintenance activities must follow a formal change management process.

Proper and timely inspection and maintenance are essential to ensure the safe operation of the system. Reactive maintenance is strongly discouraged for equipment that operates with hydrogen. A systematic approach should be taken to assess the condition of equipment within the facility in order to develop a cost-effective maintenance strategy aimed at maintaining safe and reliable operation. It is imperative to document and manage a maintenance plan. A well-planned maintenance program, often referred to as "preventive," "routine," or "scheduled," must be implemented to prevent hazardous situations before they occur [137–139].

As part of the hydrogen train operation in Charlevoix, presented in Section 4, maintenance and repair plans have been put in place by the ecosystem stakeholders.

4. *Mitigation, sensors, prevention, and risk reduction*

After identifying hazards and assessing risks, a comprehensive plan to mitigate or eliminate high-risk hazards must be implemented. It is crucial that hydrogen-based systems be planned, designed, built, and operated in a manner that minimizes risks to a level deemed acceptable. For hazards considered to pose a risk above this acceptable level, control measures are implemented, including: reducing or eliminating the probability of occurrence and/or reducing or eliminating the severity of consequences [140–144].

Several approaches can be considered to prevent or reduce risks. Among the measures to be considered are the following [137]:

- Reducing the probability of a leak to an acceptable level;
- Ensure adequate ventilation to prevent hydrogen accumulation in the event of a leak;
- Install automatic emergency shut-off devices to isolate hydrogen sources as soon as a leak is detected;
- Eliminate all sources of ignition near the hydrogen system;
- Position enclosures away from other structures and areas where people are likely to be present. The distances to be observed are specified in the codes and standards in force for the installation of hydrogen systems.

Various examples of risk analysis can be found in the literature:

- The French Environment and Energy Management Agency (ADEME) provides a risk analysis in its information guide on risks and safety measures related to decentralized hydrogen production [118];

- Gentilhomme *et al.* (2020), from INERIS, provide a safety analysis carried out on a hydrogen gas station [145] ;
- Gye *et al.* (2019) present a quantitative risk assessment of a high-pressure hydrogen refuelling station located in an urban area [143] ;
- Moradi *et al.* (2019) conduct a literature review on the current state of knowledge regarding risk analysis and the reliability of hydrogen technologies (mainly hydrogen storage and distribution) [146].

In the Charlevoix ecosystem, hydrogen is stored and distributed in gaseous form. Risk analysis and mitigation measures for each system are carried out by the various stakeholders:

- For hydrogen production, by Harnois Énergies;
- For the hydrogen train, by Alstom;
- For the tanks and refuelling module, by HTEC.

Operators who can use the refuelling interface are identified by the system manufacturer, HTEC, and are trained in its use by them (more information in Section 5: Employee training). In addition, the EPI4F[22] required to perform refuelling are listed in the GTM (Gas Transfer Module) user manual referenced H079-MAN-002 and are also recommended during the training given at the IRHF[23].

During the first filling, the lines at the station and on the trailer were purged with nitrogen to prevent hydrogen-air mixing. The lines and trailer were then purged several times with hydrogen up to 3000 PSI in order to comply with the SAE J2719 standard (see Appendix A3: Required hydrogen purity), which stipulates less than 300 ppm of nitrogen. During operations, nitrogen is used to activate the pneumatic valves.

Specific measures have been put in place for refuelling the hydrogen train:

- Secure area closed to the public;
- Outdoor operation, no roof or other potential retention area in the event of a hydrogen leak;
- Only authorized personnel may work on the systems;
- Personal protective equipment (PPE) recommended for operators present;
- No electronic devices within a defined perimeter of 5 meters;
- Fire extinguisher available at the refuelling module;
- Manual emergency stop on the refuelling module that isolates the hydrogen tanks in the event of problems.

Hydrogen refuelling of the Coradia iLint storage system must be carried out from the center of the vehicle, located at the gangway. This operation can be performed on both sides of the vehicle. The refuelling process involves the use of special couplings equipped with non-return valves. The tank connections are equipped with protective valves (Figure 16 for more details), which must be opened during filling. These protective valves are subject to electrical monitoring. A protective valve that remains open will cause the traction to stop, preventing the vehicle or multiple unit train from starting [147].

[22] Personal protective equipment.
[23] Hydrogen Research Institute.

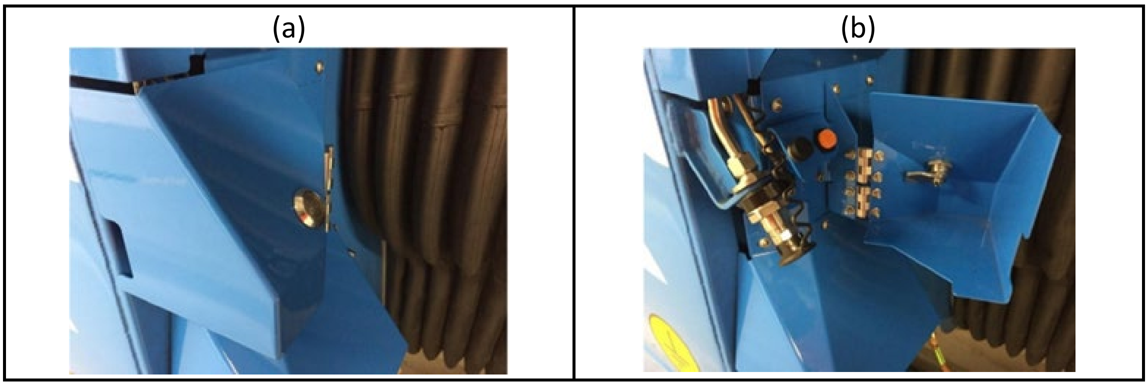


Figure 16 : Tank connections with closed (a) and open (b) protective valve [147].

During train operation with passengers, several hydrogen-specific measures were identified that differ from standard diesel operations.

- no hydrogen sensors are required in the passenger cabin as on-board storage is located on the roof to prevent internal leakage[24]);
- checks are carried out to validate the proper functioning of the safety features related to the hydrogen system in accordance with the manufacturer's recommendations during the pre-operation inspection procedure;
- the hydrogen supply and fuel cell system are shut off (selectively per car if a fire is detected in the affected system).

Only trained and authorized personnel are authorized to drive the Coradia iLint train. In addition to the general safety instructions, they must take into account all the specific recommendations for this vehicle listed in the Coradia iLint user manual [147].

It is essential to strictly comply with accident prevention measures. The external power supply must only be installed when the vehicle is switched off. It is essential to know the location and use of fire extinguishers in case of emergency. Leaning out of the driver's cab is strictly prohibited, unless necessary to observe the train, track, and signals. Before taking any action, the driver must ensure that there are no objects nearby that could cause a hazard. If the vehicle is stopped to carry out checks or work on the carrying bogies, motor bogies, or under the vehicle body, it must be immobilized to prevent any unexpected movement. While personnel are working on or under the vehicle, devices such as brakes, magnetic brakes, and other similar equipment must not be activated and must be turned off or locked. When the vehicle is running on lines equipped with overhead power lines, all operations on the vehicle must be carried out at a sufficient distance from the live parts of the overhead line. Access to the roof under a live catenary is strictly prohibited. Before any work is carried out on the electrical parts of the vehicle or coupled vehicles, as well as any work in the vicinity, it is imperative to isolate these parts on all sides and protect them against any risk of unintentional re-energization. With regard to gas fuel tanks, it is crucial not to fill them beyond the prescribed limits. In addition, tanks and partitioning devices must be leak-proof to avoid any risk of leakage. When a vehicle is cold-started, it is necessary to allow for an additional waiting period after the power supply is switched on, as the fuel cell and traction battery must be preheated to operating temperature. Interrupting the vehicle's power supply causes

[24] The management of the risk of leaks in tunnels therefore remains to be mitigated [148].

it to shut down. The duration of this shutdown depends on the state of charge of the traction batteries, as they only recharge when their energy level reaches a fixed threshold [147].

5. *Emergency Response Assistance Plan (ERAP)*

5.1. Road transport

From production to storage, and from distribution to application, accidents can occur even if safe practices are followed in these hydrogen-related activities. Uncontrolled external events, such as vehicular collisions with hydrogen transport trailers, must be evaluated. Thus, the road emergency response assistance plan consists of mobilizing personnel and equipment when an emergency situation arises during the transport of hydrogen, for example.

Compressed hydrogen is classified with a PIU index of 3000 for the transport of dangerous goods [149]. In Canada, the transport of certain dangerous goods that exceed the quantities specified in the Transportation of Dangerous Goods Regulations is carried out by persons who have a PIU [150]. Transport Canada has published guides on ERAPs, including a guide to determine when an emergency response assistance plan may be required [151]. At the time of writing, a ERAP is required when a tank larger than 0.125 L is used to transport hydrogen [152]. For more information, readers are invited to contact Transport Canada and consult the Transportation of Dangerous Goods Regulations (SOR/2001-286, 1992 Act) on the transportation of dangerous goods (see Section 5) [153].

5.2. Rail

The railway emergency response assistance plan may also be related to incidents that may occur during the transport of hydrogen. In this case, it is essential to ensure that emergency responders have an overview of the physical and chemical properties of hydrogen and therefore can effectively manage incidents involving it.

5.3. Integrated tools for risk assessment

Several methods, including approaches based on data collection and the use of tools, are being developed to improve hydrogen safety. SANDIA's HyRAM software, for example, establishes a standard methodology for performing quality assessments and autonomous consequence analyses, enabling the safety of hydrogen refuelling and storage infrastructure to be evaluated. HyRAM includes a methodology and a software toolkit that provides a platform for integrating advanced engineering models and hydrogen safety data [154]. Other integrated tools are available for assessing hydrogen risks [155–157].

There are also accident databases such as:

- European Union's Hydrogen Incident and Accident Database (HIAD) [158] ;
- US DoE, Global Hydrogen Incident Reporting Database (HIRD) [159] ;
- ENergy-related Severe Accident Database (ENSAD) [160] ;
- Japan, High-Pressure Gas Safety Act Database [161].

In addition, the h2tools.org portal provides a comprehensive resource for hydrogen safety guidelines and incident data. The portal's goal is to support the implementation of practices and procedures that will ensure safety when handling and using hydrogen in various fuel cell applications. The portal collects and enhances the usefulness of a variety of online tools and content on the safety aspects of hydrogen and fuel cell technologies to help inform those responsible for designing, approving, or using systems and facilities, as well as those who respond to incidents.

Finally, we recommend reading the report entitled "Risk Assessment of Hydrogen and Battery Power in Locomotives" by the National Research Council Canada (NRC) for Transport Canada [162–164] , and in particular the three sections discussed below:

1. Lessons learned: the study focuses on accidents involving hydrogen and highlights various lessons learned, for example, related to filling hydrogen tanks.
2. Annotated examples of hydrogen trains: the study focuses here on the five hydrogen train experiments identified worldwide at the time of the report (2022): the mining vehicle from Vehicle Projects LLC, the Green Goat from Vehicle Projects LLC, the Coradia iLint from Alstom, the Telligence Group system, and the East Japan Railway Company.
3. Failure and severity rates: The study focuses on failure rates, modes, causes, consequences, and the severity of incidents involving locomotives, trains, and switches.

It should be noted that this NRC report (phase 1) was written before the Coradia iLint arrived in Québec. Finally, a study for Transport Canada on the assessment of risks associated with hydrogen and the analysis of hazards for railway applications was carried out by Canadian nuclear laboratories and published in December 2024.

6. *Conclusion of Section 3*

Like any fuel, hydrogen has specific properties that must be understood in order to reduce risks and ensure safe use in all applications. This section opens up various avenues for reflection, raising awareness of the importance of conducting specific risk analyses when operating hydrogen systems within new ecosystems, providing the necessary specific training (see Section 5), and following the reference codes and standards for the use of the system to be implemented. In addition to understanding the specific issues related to the use of hydrogen, examining the causes of hydrogen accidents also makes it possible to take appropriate measures to mitigate risks. Potential hydrogen leaks must be avoided, particularly in confined spaces and in any retention areas where hydrogen could accumulate. In addition, in the event of a leak, it must be possible to limit the amount of hydrogen released.

In practice, it is preferable to use hydrogen in ventilated areas (ensuring that there are no areas without air circulation), to use hydrogen detectors where there is a risk of hydrogen accumulation in the event of a leak, and to install a safety device to cut off the hydrogen supply in the event of a leak. Checking the tightness of pipes before commissioning a system and using a neutral gas (e.g., nitrogen) to purge the pipes before shutdown and startup are also recommended practices to mitigate risks. Finally, on a rail network, it is mainly passages through tunnels and stations that are affected.

Section 4: Hydrogen Train Operations

1. *Topography*

The Charlevoix Train is a tourist train that runs on the Charlevoix railway, connecting Québec City to La Malbaie along the St. Lawrence River for 125 km. The train passes through seven coastal towns and villages and offers various stops, from Baie-Saint-Paul to Saint-Irénée beach and La Malbaie (see Figure 17). The line began operating in 2011 following an initiative by Le Massif, owner of the Le Massif de Charlevoix tourist resort. The previous passenger train operating on the Charlevoix railway, the Tortillard du Saint-Laurent, ceased operations in 1961. The service was suspended until 2015 before returning to operation. Since then, it has been operated by Train de Charlevoix. The service is provided by only two trains, with a third available in case of technical problems with one of the two trains.

Figure 17 : Train route proposed by Train de Charlevoix.

The hydrogen train operated over 87 km between the stations of Chute-Montmorency, near Québec City, and Baie Saint Paul. The topography of the Charlevoix railway is presented in Appendix A4: Channel diagram.

2. *Commercial operation of the hydrogen train*

During the summer of 2023, the Coradia iLint was deployed in Québec as part of a public demonstration project. Between June 17 and September 30, five days a week, the Coradia iLint transported passengers between Montmorency Falls Park in Québec City and the town of Baie-Saint-Paul in the Charlevoix region. Running along the St. Lawrence River for 87 km, this section of track managed by Réseau Charlevoix[25], part of the Le Massif Group, offers passengers the chance to discover the beauty of the landscapes of this area, designated a biosphere reserve by UNESCO.

[25] Chemin de fer Charlevoix is a private, local railway that has been owned by the Le Massif group since 2009, the environment in which the experiment took place. Réseau Charlevoix is the public facilities management company whose flagship product is the Train de Charlevoix.

In 2021, Alstom launched the exploratory phase of its project in Québec, seeking to establish a framework for experimentation and identify the necessary stakeholders. After discussions with Réseau Charlevoix and Harnois Énergies, several scenarios were studied to select the demonstration site and the green hydrogen supplier/distributor. Subsequently, a prototype of the train, the BR654, was imported from Germany by Alstom for the experimental project in Québec with $3 million in financial support from the Québec government, with the total cost of the project amounting to $8 million. This BR654 prototype is one of the first two Coradia iLint demonstration trains manufactured by Alstom. Modifications were made to comply with provincial and federal regulations (see Section 2).

Alstom also organized training in Germany for Réseau Charlevoix drivers and managers to familiarize them with the train's technology (see Section 5). Meetings were held with the two municipalities through which the train passes. In collaboration with the Hydrogen Research Institute at the University of Québec at Trois-Rivières, training on green hydrogen safety was developed for operators. A hydrogen-specific emergency plan was put in place to train Charlevoix emergency services. After reviewing the Coradia iLint safety file, Québec's Ministry of Transport and Sustainable Mobility authorized the Charlevoix Railway to operate the train on its private network.

Alstom has partnered with Harnois Énergies for its hydrogen supply. In 2018, Harnois Énergies set up the very first hydrogen refuelling station open to the public in Québec. Produced locally by electrolysis of water using renewable electricity from Hydro-Québec, Harnois Énergies supplies hydrogen to power 75 Toyota Mirai cars in 2023, which have been undergoing tries in the province since 2019. Harnois Énergies delivered hydrogen produced at its Québec City station to Baie-Saint-Paul to refuel the Coradia iLint at a rate of 50 kg of hydrogen per day, every day the train operates.

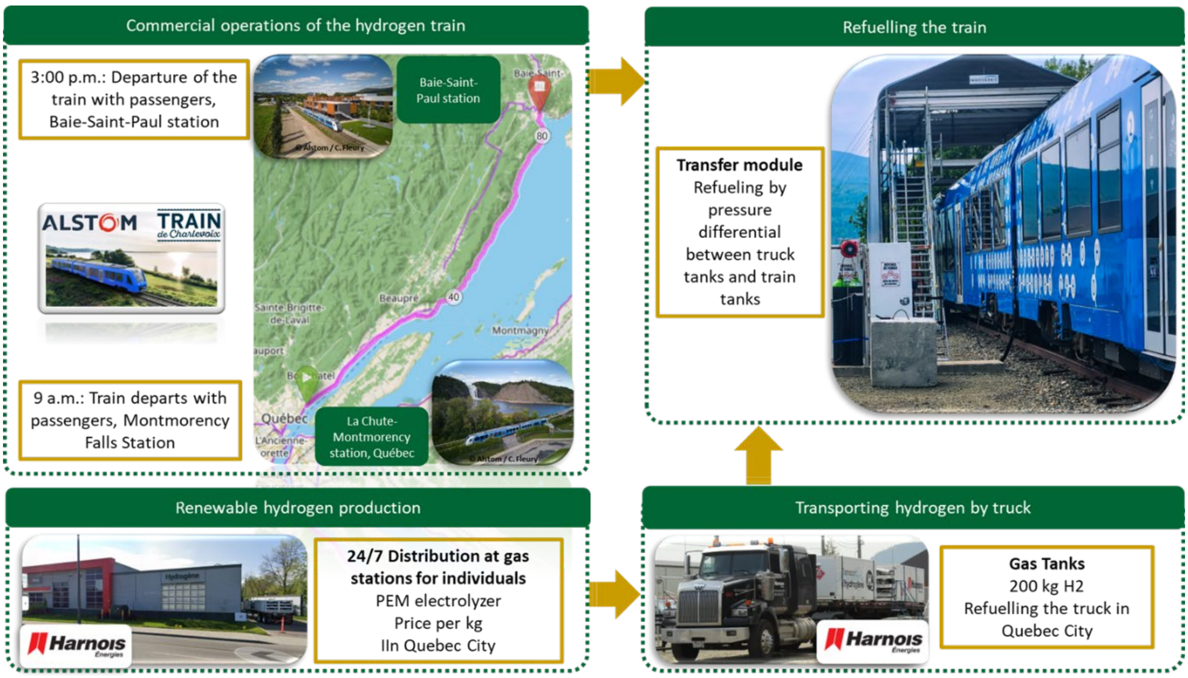


Figure 18 : Hydrogen train operations in the Charlevoix ecosystem.

The Baie-Saint-Paul site was chosen for the train's operation, maintenance, and refuelling (see Figure 19). This site already hosts the Train de Charlevoix facilities for its diesel trains. The second station on the route between

Québec City and Baie-Saint-Paul is located in the Chute-Montmorency Nature Park, which is administered by the Société des établissements de plein air du Québec (Sépaq) and does not belong to the train company. This imposed choice of site has therefore made it necessary to transport hydrogen by truck from the production site to the train refuelling site. It should be noted that the fuel used in Train de Charlevoix's diesel trains is also delivered by truck (50 km round trip from a gasoline station, twice a week), with refuelling taking place in Baie-Saint-Paul.

Figure 19 : General photo of the site in Baie-Saint-Paul during the hydrogen train operation in the summer of 2023.

3. *Hydrogen production and refuelling*

3.1. Refuelling during summer 2023 operations

The Coradia iLint's tanks can store 4.3 MWh of energy, corresponding to 130 kg of hydrogen at a pressure of 350 bar. By comparison, this is the same amount of energy contained in 400 liters of diesel[26]. The Coradia iLint must be refueled at a pressure of 350 bar. There are two possible methods:

- delivery of hydrogen at a pressure higher than the operating pressure of 350 bar;
- using an on-site compressor to reach the pressure required for refuelling.

When using an on-site compressor, the hydrogen can either be produced directly on site or transported at a pressure lower than the final pressure required (see Section 1). To avoid the complexity of installing a hydrogen compressor in Baie-Saint-Paul, the solution chosen by the various stakeholders was to transport the hydrogen at high pressure and fill the Coradia iLint by pressure transfer.

[26] This BR654 demonstration train does not have the same tank capacity as the Coradia iLint marketed by Alstom, which set a range record of 1,175 km in September 2022 [165].

To store and transport the hydrogen, Harnois Énergies used HTEC PC-45 hydrogen storage units. These storage units consist of five 315-liter tanks that can each hold 9 kg of hydrogen at a pressure of 450 bar. With four PC-45 units per trailer, 180 kg of hydrogen can be transported at a pressure of 450 bar.

To interface between the delivery truck and the train, a transfer and control module also manufactured by HTEC is used to perform refuelling (see Figure 20).

Figure 20 : Harnois Énergies truck and transfer module used to refuel the hydrogen train during the summer of 2023.

The transfer module is used in accordance with HTEC procedures for refuelling the train. The interface allows the train's tanks to be connected to those transported by the truck to be connected by fluidic hoses (mechanically secured). All equipment and the operator must be at the same electrical potential. The module allows pressure changes to be monitored and has a safety system in case of problems (health and safety aspects are detailed in Section 3). Refuelling is carried out by the train technician (Alstom) with the train manager (Alstom), the truck driver (Harnois Énergies), and the train driver (Train de Charlevoix). It should be noted that these personnel have undergone specific training, which is detailed in Section 5.

The refuelling principle directly involves the pressure differential. The technician opens the truck's hydrogen tanks two at a time. The truck has a total of twenty tanks. When the valves are opened, the hydrogen gas will flow until the tanks reach equilibrium pressure, at which point the technician closes the valves. He can then open the valves of two other tanks on the truck. This procedure is repeated until the desired pressure is reached in the train's hydrogen tanks.

It should be noted that throughout the truck's operations, the tanks of the Harnois Énergies truck always carry a certain amount of hydrogen. Once each pair of tanks reaches equilibrium pressure with the train, the remaining hydrogen is contained in the truck's tanks until refuelling is performed again at the Québec City station.

When filling the train's tanks, the 400 V external power supply (see Section 4) is connected to a diesel generator to power the auxiliary equipment, as the Baie-Saint-Paul facility does not allow for direct high-power electrical recharging (see Figure 21).

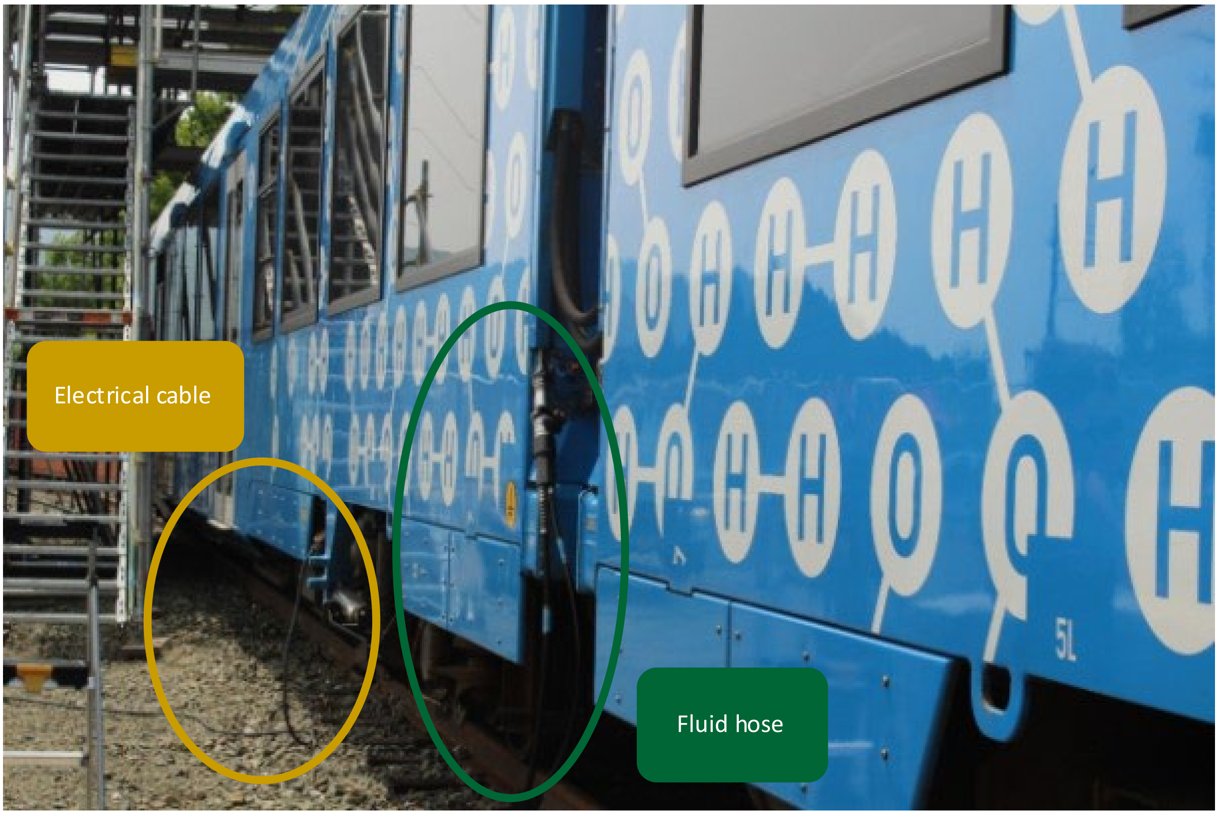


Figure 21 : The hydrogen filling hose and the cable for the external power supply, connected to the train.

As part of this operation, which will last several months, this simple-to-implement solution was selected. In the case of train operation over several years, other refuelling scenarios could be considered.

3.2. Other potential refuelling scenarios

Although hydrogen technologies are mature, the limited number of industry participants presents logistical and technical challenges within the ecosystem. In addition to the need for reliable hydrogen production, hydrogen must be delivered at the right pressure, purity level, and in sufficient quantities. For example, conventional delivery methods for hydrogen gas are carried out at pressures between 150 and 200 bar, while refuelling hydrogen systems in mobile applications requires pressures ranging from 350 to 700 bar.

As part of the Coradia iLint operations in Charlevoix, hydrogen was delivered directly at high pressure. This method allows for a minimalist installation in the refuelling area, compared to the more substantial installation of a compression and storage unit [7,58]. It was this simplicity of on-site installations that was prioritized in Alstom's Coradia iLint demonstration project. Four main hydrogen supply categories have been identified and discussed in the following section.

This section compares several options currently available for creating a new hydrogen ecosystem for rail transport: producing hydrogen on site or delivering it from a production site. There are also other possibilities, particularly for transport, which have not been considered here to focus on solutions applicable to a rail ecosystem, with production tailored to demand and as close as possible to the user (see Section 1). It is therefore possible to create new production or use existing production and only organize transport. In both cases, a backup solution can be considered with a second production facility to minimize risks in the event of a malfunction in the main production facility. Each new ecosystem must then be analyzed according to the following criteria:

- the complexity of installation;
- initial investment;
- maintenance;
- energy efficiency;
- operating costs;
- carbon footprint.

3.2.1.On-site gas production, compression, and storage

In this approach, hydrogen is produced directly on site by electrolysis of water. Once produced, the hydrogen is compressed and stored according to the project's pressure and storage requirements.

For mobile applications, there are two pressure standards: 350 and 700 bar [166]. As these are filling pressures, hydrogen installations are normally designed to operate at pressures higher than these filling pressures, typically 400-450 bar and 900-1000 bar respectively. In 700 bar installations, it is common to see compression and storage in two stages:

- first compression and storage at around 300 bar,
- followed by a second compression phase up to the final pressure of around 900 to 1000 bar.

This two-stage compression increases overall compression efficiency. Long steel tubes (type I tanks, see Figure 22) are generally used for medium and high-pressure storage. Storage capacity depends on the specific requirements of the facility and typically ranges from a few dozen to several hundred kilograms of hydrogen.

Figure 22 : Stationary hydrogen storage using Type I tubes [167].

The notable advantages of this approach are that it avoids the need to transport hydrogen, thereby saving on transportation costs. In addition, most hydrogen is currently transported using means of transport that themselves emit greenhouse gases (trucks, trains, ships, etc.). The carbon emissions resulting from this transportation will have an impact on the overall balance, which will generally be higher than that of hydrogen produced and consumed on site.

However, on-site production requires a large facility, which entails a significant initial investment. In addition, production capacity is normally sized according to the project's estimated needs. The downside of this sizing is that it makes it very complex to modify the site in the event of changes in needs.

The typical energy cost of operating an on-site hydrogen production facility (using water electrolysis) is approximately 55 kWh/kg of hydrogen for production [168] , then approximately 3.3 kWh/kg of hydrogen for compression to 900 bar [169].

The lack of redundancy is also an issue to consider. In a facility with an electrolyzer, compressor, and storage, the failure or simple shutdown for maintenance of one of the critical components in the chain paralyses the final hydrogen supply.

The hydrogen refuelling station operated by Harnois Énergies in Québec City is a typical example of on-site production, compression, and storage [5]. This station, which cost nearly $6 million to build, has a production capacity of 200 kg of carbon-free hydrogen per day, equivalent to 40 full refills of a Toyota Mirai car (see Figure 23).

Figure 23 : 1.2 MW electrolyzer manufactured by Hydrogenics (now Accelera by Cummins). Credit: Harnois Énergies.

Table 10 : On-site gas production, compression, and storage.

Installation complexity	**Significant.** Due to the need to install an electrolyzer and hydrogen compressors as well as auxiliary systems (cooling and demineralized water for the electrolyzer, for example). Note that for every 100 kg of hydrogen produced per day, the electrolyzer will normally require a power supply of around 250 kW.
Initial investment	**Significant.** The electrolyzer and hydrogen compressors represent a significant cost in an installation.
Maintenance	**Significant.** The electrolyzer, hydrogen compressors, and auxiliary systems require more maintenance than the piping and valves.
Energy efficiency	**High.** By avoiding the transport of hydrogen, overall efficiency depends mainly on the efficiency of the electrolyzer and compressors.
Operating costs	**Low.** Without taking into account the initial investment, the cost per kilogram of hydrogen produced depends only on the efficiency of the electrolyzer and the additional cost of compression.
Carbon footprint	**Very low.** The carbon footprint is minimal for this type of installation, provided that the hydrogen is produced from a carbon-free energy source.

3.2.2. Low-pressure hydrogen delivery, compression, and on-site storage

A more modest solution involves receiving hydrogen in low-pressure trailers (between 150 and 200 bar, see Figure 24), then using an on-site compressor with high-pressure storage. This approach eliminates the critical issue of on-site production by electrolysis.

Figure 24 : Low-pressure tube trailer (386 kg of hydrogen at 180 bar) [170].

Reducing the number of critical components (such as the electrolyzer and compressor) normally increases the resilience of the facility, thereby reducing downtime. In addition, since hydrogen can come from different producers, this provides partial redundancy to the facility, at least in terms of supply.

However, transporting hydrogen at low pressure increases the carbon footprint. Furthermore, at present in Québec and elsewhere in the world, there are few low-carbon hydrogen producers, and the risk of having to resort to carbon-based hydrogen (grey hydrogen, for example) is very real.

Another limitation of this type of facility is the quantities of hydrogen required. Low-pressure transport allows for the transport of relatively small amounts of hydrogen (typically 100 kg to 500 kg) [170]. This type of facility is more consistent with smaller-scale projects rather than large-scale projects that require a high number of hydrogen deliveries.

The Harnois Énergies refuelling station in Québec City has this type of facility, which is a small mobile station powered by a tube trailer supplied by Messer (see Figure 25). This second station provides redundancy in the event of a breakdown or shutdown of the main station.

Figure 25 : Mobile hydrogen station manufactured by Powertech and supplied by Toyota for the project with Transition énergétique Québec, the Government of Québec, and NRCAN. Credit: Harnois Énergies.

Table 11 : Low-pressure hydrogen delivery, compression, and on-site storage

Installation complexity	**Intermediate.** Less complex than an installation with electrolyzers, however, it still requires the installation of hydrogen compressors. A hydrogen supplier is also required.
Initial investment	**Intermediate.** As the electrolyzer is potentially the most expensive component, the initial investment is reduced.
Maintenance	**Intermediate.** Although hydrogen compressors require more maintenance than piping and valves.
Energy efficiency	**Intermediate.** Overall efficiency remains high and depends on the efficiency of the supplier's facilities, it is nevertheless reduced by the inefficient transport of low-pressure hydrogen.
Operating costs	**High**. The significant cost associated with the inefficient transport of low-pressure hydrogen is added to the cost of production and compression.
Carbon footprint	**Moderate**. Here, the carbon footprint is mainly due to the significant contribution of low-pressure hydrogen transport. It is assumed that hydrogen is produced from a carbon-free energy source.

3.3. Delivery of liquid hydrogen, compression, and on-site storage

To compensate for the low quantities of hydrogen that can be delivered at low pressure, it is also possible to transport hydrogen in liquid form. Liquid hydrogen allows for the transport of considerably higher quantities than hydrogen in gaseous form, typically around 4,000 kg of hydrogen, making it an economical solution for long-distance transportation [171]. In such a facility, liquid hydrogen must be stored in a cryogenic tank before being pumped into a vaporizer and then stored in high-pressure gaseous form.

The main disadvantage of this option is the significant energy cost required to liquefy hydrogen. In fact, liquefaction alone requires 13 to 15 kWh per kilogram of hydrogen [171]. In comparison, hydrogen production by water electrolysis requires approximately 55 kWh/kg of hydrogen [168] and 3.3 kWh/kg for compression to 900 bar [169].

During the 2010 Vancouver Olympic Games, a demonstration project involving twenty hydrogen-powered buses was implemented (seeFigure 26). During this project, the hydrogen required was transported in liquid form from Bécancour to Whistler by Air Liquide [172]. The Whistler refuelling station, built at a cost of $6 million, had a refuelling capacity of 800 kg per day at a pressure of 350 bar. Reason for the shutdown?

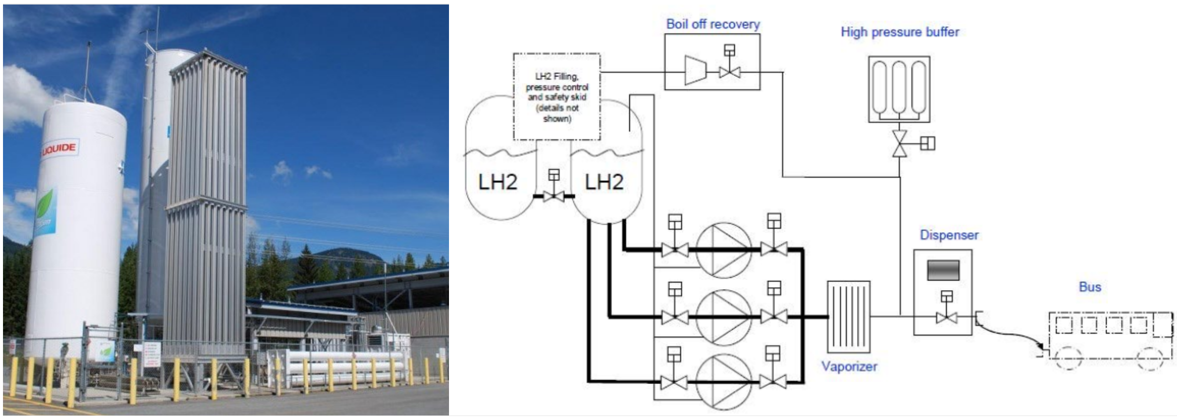


Figure 26 : Photo (left) and diagram (right) of the Air Liquide refuelling station used in Whistler from 2010 to 2014 [172].

Table 12 : Delivery of liquid hydrogen, compression, and on-site storage

Installation complexity	**Intermediate-high.** Less complex than an installation with electrolyzers, but requires the installation of a vaporization tower, cryogenic pumps, high-pressure storage and possibly compressors. A hydrogen supplier is also required.
Initial investment	**Medium-high**. The installation saves on the cost of the electrolyzer, but the addition of storage and cryogenic pumps increases the initial investment.
Maintenance	**Intermediate**. Although hydrogen compressors and cryogenic pumps require more maintenance than piping and valves.
Energy efficiency	**Low.** The liquefaction of hydrogen is an energy-intensive step in the process.
Operating costs	**Intermediate.** Liquefaction represents a significant additional cost, but is nevertheless an economical option for long-distance transport compared to low-pressure transport.
Carbon footprint	**Low to moderate.** The carbon footprint of hydrogen transport is lower than in the case of low-pressure transport, but the carbon footprint of liquefaction can be significant depending on the carbon intensity of the electricity used.

3.3.1.High-pressure hydrogen delivery without compression or on-site storage

High-pressure hydrogen delivery without compression requires the least amount of installation at the point of use. When the operating pressure allows, hydrogen can be delivered directly at high pressure and simply transferred by pressure cascade using a transfer module (see Figure 27).

This versatile option is ideal for short-term operations, pilot projects, or small-scale hydrogen requirements. Due to the lack of on-site compression, it is not possible to empty the delivery truck's tanks, meaning that only a fraction of the hydrogen transported can be used. However, when delivery distances are short and hydrogen volumes allow, this option represents a minimal initial investment compared to a typical installation.

When the Coradia iLint was operated in Québec in the summer of 2023, this option was chosen mainly for its speed and ease of implementation, considering the short operating time of the train. Harnois Énergies and

HTEC developed a solution to deliver hydrogen at 450 bar. Since the Coradia iLint operates at a filling pressure of 350 bar, refuelling was carried out directly from the delivery truck to the train using a transfer module whose function is to control the filling process.

Figure 27 : High-pressure tanks installed on a trailer. Hydrogen capacity of 180 kg at 450 bar. Credit: Harnois Énergies.

Table 13 : Delivery of high-pressure hydrogen without compression or on-site storage

Complexity of installation	**Low.** Only an on-site transfer module is required. A hydrogen supplier is also needed.
Initial investment	**Minimal.** Only the transfer module is required, as well as a means of delivering high-pressure hydrogen.
Maintenance	**Low.** The transfer module consists simply of piping, valves, and pressure regulators.
Energy efficiency	**Intermediate.** Hydrogen compression consumes much less energy than liquefaction, but transportation
Operating costs	**High.** The cost of transporting hydrogen is significant, as only a fraction of the hydrogen transported can be transferred due to the absence of on-site compressors.
Carbon footprint	**Moderate.** The carbon footprint due to transportation is significant, as only a fraction of the hydrogen transported can be transferred due to the lack of on-site compressors.

Ultimately, each hydrogen facility is unique and must be designed according to the specific needs and constraints of each project.

4. *Hydrogen consumption and energy performance compared to diesel*

4.1. General characteristics of trains in service in Charlevoix

The Table 14 compares the two types of trains in service on the Charlevoix Railway in the summer of 2023. It should be noted that this BR654 demonstration train does not have the same tank capacity as the Coradia iLint marketed by Alstom, which achieved a record range of 1,175 km in September 2022 [71].

Table 14 : Comparison of the hydrogen and diesel trains operated by Train de Charlevoix in 2023.

Train	**Alstom Coradia iLint BR654 (Prototype) [147]**	**Deutsche Bahn Class 628 [173]**
Class	Hydrogen train	Diesel train
Year	2016	1981
Number of cars	2	2
Number of seats	148	140
Length (m); Width (m); Height (m)	54; 2.75; 4.3	45.4; 2.85; 4.3
Total weight on rails (T)	106	76.9
Maximum speed* (km/h)	140 km/h	120 km/h
Traction power (wheel-rail)	2x272 kW	1x485 kW (650 hp) at 2100 rpm
Traction motor	Electric	4-stroke, MTU 12V 183TD 11
Fuel	Hydrogen	Diesel
Number x tank capacity	2x65 kg	1x960 L

*Note: Train speed is limited to 50 km/h on the Charlevoix railway.

4.1.1.Coradia iLint train BR654

Energy and power in the hydrogen train

The hydrogen equipment consists primarily of two components (hydrogen storage and fuel cells). The hydrogen is stored at a nominal pressure of 350 bar and made available to the fuel cells during operation. The hydrogen storage system is mounted on the roof of car A and car B for safety reasons (see Figure 28). The hydrogen storage system is refueled via pipes with special connections and check valves for each car. Refuelling can be performed from both sides of the vehicle.

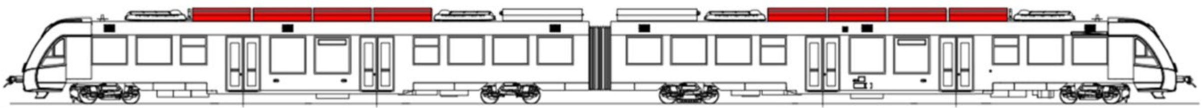


Figure 28 : Overview of the hydrogen tanks (in red).

The fuel cells are mounted on the roofs of both car A and car B and are used to generate electrical energy (see Figure 29). Each fuel cell system is comprised of eight individual fuel cell modules (see Figure 30).

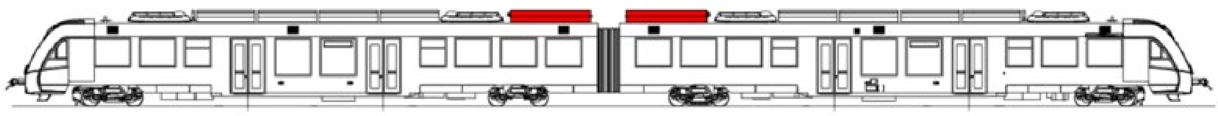


Figure 29 : Overview of fuel cell equipment (in red).

Figure 30 : Hydrogen train fuel cells.

To operate, a fuel cell requires various pieces of equipment, as shown in the Appendix A5: Functional diagram of the Coradia iLint fuel cell. In a fuel cell, the available hydrogen is converted into electricity during a chemical process (an oxidation-reduction reaction involving oxygen in the air, which produces water vapor). The electrical energy is transmitted to the DC/DC converter. In the DC/DC converter, the electrical energy is used to charge the traction battery and supplies the intermediate circuit with 700 V to 900 V. The following components are supplied by the intermediate circuit:

- Traction battery system (lithium-ion battery) as an intermediate energy storage device;
- Power converter with:
  - DC/DC converter for regulating the output voltage of the fuel cell;
  - Traction converter for supplying the traction motors and regenerating electrical energy during braking.
- Auxiliary converters for charging the supply batteries (24 VDC) and for supplying all power consumers from 24 VDC, 230 VAC, and 400 VAC;
- Coolant compressor for roof-mounted equipment for cooling the air conditioning system;
- Heating water station for heating the heating water circuit inside the air conditioning system.

The intermediate circuit power supply is isolated for each car and can be connected to the DC-Link circuit in the event of a failure.

Cold start

When a vehicle has been shut down cold, an additional waiting time must be allowed after the power supply is turned on, as the fuel cell and traction battery must be preheated to operating temperature. Shutting down the vehicle's power supply leads to a shutdown. Note that the shutdown time depends on the state of charge of the batteries.

Traction transmission

Three-phase alternating current is generated in the inverter for the traction motor. For this purpose, electrical energy from the traction battery or fuel cell of the intermediate circuit is used, converted into three-phase current, and then fed to the traction motor (see Figure 31). The rotary traction motor is directly connected to the drive shaft of the axle housing[27] of the bogie[28] motor.

[27] The axle (derived from the word "axis") is a mechanical assembly consisting of two wheels and a transverse axle.
[28] A bogie is a carriage located under a rail vehicle, to which the axles are attached.

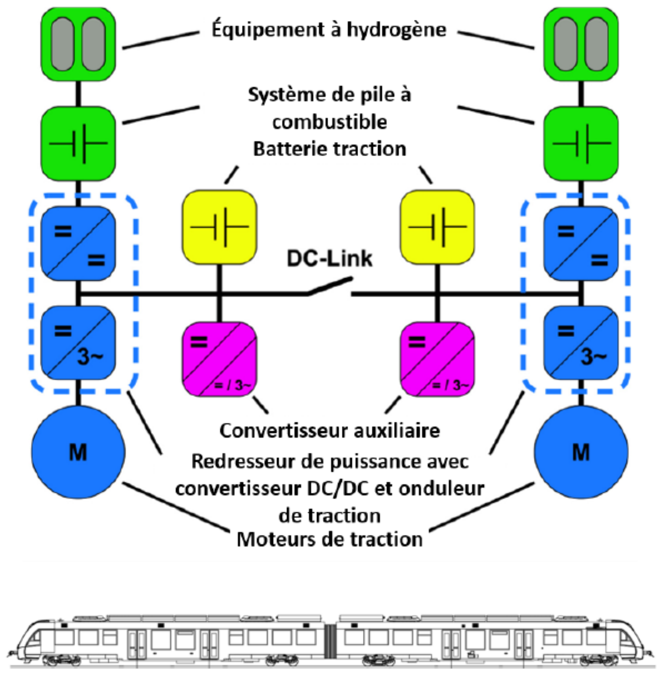


Figure 31 : Overview of energy production throughout the vehicle

400V power supply

The 400V three-phase distribution is installed between the following equipment (see Figure 32):

- Fuel cells on car A/B;
- Power converter on car A/B;
- Traction batteries on cars A/B;
- Cabin power outlets on cars A/B (230V between phase and neutral);
- Power outlets in the passenger compartments on cars A and B;
- Air compressors on car B;
- Heating in the toilets in car A;
- HVAC: air conditioner (2 per car).

The vehicle is equipped with an external 400 V power supply for each car. The 24 V vehicle batteries are charged from the external 400 V power supply and the vehicle is protected against freezing (toilets, traction batteries, and fuel cell).

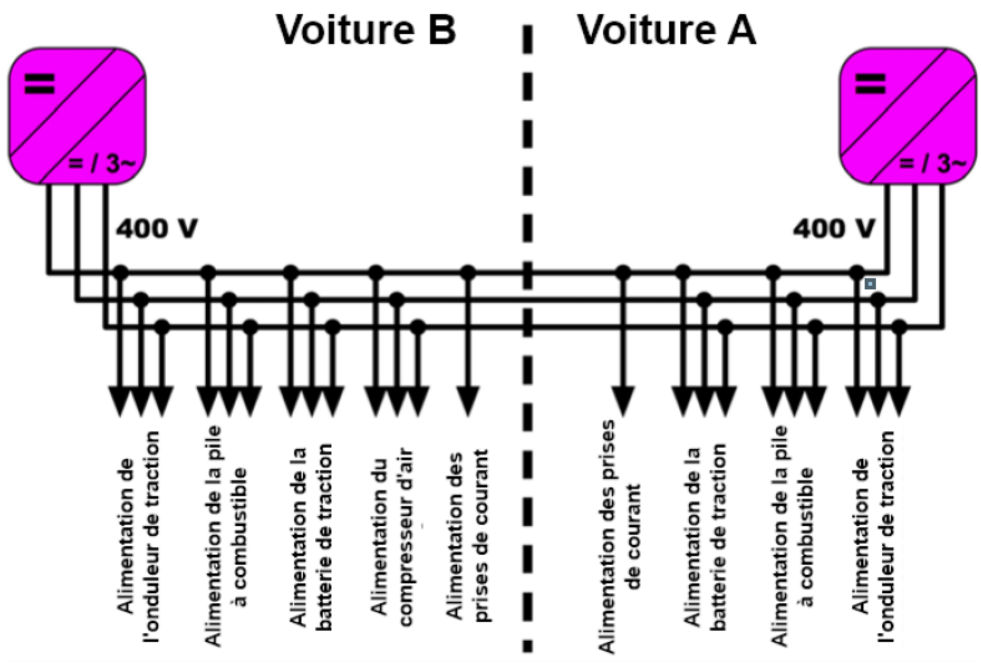


Figure 32 : Overview of the 400 V distribution.

Braking

The train uses five braking systems:

- Spring brake (parking);
- Electrodynamic brake (service);
- Automatic indirect-acting pneumatic brake (service brake assist);
- Direct-acting electro-pneumatic brake (emergency braking);
- Electromagnetic rail brake (emergency braking, high speed).

The electrodynamic brake is the vehicle's main brake. It should be noted that, unlike a mechanical brake, it operates without generating wear. If the required braking power cannot be achieved using the electrodynamic brake, the missing braking force is automatically applied by the indirect-acting pneumatic brake. In the event of a failure of the electrodynamic brake, the pneumatic brake can produce the full braking force.

However, in various emergency braking situations, the electrodynamic brake is never applied. If the train is traveling at a speed greater than 20 km/h, the electromagnetic brake is automatically applied during emergency braking in combination with the direct-acting electro-pneumatic brake, applied at all speeds.

Regenerative energy

When the electrodynamic brake is used, the electrical energy generated in the traction motor is transmitted to the DC/DC converter. At the converter, the electrical energy is rectified and the traction battery is charged.

Special features for testing in Québec

Alstom worked closely with Québec's Ministry of Transport and Sustainable Mobility to certify the Coradia iLint hydrogen train in accordance with the most stringent European standards, thereby ensuring safety and regulatory compliance for passenger transport. Two representatives from the Ministry of Transport and Sustainable Mobility even traveled to Germany to familiarize themselves with the technology.

Significant work was carried out in collaboration with Réseau Charlevoix to enable the train to be tested in Québec, taking into account the 21 criteria issued by the Association of American Railroads. In particular, modifications were made to the horn system and lighting to comply with current regulations. Minor adjustments were also made, such as the addition of a second driver's seat to comply with provincial regulations.

4.1.2.DB Class 628 train

Power and performance in diesel trains

The DB Class 628 consists of a power car (diesel locomotive, VT) and a control car (VS) (see Figure 33). The units are permanently coupled and cannot be separated during operation. Traction is provided by a 410 kW (at 2130 rpm) Daimler-Benz OM 424 A direct-injection diesel engine. The engine's lower idle speed is 800 rpm and its upper idle speed is 2400 rpm. This four-stroke engine has a 12-cylinder V-90° design with a water cooling system. A cooling water coil passes through the oil to preheat it.

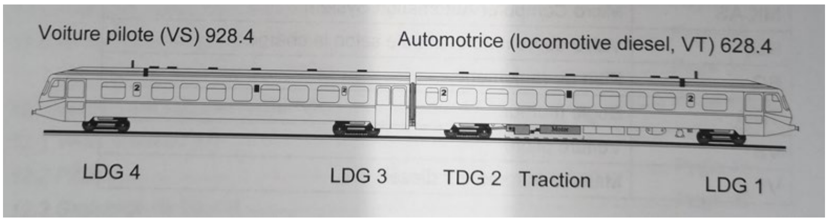


Figure 33 : Diagram of the diesel train.

Fuel system

The diesel and fuel oil tanks are installed under the train floor. The tank capacity is 960 L of diesel and 240 L of fuel oil[29] in two separate chambers. The driver's cab does not have a fuel oil reserve. In low temperatures, the fuel can be heated with fuel oil (see Figure 34).

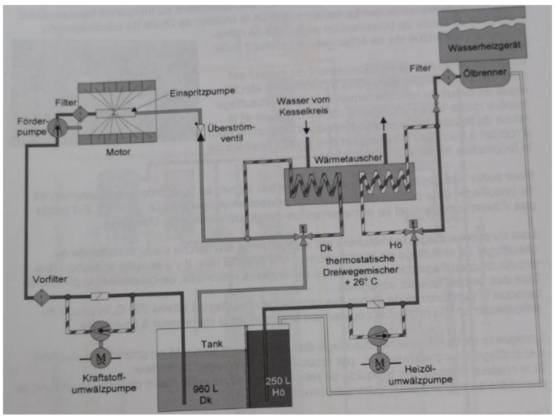


Figure 34 : Diagram of the fuel system for the diesel train.

[29] A fossil fuel, fuel oil or heating oil is a petroleum-derived fuel used in particular in boilers. The only notable difference between fuel oil and diesel is its cetane number, which is lower than that of diesel.

Traction

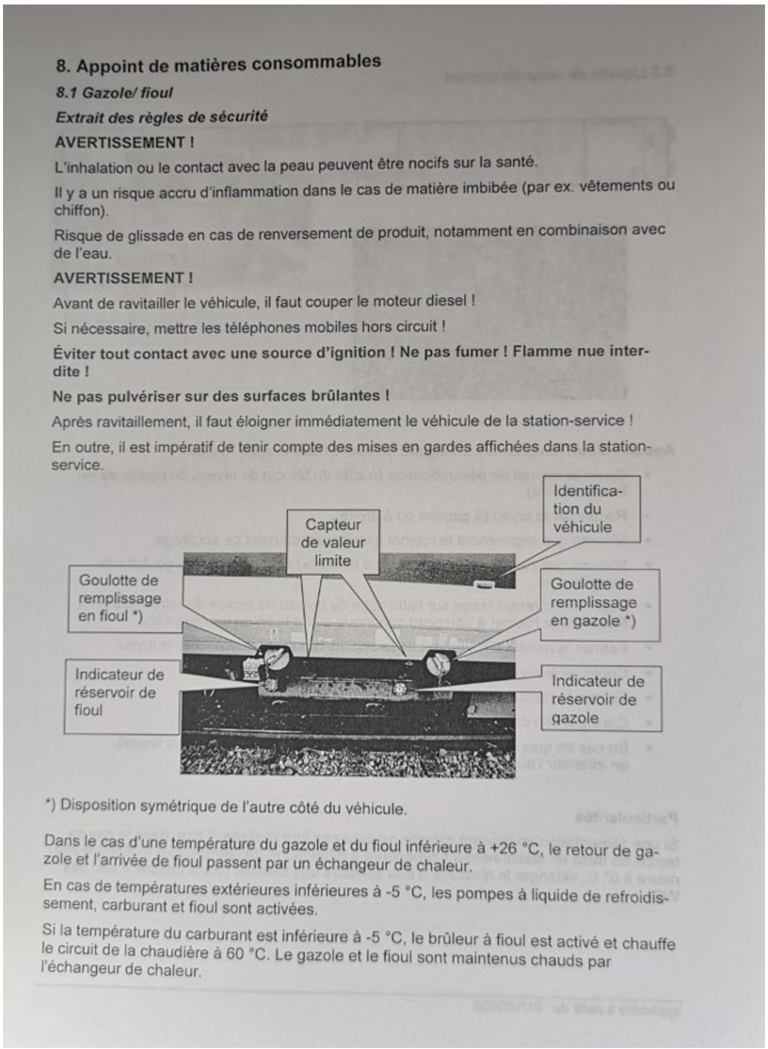
Traction is provided by a diesel engine located under the railcar, which drives the two bogie axles. The entire engine is located under the train floor and is secured to the chassis by elastic suspension. The traction system consists of:

- Diesel engine;
- Hydraulic transmission;
- Reversing gear;
- Drive axle[30].

Special feature

The diesel engine monitors itself: depending on requirements, it does not start, switches off automatically, or adjusts the idle speed.

Refuelling (see Figure 35)



8. Appoint de matières consommables

8.1 Gazole/ fioul

Extrait des règles de sécurité

AVERTISSEMENT !

L'inhalation ou le contact avec la peau peuvent être nocifs sur la santé.

Il y a un risque accru d'inflammation dans le cas de matière imbibée (par ex. vêtements ou chiffon).

Risque de glissade en cas de renversement de produit, notamment en combinaison avec de l'eau.

AVERTISSEMENT !

Avant de ravitailler le véhicule, il faut couper le moteur diesel !

Si nécessaire, mettre les téléphones mobiles hors circuit !

Éviter tout contact avec une source d'ignition ! Ne pas fumer ! Flamme nue interdite !

Ne pas pulvériser sur des surfaces brûlantes !

Après ravitaillement, il faut éloigner immédiatement le véhicule de la station-service !

En outre, il est impératif de tenir compte des mises en gardes affichées dans la station-service.

*) Disposition symétrique de l'autre côté du véhicule.

Dans le cas d'une température du gazole et du fioul inférieure à +26 °C, le retour de gazole et l'arrivée de fioul passent par un échangeur de chaleur.

En cas de températures extérieures inférieures à -5 °C, les pompes à liquide de refroidissement, carburant et fioul sont activées.

Si la température du carburant est inférieure à -5 °C, le brûleur à fioul est activé et chauffe le circuit de la chaudière à 60 °C. Le gazole et le fioul sont maintenus chauds par l'échangeur de chaleur.

Figure 35 : Photograph of the page concerning diesel train refuelling.

[30] A drive axle transmits power to the two wheels of the same axle on a motor vehicle.

4.1.3.Consumption

During the Coradia iLint's period of operation in the summer of 2023, hydrogen refuelling data was recorded and used to estimate hydrogen consumption. The refuelling data[31] relative to the distance traveled is presented at Figure 36. Based on this data for a distance of 100 km, for the entire duration of the Coradia iLint's operation, the average hydrogen consumption obtained is 26.8 kg of H_2 per 100 km.

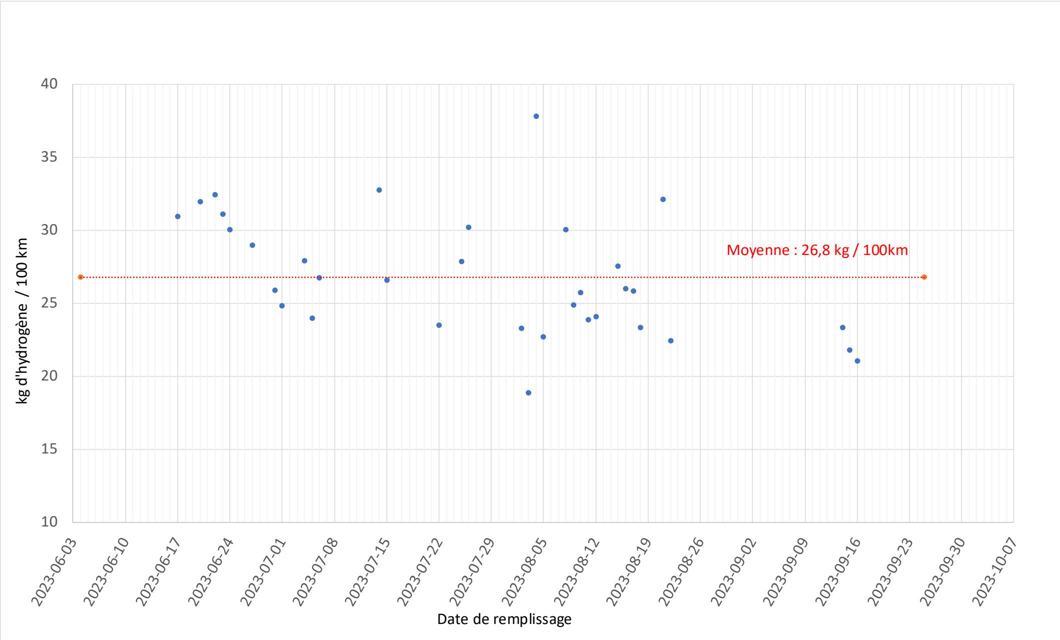


Figure 36 : Hydrogen refuelling data for the Coradia iLint BR654 in kg/100 km.

The variations observed in the refuelling data may be due to various factors:

- Operational factors
  - Number of passengers (impact on train weight and HVAC system consumption)
  - Driving style, number of train stops
  - Extraordinary maneuvers (unscheduled train movements for demonstration or testing purposes)
- Operations during refuelling (e.g., purging)
- Weather factors (temperature, humidity, winds)
- Technical factors
  - State of charge of the traction battery at departure
  - Fuel cell performance

Although a correlation between the variations and these factors could not be established, the average can be considered a realistic indicator, given the number of days of operation.

To compare the efficiency of these two trains, we will estimate their energy performance based on refuelling data for the trip from Québec City to Baie-Saint-Paul. First, the energy contained in 26.8 kg of hydrogen is

[31] The amount of hydrogen used is determined based on the pressure in the tanks before and after filling. The Abel-Nobel equation of state is used to convert pressure into density and then finally into kilograms of hydrogen.

4075.4 MJ[32]. In comparison, the estimated consumption[33] by Train de Charlevoix for DB Class 628 trains is 100 liters per 128 km on average, or 78.12 liters per 100 km. The energy contained in 78.1 liters of diesel is 4189.8 MJ. Based on this data, the Coradia iLint BR654 thus has 2.8% better energy performance than the DB Class 628 on the route between Québec City and Baie-Saint-Paul.

Let us now compare energy performance relative to train weight. The hydrogen-powered Coradia iLint BR654 is 38% heavier than DB Class 628 diesel trains. In this calculation, the weight of fuel and passengers is negligible compared to the weight of the train. In fact, as a more recent design (around forty years old), the Coradia iLint is heavier due to its higher structural integrity standards (collision safety) and its more advanced heating, ventilation, and air conditioning systems than the DB Class 628. The Coradia iLint is therefore 42% more energy efficient when compared to the total mass of the train.

As the purpose of this train is to transport passengers, energy efficiency is ultimately calculated in relation to the number of passengers carried. With a maximum capacity of 148 seats compared to 140 for the diesel train, the Coradia iLint is 8% more energy efficient when compared to the maximum number of passengers. It should be noted that both trains can also accommodate standing passengers, who are not included in these figures.

4.2. Noise emissions

4.2.1.Interior

Interior acoustic tests were carried out on September 4-5, 2023, on the Coradia iLint in accordance with ISO 3381 [174]. Microphones were positioned in accordance with Figure 37. A photograph taken during the tests is available at Figure 38. The results were analyzed by the acoustic engineer from the Alstom team responsible for these tests. The equivalent sound level[34] (LAeq) is shown in the Table 15.

Figure 37 : Location of the six microphones (red squares) for interior measurements.

Figure 38 : Photograph of microphones 2, 3, and 4 in the train.

[32] Taking a mass energy density of 45.6 MJ/kg of hydrogen and a volume energy density of 0.85 MJ/L of diesel.
[33] We do not have refueling records for diesel trains. This total is estimated by Train de Charlevoix for the entire route of its diesel trains, i.e., between Québec City and La Malbaie.
[34] This is the data that best characterizes noise that fluctuates over time (another example is traffic noise). It is the average energy level for a given period.

Table 15 : Results of static and dynamic interior acoustic tests.

Measurement	Average LAeq (dBA)
Coasting 50 km/h	62
Acceleration 0 - 50 km/h	61
Deceleration 50 - 0 km/h	61
Static	60

4.2.2. Exterior

External acoustic tests were carried out on the Coradia iLint in accordance with ISO 3095 [175]. The results of the static test are available at Figure 39 and those of the dynamic test at Table 16.

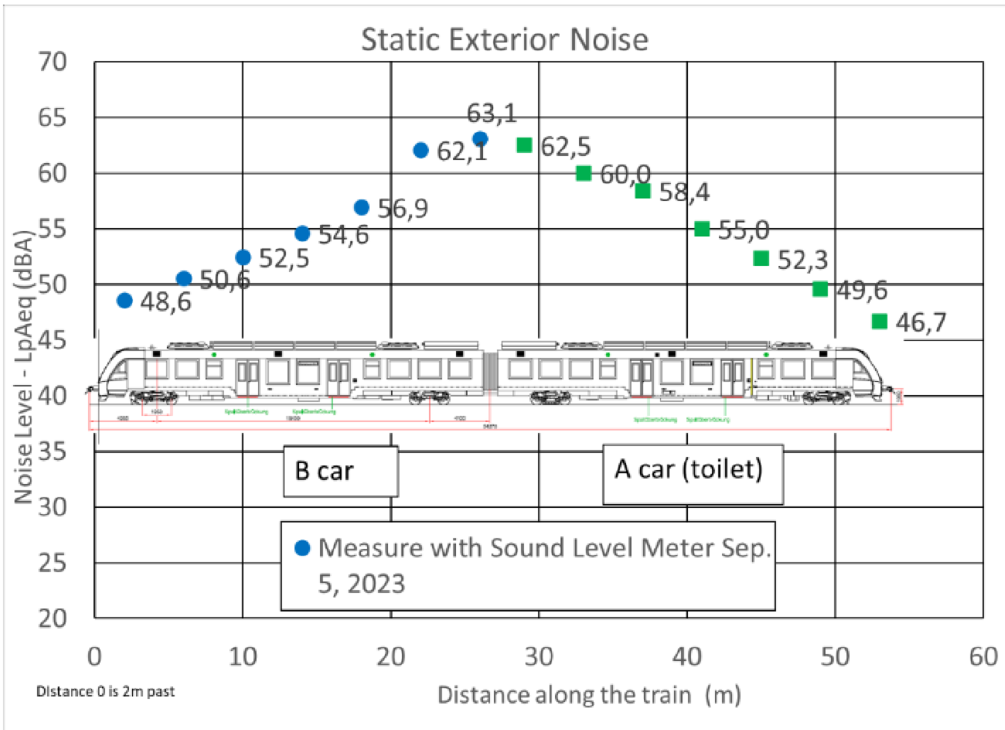


Figure 39 : Static exterior acoustic measurements

Table 16 : Results of outdoor dynamic acoustic tests

	Run	LpAFmax
Acceleration 0–30 km/h	accel1	74.7
	accel2	68.2
	accel3	73.0
	accel4	76.1
Deceleration 30–0 km/h	braking1	77.3
	braking2	81.8
	braking3	76.9
Coasting 50 km/h	50kph1	76.6
	50kph2	77.1
	50kph3	77.6

Tests on the diesel train could not be carried out to obtain a comparison on the same section of track. An initial attempt was made, coordinated between Train de Charlevoix and Alstom, but was unsuccessful (*Reason: Alstom/Train de Charlevoix*). A second attempt was planned but could not be carried out due to weather conditions, as snow began to settle on the section where the tests could be performed. Alstom indicated that the presence of snow could distort the acoustic measurements. This is because snow is less dense than soil, resulting in higher sound absorption. In order to provide a comparison in the report, Alstom provided the results of a test carried out in Europe (Figure 40), which shows that the noise level measured outside the Coradia iLint BR654 train is lower than that of an equivalent diesel train. This result is consistent with the findings of a report produced by the city of Groningen in Germany, which presents comparative acoustic measurements of the Coradia iLint BR654 with an equivalent diesel train [176]. It should be noted that a reduction of 3 dB is equivalent to a halving of emission power.

ILINT accoustic performance comparison

	ILINT pre-serial train	Diesel L 54
Exterior Noise at 0 km/h	52	67
Exterior Noise up to 30 km/h	78	82
Exterior Noise up to 40 km/h	78	82

Figure 40 : Data capture from a test conducted by Alstom (TSI NOI; DIN EN ISO 3095:2014, in dB).

4.3. GHG emissions

In Canada, transportation is the second largest source of GHG emissions. In 2021, this sector alone contributes 188 million tons of CO_2, which corresponds to 28% of Canada's total GHG emissions. Most of these emissions are caused by light and heavy-duty road vehicles. Canadian railways (passenger and freight), on the other hand, account for less than 4% of GHG emissions from the transportation sector. To achieve Canada's goal of reducing GHG emissions by 40-45% from 2005 levels by 2030 and reaching net-zero emissions by 2050, the transportation sector will need to make a significant contribution.

In 2021, 82.9% of the fleet met the emission standards set by the Locomotive Emissions Regulations or the U.S. Environmental Protection Agency (EPA) regulations. However, rail companies invested $2.3 billion in their Canadian networks in 2021 to further reduce their emissions. These investments were made in fleet renewal/modernization, fuel-saving technologies, operational efficiency, and the use of low-carbon fuels[35] [177].

Diesel trains and hydrogen trains have different emissions profiles, particularly in terms of greenhouse gas emissions. Diesel trains emit greenhouse gases directly from their exhaust pipes, mainly in the form of carbon dioxide CO_2, nitrogen oxides (NOx), and particulate matter (see Appendix A6: GHG measurements and air pollution emissions from a train). In contrast, the fuel cells used to generate electricity on board a hydrogen

[35] Railways use renewable fuels such as biodiesel up to 5% (B5) and hydrogenation-derived renewable diesel (HDRD) up to 30%. Most North American engine manufacturers approve biodiesel blends up to B5. There are a few important caveats to note: (i) biodiesel and HDRD have a slightly lower energy density than fossil diesel; (ii) fuel suppliers are not always required to disclose exact blend levels, so railways do not have a clear picture of the fuel they are using; (iii) locomotive performance may be affected by increased renewable fuel content, and manufacturer warranties may be voided [177].

train produce only water vapor (H_2O). This feature is particularly important in urban areas where rail traffic is heavy and can pose a health risk to the surrounding community (see Section 3). Therefore, hydrogen trains may be a promising solution to the problems of pollution around railways and stations, which can be harmful to people.

It should also be noted that stations contribute to greenhouse gas emissions from rail infrastructure through their operation, maintenance work on the tracks, and freight operations. For example, diesel locomotives used for shunting, local service, and freight or passenger rescue operations are also a source of GHG emissions [178].

Burning one liter of diesel produces 2.68 kg of CO_2 equivalent [179]. In the case of the Charlevoix train operation, considering only the train operation[36], for every 100 km served by the Coradia iLint rather than one of the diesel trains, 268 kg of CO_2 emissions were avoided locally.

It should be noted that Train de Charlevoix estimates the average fuel consumption of the diesel train at approximately 78.1 L of diesel per 100 km. Alstom reported traveling 10,660 km in the summer of 2023 with the Coradia iLint [180]. Assuming that the same distance would have been covered by a diesel train, the Coradia iLint will have prevented the local emission of 22.21 tons of CO_2 equivalent[37].

4.4. Well-to-wheel life cycle analyses

In the context of the climate crisis, it is crucial to undertake a comprehensive analysis of the entire cycle using the "well-to-wheels" (WTW) approach. It is essential to consider the total amount of pollution generated by each method, which can be achieved through a careful assessment of the emissions created throughout the entire process. WTW analysis is an approach that considers energy consumption and greenhouse gas emissions associated with production chains and propulsion systems. The analysis considers energy consumption and greenhouse gas emissions at every stage of the process, from the source of origin to the delivery of energy to the wheels. It comprises two stages: well-to-tank (WTT), which is the fuel cycle stage, and tank-to-wheel (TTW), which is the vehicle efficiency stage.

Considering the entire life cycle of diesel fuel (extraction, refining, transportation, and combustion), diesel trains have relatively high well-to-wheel emissions, contributing to significant greenhouse gas emissions. The well-to-wheel emissions of hydrogen trains depend mainly on the method of hydrogen production.

The WTW approach allows for the comparison of powertrains powered by the same fuel [60]. High WTW efficiency can reduce the amount of energy required from the original source, resulting in lower overall emissions. However, high well-to-wheel efficiency does not necessarily lead to lower emissions (example of diesel traction).

The use of hydrogen as an energy carrier to power rail vehicles is an efficient and environmentally friendly solution when using a fuel cell. Compared to diesel traction, the use of hydrogen produced by steam reforming of methane and used in a fuel cell vehicle can reduce CO_2 emissions by approximately 19% [60]. If hydrogen is

36 That is, only CO_2 emissions from the combustion of the train's diesel engine.
[37] Alstom's announcements in its press release of October 10, 2023 (22 tons of CO_2 equivalent for 8,400 liters of diesel consumed) only take into account the GHGs emitted during the operation of the hydrogen train (compared to the diesel train, without considering energy transportation or production) [180].

produced using renewable energy sources (such as electrolysis powered by wind or solar energy), emissions from well to wheel can be minimal and close to zero.

In order to compare diesel and hydrogen ecosystems, a preliminary well-to-wheel life cycle analysis is provided in Appendix A7: Analysis of greenhouse gas emissions . The executive summary of this study conducted by McGill University is presented below.

Hydrogen fuel cell technology is a compelling alternative for the electrification and decarbonization of passenger trains. Life cycle assessment (LCA) is a tool that can be applied to quantify the environmental impacts of transportation applications from feedstock extraction through waste disposal. The report takes a life cycle approach by conducting a well-to-wheel analysis (including the fuel cycle and passenger train operation) for a hydrogen fuel cell train and comparing it to a diesel multiple unit train operating in Quebec. The results presented here comprise a preliminary analysis which will be developed into a more complete life cycle assessment.

The analysis of both trains quantifies greenhouse gas (GHG) emissions in carbon dioxide equivalent [CO2-eq], including carbon dioxide [CO2], methane [CH4], and nitrous oxide [N2O]. Criteria air pollutants such as and nitrogen oxides [NOx] emissions and particulate matter [PM2.5 and PM10], referred to as PM, are also considered. The emissions from life stages of the fuel life cycle are estimated, encompassing feedstock extraction, fuel production, transportation, and train operation. In addition, we analyze the impact of various fuel transportation modes on greenhouse gas (GHG) emissions and criteria air pollutants for the hydrogen train.

Primary data were collected by interacting with experts from the hydrogen production facility (Harnois Énergies) and the Alstom train manufacturing company. In addition, secondary data were collected from previous studies and Ecoinvent LCA database to complete the information gap for model integration.

The study demonstrates a considerable decrease in greenhouse gas (GHG) emissions associated with the hydrogen train, achieving an approximately 33% reduction in CO2-equivalent emissions. Furthermore, employing fuel cell trucks and pipelines for fuel transportation, rather than diesel trucks, leads to notable GHG reductions of 79% and 83%, respectively. An additional strategy to consider is the on-site production of green hydrogen at the consumption facility, potentially eliminating GHG emissions.

The study delivers insights into the environmental implications of diverse transportation strategies within hydrogen train rail operations. It also aims to assist decision-makers in understanding the potential of decarbonizing railway systems renewable energy to fuel passenger trains. Notably, the WTW analysis presented in this study is a one step towards a more comprehensive LCA of hydrogen rail operations. In this study, we outline the key and necessary analyses that must be completed to a achieve a state-of-the-art LCA.

5. *Interviews and passenger experience results (environmental awareness, noise, environmental friendliness)*

The energy transition is not solely technological. It involves social and political transitions that are just as complex. The implementation and evaluation of a sustainable mobility project, such as the hydrogen train in Charlevoix, requires an analysis of social impacts. These impacts are necessarily multiple and varied. For example, we can seek to understand the impact of a changing infrastructure on the surrounding community. We can study the different tensions and synergies that a project generates among different groups of people. We can also analyze the relationship between industry, researchers, and the community with the aim of integrating local populations as inclusively as possible. These few non-exhaustive examples demonstrate the different dynamics at play in the energy transition.

5.1. Qualitative survey on the train

During the hydrogen train activity in Charlevoix, various interviews were conducted. The questions are presented in Appendix A10: Questions from qualitative interviews with passengers during two trips and Appendix A11: Questions from the quantitative survey with passengers. The initial results presented concern passengers encountered during two trips on the hydrogen train.

Passengers were impressed by its aesthetics and quality, in particular:

- The large windows offering a panoramic view;
- Stairways facilitating movement;
- The overall cleanliness and lack of odors, including in the restrooms;
- However, some found the seats too hard;
- They noted that the hydrogen train was quieter than diesel trains on the tracks—possibly due to better suspension?
- Some passengers were bothered by the whistle/horn and the air conditioning defects.

The questions asked of passengers provided an initial insight into their perception of hydrogen. We note the following points:

- **Confidence and lack of concern:** passengers expressed confidence in hydrogen. The factors that build this confidence are the fact that the train has been in operation for several years and their assumption that the train must have been thoroughly tested.
- **Engine smell and noise:** some did not notice any difference between the diesel train and the hydrogen train in terms of engine smell and noise, while others, who were familiar with hydrogen, did notice a difference.
- **Understanding of hydrogen:** Some described hydrogen as a source of electrical energy. Others are already familiar with its use in various contexts. Some questioned the relationship between hydrogen, electricity, and energy. It was mentioned that hydrogen should be used for specific purposes such as heavy transport. Many had questions about the more technical details of how hydrogen works to power trains. Finally, a few people mentioned having questions about safety and explosion risks.
- **Environmental awareness and critical questions**: Passengers shared their view of hydrogen trains as a more environmentally friendly solution than diesel trains or other forms of transportation powered by fossil fuels. Despite their positive impression of the train in terms of the environment, passengers raised questions about the total environmental footprint of hydrogen trains, including the manufacture of the train and the production of hydrogen. Some wondered whether it was really better for the environment and asked questions about the amount of water and energy used. More generally, passengers described themselves as being more aware than before, but

recognized the complexity of the systems and felt they were not fully equipped to understand them.

- **End of the oil era:** some passengers expressed hope for a future without oil companies. However, they question the efficiency and reliability of alternative energies.

Finally, the impacts and prospects:

- **Positive impact on passengers:** the hydrogen train had a positive impact on passengers, showing them a concrete example of technological innovation.
- **Questions about the future:** passengers wonder what the next steps will be for Québec in terms of transportation. They want to know Alstom's plans, the vision for hydrogen, and the direction of the energy transition for Québec.

5.2. Quantitative online survey

A survey was sent by Enipso to 1,734 email addresses voluntarily provided by passengers on the hydrogen train in the summer of 2023. The surveys were sent in three groups and there were 304 respondents, giving a participation rate of 17%. The questions and answers can be found in Appendix A11: Questions from the quantitative survey with passengers and in Appendix A12: Quantitative online survey of hydrogen train passengers. A summary of the results is provided below.

It should be noted that of the 304 respondents, 160 were aged 65 and over and 80 were aged 55 to 64. 135 respondents traveled as a couple and 97 with their family. The income categories are evenly distributed.

Figure 41 : Header of the email sent for the survey.

Very few respondents had ever used a hydrogen system before boarding the hydrogen train. Passengers chose the hydrogen train (they had the option of the diesel train) mainly because of the novelty of the technology and the environmental issue. Most of them wanted to try a new experience, as they were already familiar with diesel trains. Respondents found the train comfortable and greatly appreciated the windows and the overall atmosphere of the train. Respondents reported that the train was neither noisy nor smelly, both inside and out. Respondents indicated they partially understood how a hydrogen train works and that the train has an environmental impact. Most respondents had no concerns about safety.

Respondents were optimistic about the deployment of rail transport as an alternative to private cars. They are also optimistic about the deployment of hydrogen-powered transportation. Respondents believe that hydrogen should play a greater role in transportation. Respondents would be willing to pay 10% more for their ticket to use zero-emission public transportation compared to conventional public transportation. It should be noted that 87 respondents would not pay more for their ticket.

5.3. Information for passengers

Figure 42 : Poster displayed by Alstom in the hydrogen train.

6. *Conclusion of Section 4*

During the 2023 summer tourist season, the hydrogen train was used to cover 87km between the stations of Chute-Montmorency, near Québec City, and Baie-Saint-Paul. During this period, it made 117 trips and carried more than 10,000 passengers, replacing a conventional diesel train. The average consumption of this hydrogen train was calculated at 26.8 kg of H_2/100 km based on refuelling data. These trips were made under normal operating conditions, with passengers on board and all train systems running, including air conditioning, and maintaining a cruising speed of less than 50 km/h. The 10,660 kilometers traveled by the Coradia iLint train during the summer of 2023 reduced CO_2 emissions by 22.24 tons compared to an equivalent diesel train (excluding energy production and transport).

Preliminary analysis of the life cycle, from well-to-wheel, reveals that the main environmental impact that could have been avoided is that associated with diesel trucks transporting hydrogen daily between Québec City and Baie-Saint-Paul. These trucks were not operating at optimal capacity, delivering small quantities of hydrogen daily, unlike the supplies for the diesel train. It is important to note that Alstom purchased carbon credits on the Québec carbon market to offset the emissions generated. To ensure more sustainable use of the hydrogen train (the operation was limited to a few months), it would have been beneficial to produce the hydrogen close to the refuelling area, which would have significantly reduced emissions. Another option that could have been considered would have been to use hydrogen-powered trucks, a technical solution that Harnois Énergies will implement for its future deliveries. Finally, these emissions could also have been avoided if refuelling had been possible, for example, at the Chute-Montmorency station in the Sépaq park.

Compared to a diesel engine, which emits various greenhouse gases and particulates, the fuel cells of the Coradia iLint train emit only water. In addition, during normal operation, a train also emits particulates during mechanical braking. Since mechanical braking is not the main braking mode of the Coradia iLint, it necessarily produces fewer emissions in this regard than diesel trains, which are not equipped with an electric braking system. An in-depth life cycle analysis of the two systems will allow for a comparison of the ecological footprint of each energy ecosystem used to operate these two trains. Finally, the Coradia iLint is quieter than an equivalent diesel train, both when stationary at stations and when in motion.

Finally, in terms of the passenger experience, train attendants were approached by passengers who showed interest and curiosity. Alstom produced a display in the train, available in French and English. To improve the passenger experience and take advantage of the train as a technological showcase, quick training could be given to train attendants, whose privileged position places them at the interface between the ecosystem's stakeholders and passengers. Another complementary idea could be to provide them with a booklet containing easily accessible general information to answer the following questions:

- How does a hydrogen train work?
- How is electricity generated in the train?
- Where are the hydrogen tanks located?
- What specific safety features are installed in the train?
- Why a hydrogen train rather than a battery train or electrification of the lines?
- How and where is hydrogen produced?
- How is hydrogen transported?

Section 5: Employee training

1. *Hydrogen handling*

1.1. Transportation of hazardous materials in Québec, Canada

Regulations governing the transportation of dangerous goods apply from the place of manufacture or distribution to the point of delivery or unloading. The fundamental objective of these regulations is to ensure the safety of road users, first responders, and the environment during the transportation of potentially hazardous substances. It is important that anyone responsible for handling or transporting hazardous materials has undergone appropriate training.

The main goods considered dangerous in relation to hydrogen by the conventions on the transport of dangerous goods are as follows [181]:

- UN 1049 Compressed hydrogen;
- UN 1966 Refrigerated liquid hydrogen;
- UN 3166 Fuel cell powered vehicle containing flammable gas or liquid;
- UN 3468 Hydrogen in a metal-hydride storage device;
- UN 3478 Fuel cell cartridges or fuel cell cartridges contained in equipment or fuel cell cartridges packaged with equipment containing hydrogen in a metal hydride.

The consignor must ensure that individuals responsible for handling or transporting dangerous goods have received adequate training. Similarly, the carrier must ensure that the transport of dangerous goods is entrusted to employees (including drivers) who have received appropriate training. Both the shipper and the carrier are required to keep a training record for a period of two years after the expiration date, starting from the date the training was provided.

As stipulated in paragraph 9 of section 51 of Québec's Occupational Health and Safety Act [182]:

> "The employer must take the necessary measures to protect the health and ensure the safety and physical and mental integrity of the worker. In particular, they must: **[...]** adequately inform workers about the risks associated with their work and provide them with appropriate training, instruction, and supervision to ensure that they have the skills and knowledge required to perform the work assigned to them safely."

It is therefore the employer's responsibility to provide adequate training to employees who handle or transport hazardous materials. Drivers who transport hazardous materials must carry proof of training with them.

Furthermore, all transportation of dangerous goods is regulated by Transport Canada under the Transportation of Dangerous Goods Regulations [153]. We can refer to Part 6 [183]:

> "***Training***.
> ***Training certificate requirements:***
> *6.1 (1) Every person who handles, requests the transportation of, or transports dangerous goods must, as applicable:*
> *(a) have appropriate training and hold a training certificate in accordance with this Part;*
> *(b) perform these operations in the presence and under the direct supervision of a person who has appropriate training and holds a training certificate in accordance with this part.*
> ***[…]***

Appropriate training

6.2 A person is considered to have appropriate training if they have a thorough knowledge of all the subjects listed in paragraphs (a) to (m) that are directly related to the duties they are required to perform and to the dangerous goods they are required to handle, request to be transported, or transport:

[...]

Foreign carriers

6.4 (1) Any document issued to a driver of a motor vehicle registered in the United States or to a member of a train crew subject to the provisions of 49 CFR for the transportation of dangerous goods indicating that they have received training that complies with sections 172.700 to 172.704 of 49 CFR is recognized as a valid training certificate for the purposes of these Regulations when that document is valid in the United States.

[…]

Expiration of a training certificate

6.5 The training certificate expires:

[…]

(b) for transportation by road vehicle, rail vehicle, or vessel, 36 months after the date of issue.

SOR/2017-253, s. 52

Retention of proof of training: responsibility of the employer and the self-employed worker

6.6 Every employer or self-employed person shall keep, in electronic or paper form, a training record or statement of experience, as well as a copy of the training certificate, from the date of its issuance until two years after its expiry date.

Presentation of proof of training: responsibility of the employer and the self-employed worker

6.7 The employer of a person who holds a training certificate or the self-employed worker shall, within 15 days after receiving a written request from an inspector, provide the inspector with a copy of the training certificate and, where applicable, the training record or statement of experience, and a description of the teaching materials used for the person's training.

Presentation of proof of training: responsibility of the person being trained

6.8 A person who handles, requests the transportation of, or transports dangerous goods, or who directly supervises another person performing these operations, shall immediately present his or her training certificate or a copy thereof to an inspector who requests it.

In addition, according to the Guide to the Transportation of Dangerous Goods in Québec [184]:

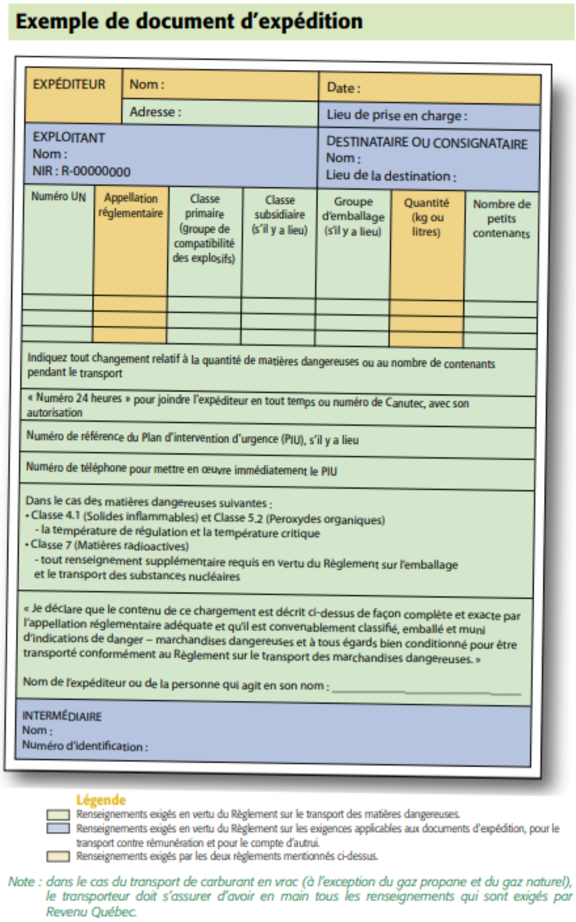
"Before authorizing a carrier to take possession of dangerous goods for transport, the shipper must prepare and provide the carrier with a shipping document. At the time of transport, the carrier must have in its possession a paper document, whether handwritten or printed.

The shipping document must contain the following information:

• the name and address of the shipper's establishment in Canada;
• the date on which the document was completed or submitted;
• a description of each dangerous substance,
in the following order:
- the UN number,
- the proper shipping name,
- the primary class,
- the letter of the explosives compatibility group, if applicable,
- the subsidiary class(es), if applicable (this information must be enclosed in parentheses),
- the packing group, if applicable,
- in the case of dangerous goods covered by Special Provision 23 of the TDG Regulations, the words "toxic by inhalation";
• the quantity of each substance and the unit of measurement used to express the quantity. It should be noted that any shipping document prepared in Canada must specify quantities according to the International System of Units (SI);
• the number of small containers for each dangerous substance, if applicable;
• The words "24-hour number," followed by the number where the shipper can be reached at all times, or the telephone number of a person other than the shipper who can provide technical information (the CANUTEC number cannot be used without written authorization from CANUTEC).
• any changes in the quantity of dangerous goods or the number of containers during transport;

• the reference number of the emergency response assistance plan (ERAP) assigned by Transport Canada and the telephone number to implement the ERAP, if applicable;
• a certificate from the shipper;
• any additional information required, if applicable.

Here is an example of the shipping document proposed in the Guide to the Transportation of Dangerous Goods in Québec [184] presented in Figure 43:



Exemple de document d'expédition

EXPÉDITEUR	Nom :			Date :		
	Adresse :			Lieu de prise en charge :		
EXPLOITANT Nom : NIR : R-00000000				DESTINATAIRE OU CONSIGNATAIRE Nom : Lieu de la destination :		
Numéro UN	Appellation réglementaire	Classe primaire (groupe de compatibilité des explosifs)	Classe subsidiaire (s'il y a lieu)	Groupe d'emballage (s'il y a lieu)	Quantité (kg ou litres)	Nombre de petits contenants

Indiquez tout changement relatif à la quantité de matières dangereuses ou au nombre de contenants pendant le transport

« Numéro 24 heures » pour joindre l'expéditeur en tout temps ou numéro de Canutec, avec son autorisation

Numéro de référence du Plan d'intervention d'urgence (PIU), s'il y a lieu

Numéro de téléphone pour mettre en œuvre immédiatement le PIU

Dans le cas des matières dangereuses suivantes :
• Classe 4.1 (Solides inflammables) et Classe 5.2 (Peroxydes organiques)
 - la température de régulation et la température critique
• Classe 7 (Matières radioactives)
 - tout renseignement supplémentaire requis en vertu du Règlement sur l'emballage et le transport des substances nucléaires

« Je déclare que le contenu de ce chargement est décrit ci-dessus de façon complète et exacte par l'appellation réglementaire adéquate et qu'il est convenablement classifié, emballé et muni d'indications de danger – marchandises dangereuses et à tous égards bien conditionné pour être transporté conformément au Règlement sur le transport des marchandises dangereuses. »

Nom de l'expéditeur ou de la personne qui agit en son nom : ____________

INTERMÉDIAIRE
Nom :
Numéro d'identification :

Légende
- Renseignements exigés en vertu du Règlement sur le transport des matières dangereuses.
- Renseignements exigés en vertu du Règlement sur les exigences applicables aux documents d'expédition, pour le transport contre rémunération et pour le compte d'autrui.
- Renseignements exigés par les deux règlements mentionnés ci-dessus.

Note : dans le cas du transport de carburant en vrac (à l'exception du gaz propane et du gaz naturel), le transporteur doit s'assurer d'avoir en main tous les renseignements qui sont exigés par Revenu Québec.

Figure 43 : Example of a shipping document for Québec [181].

When accepting a shipment of dangerous goods, the carrier must always ensure that they have the required shipping document. They must give the shipping document or a copy of it to the person to whom they are entrusting the dangerous goods. A person may be both the shipper and the carrier of the same shipment (e.g., a manufacturer who transports the dangerous goods it produces). The shipper and the carrier must keep a copy of the shipping document for at least two years, in one form or another. The TDG Regulations do not prescribe the use of any particular form for the shipping document. It is sufficient that all the required information be entered, in English or French, in a legible and indelible manner.

Therefore, all companies involved in the transport of dangerous goods are required to provide training to their employees on the associated risks, in accordance with the provisions of the Labour Code. More specifically, for employees involved in the transport of hazardous materials, the company must provide training on the specific risks associated with the transport of these goods, as well as on the measures to be taken to ensure their safety, the safety of others, and the protection of the environment and property.

In Canada, there is an exemption for the transport of hydrogen, including compressed hydrogen under UN code 1049. This exemption allows the transport of hydrogen in limited quantities, in a tank with a maximum capacity of 0.125 L.

In addition, transportation operations may be carried out without the requirement to undergo training in the transportation of dangerous goods. Furthermore, it is not necessary to complete the shipping document normally required for the transportation of dangerous goods.

This exemption is intended to facilitate the safe transport of small quantities of hydrogen, providing a practical solution without the regular training and documentation requirements associated with the transport of dangerous goods.

Anyone involved in the handling (shipping, transporting, or receiving) of dangerous goods by road must comply with the provisions of the Transportation of Dangerous Goods Regulations. Handling is defined in the following terms in the Transportation of Dangerous Goods Act [185] :

"Any loading, unloading, packing, or unpacking of dangerous goods carried out for the purpose of transport, during transport, or after transport. Storage operations carried out during transport are included in this definition."

All stages of transportation must be carried out in accordance with the TDG Regulations, including those parts of transportation carried out within a facility (e.g., loading, unloading, labeling, placarding, etc.). Please note that the TDG Regulations do not generally apply when dangerous goods are moved only within the premises of the company, its facilities, or property owned by it.

Driver training

Individuals involved in the handling or transportation of dangerous goods (TDG) must complete training that meet the requirements of Part 6 of the Transportation of Dangerous Goods Regulations. Alternatively, they may perform these tasks under the direct supervision of a person who has the relevant training and a valid training certificate.

To be considered adequately trained in the transportation of dangerous goods, employees must demonstrate a thorough knowledge of all aspects directly related to their duties, in accordance with section 6.2 of the TDG Regulations. In addition, individuals who have completed appropriate training and are performing tasks related to that training must hold a valid training certificate that complies with the information specified in section 6.3 of the Transportation of Dangerous Goods Regulations [153]**.**

Training Standard

Transport Canada has not defined specific prerequisites for course content, either for programs intended for trainers or for "training of trainers." It is the responsibility of employers to identify their training needs and approve the relevant program or course. To guide employers when determining the type of training required for their employees, Transport Canada has issued a TDG Bulletin outlining the training requirements for the Transportation of Dangerous Goods (TDG) [153].

Places to train employees

The Transportation of Dangerous Goods (TDG) office maintains an up-to-date list of companies offering dangerous goods training. However, it has not evaluated or validated the courses offered by external training companies. It is the employer's responsibility to choose a qualified trainer who can meet their training requirements [153].

Training requirements

Employees who plan to handle substances that meet the definition of dangerous goods as established by the Transportation of Dangerous Goods Act (TDG) and its regulations are required to undergo training. It is imperative for employees to complete this training before they begin handling hazardous materials. This training is not required if the employee is directly supervised by a TDG-certified employee, or when specific exemptions apply [185].

Prospects for standards and regulations in Europe

France Hydrogène has developed a practical guide on the regulations applicable to the hydrogen sector, specifically the transportation of hydrogen. This document contains a wealth of relevant information. It is an interesting reference for Québec and Canada, given the growing development of the hydrogen sector in the transportation industry.

Among other things, section 3 of the fact sheet states:

"*Practical guide to regulations applicable to the hydrogen sector*

Hydrogen transportation

[...]

3.8.2 Training of vehicle crew

The training of tanker vehicle drivers is divided into two parts.

Basic training, the main objectives of which are to make drivers aware of the risks involved in transporting dangerous goods and to teach them the basic concepts essential for minimizing the risk of incidents and, if an incident does occur, enabling them to take the necessary measures for their own safety and that of the public and for the protection of the environment, as well as to limit the effects of the incident.

Specialized tanker training for drivers of vehicles transporting dangerous goods in fixed or removable tanks with a capacity greater than 1m3, or in mobile tanks with an individual capacity greater than 3m3.

The training must be assessed by an examination and refreshed at least every 5 years.

Drivers transporting packages are only required to undergo basic training. Drivers transporting goods under the partial exemption of 1.1.3.6 are only required to undergo training 1.3.

[…]

3.9.1 High-risk goods (1.10.3 ADR)

High-risk dangerous goods are those that could be used to cause serious damage to property and people.

Hydrogen transported in tanks larger than 3,000 litres is considered high-risk dangerous goods and, as such, must be covered by a safety plan including, at a minimum:

- The carrier, consignee, shipper, packer, filler, tank container or portable tank operator, and unloader involved in the transport of high-risk goods must adopt and implement a security plan that includes at least:

- The specific assignment of security responsibilities to persons with the necessary skills, qualifications, and authority.

- A list of the dangerous goods or types of dangerous goods concerned.

- An assessment of routine operations and the resulting security risks, including stops required by transport conditions, the storage of dangerous goods in vehicles, tanks, and containers required by traffic conditions before, during, and after the change of location, and the temporary intermediate storage of dangerous goods for the purpose of changing the mode or means of transport (transshipment), as appropriate.

- A clear statement of the measures to be taken to reduce security risks, considering the responsibilities and functions of the operator, including the following:

-training,

-security policy (e.g., measures in the event of an increased threat, screening when hiring employees or assigning employees to certain positions, etc.),

-operating practices (e.g., choice and use of routes when already known, access to dangerous goods in temporary intermediate storage (as defined in paragraph c)), proximity to vulnerable infrastructure facilities, etc.),

- Equipment and resources to be used to reduce security risks.

- Effective and up-to-date procedures for reporting and responding to threats, security breaches, or related incidents;

- Procedures for evaluating and testing security plans and procedures for periodically reviewing and updating plans;

- Measures to ensure the physical security of transportation information contained in the security plan; and

- Measures to ensure that the distribution of information concerning transport operations contained in the security plan is limited to those who need to have it. However, these measures shall not prevent the communication of information otherwise required by the ADR. A security plan developed in accordance with the CIFMD interprofessional guide is deemed to comply with the requirements of the ADR.

1.2. Handling hydrogen in Québec, Canada

The safe deployment of hydrogen technologies in energy applications must be accompanied by the development of appropriate training for the various players in these new ecosystems. Hydrogen has already been used extensively in industrial application for decades. The industry has already trained its personnel to reduce risks to an acceptable level. As these internal training courses have been developed mainly in isolation, there are currently few training courses specifically focused on hydrogen safety.

Hydrogen safety training must place particular emphasis on the specific risks associated with hydrogen. Beyond the flammable nature of hydrogen, the physical and chemical properties of this gas mean that the risks associated with it are sometimes like those of other flammable substances, and sometimes quite distinct and specific. For example, comparing a leak of propane, a flammable gas heavier than air, with a leak of hydrogen, which is 14 times lighter than air, will lead to completely different risk mitigation and response measures. For more information on the properties of hydrogen, we invite readers to consult the Section 3.

According to Québec's Occupational Health and Safety Act, employers have an obligation to ensure the safety of their employees and to ensure that they have the training and information required to work safely. In fact, section 62.5 states:

"62.5. In addition to the obligations imposed on him under section 51, an employer must implement a training and information program concerning dangerous products, the minimum content of which is determined by regulation.
The employer must also ensure that the training and information received by a worker, at the times and in the cases prescribed by regulation, provide the worker with the skills required to perform the work assigned to him or her safely.

The training and information program is established by the health and safety committee. The procedure set out in section 79 applies in the event of disagreement within the committee.
In the absence of a health and safety committee, the training and information program is established by the employer, in consultation with the accredited association or, failing that, with the workers or their representative, where applicable, within the establishment.
This program must be updated in accordance with the terms and conditions set out in the regulations.
It shall be integrated into the prevention program when such a program must be implemented in the establishment [182].
1988, c. 61, s. 2; 2015, c. 13, s. 5."

Section 51 of the same Act states that it is the employer's responsibility to ensure the safety of its employees and that it is up to the employer to provide the appropriate protective equipment for the tasks to be performed:

"51. The employer must take the necessary measures to protect the health and ensure the safety and physical and mental integrity of the worker. In particular, the employer must:
(1) ensure that the establishments under their authority are equipped and arranged in such a way as to ensure the protection of workers;
[…]
9° adequately inform workers of the risks associated with their work and provide them with appropriate training, instruction, and supervision to ensure that they have the skills and knowledge required to perform the work assigned to them safely;
[…]
11° provide workers, free of charge, with all personal protective equipment selected by the health and safety committee in accordance with paragraph 4° of section 78 or, where applicable, the personal or collective protective equipment specified by regulation, and ensure that workers use such equipment in the course of their work;

Anyone who handles hydrogen in Québec must have completed general training on hazardous products. This training must include several important pieces of information, as explicitly detailed in Section VI of the Québec Hazardous Products Information Regulation.

The handling of hydrogen in Québec requires general training on hazardous products, in accordance with Section VI of the Québec Hazardous Products Information Regulation. This section sets out a training program applicable to all individuals exposed or likely to be exposed to hazardous products in the workplace.

The training program must cover various elements, including information on the nature of identification, labeling, container or tank placarding, and safety data sheets. It must also provide training on the hazards associated with each hazardous product in the workplace, as well as guidelines for the safe use, handling, storage, and disposal of these products.

The training also covers precautions to take in the event of leaks or spills. It explains the steps to follow in the event of a reactive mixture between two products that interfere with each other and can cause, among other things, toxic fumes. In addition, it includes a clear explanation of emergency procedures in the event of an incident.

The program must be updated annually. In the event of changes affecting work methods, exposure risks, or emergency procedures, training must be renewed for the workers concerned. Under section 62.1 of the Québec Occupational Health and Safety Act, employers must ensure that workers receive relevant training on the hazardous products to which they are exposed in the workplace. This also applies to new workers.

The training strongly recommended for companies is called the "Workplace Hazardous Materials Information System," commonly known as WHMIS.

1.3. Level of specialization according to tasks and responsibilities

In its White Paper on skills and professions in the hydrogen sector, France Hydrogène presents a study focused on France in which the skills and professions required for the hydrogen sector are analyzed. In this study, as an industrial company, Alstom was surveyed; notably, hydrogen-powered trains are included in the objects analyzed. This study reveals that in France, only a varying degree of "hydrogen coloration" is necessary. Half of the skilled occupations identified would require only minimal coloration. In other words, depending on the tasks and responsibilities related to the hydrogen environment, the level of specialization will require at least general information and may extend to a more specific qualification.

This document provides information on the following occupations, among others, that are present in the hydrogen train ecosystem:

1. **Truck driver**
   - High school diploma
   - ADR certificate
   - H_2 expertise: basic
   - Activity: operation
2. **Train driver**
   - High school diploma
   - Expertise H_2: basic
   - Activity: operations

Commissioning, operations, and maintenance technicians must be trained in the specific characteristics of hydrogen and the systems they work on. For example, bus and truck drivers must be familiar with emergency procedures in the event of an incident, while a commissioning technician must secure the equipment to perform tests and checks. Similarly, a repairer of explosion-proof equipment (ATEX) must be familiar with the specific characteristics of hydrogen equipment to apply safety procedures during repairs. Some professions require a more in-depth knowledge of hydrogen, such as the design of materials, components, or systems that must consider the specific characteristics of hydrogen in the design and qualification of equipment.

One of the interesting findings of this study is that some of the skills needed to develop this sector are in professions that are already experiencing staff shortages and/or recruitment difficulties.

2. *Front-line contributors to the project*

2.1. The project ecosystem and training

The ecosystem set up for the hydrogen train operation and the various stakeholders are presented at Section 1. The various stages of hydrogen train operation require a varying understanding of the specific characteristics of hydrogen. The questions asked of the project stakeholders during the field survey are presented in Appendix A9: Questions related to training.

When ranked according to their importance in terms of specific hydrogen training:

- Hydrogen production,
  - for employees responsible for the operation and maintenance of the station, it is the operational phase requiring the most specialized expertise;
- Refuelling the truck;
- Refuelling the train;
- Starting the train;
- Driving the truck;
- Train operation.
  - The fact that the train runs on hydrogen has little impact on day-to-day train operations for train employees. The only difference for each operation is in the event of a problem or emergency.

This classification must be reviewed for each specific situation. Firefighters or first responders who may be called upon to intervene must be aware of the risks and must use appropriate means in the event of an incident involving a hydrogen system.

Training as part of the project

As part of the Coradia iLint operation in Charlevoix, two specific training courses were given to staff:

- Training on the train;
- Training on the characteristics and safety aspects of hydrogen.

It should be noted that other training courses or certifications had already been provided to some of the participants before the train became operational.

- **Specific training on the Coradia iLint train**

Alstom offered a week of training in Germany to train drivers and certain members of Train Charlevoix staff, including train managers. This training covered the general operation of the train, driving, and everything related to its functioning and operations. There was a classroom session, with the manual, and a session on the train.

- **Hydrogen training**

The IRH was commissioned to provide training on hydrogen safety to the main players in the project ecosystem. During these training sessions on the characteristics, risks, and safety practices related to hydrogen, around 30 people were trained. Among the personnel trained by the IRH were all the front-line workers involved in the project's operation. The front-line workers involved in the Charlevoix operation are:

1. hydrogen delivery truck drivers (Harnois Énergies);
2. train drivers (Train de Charlevoix);
3. on-board technicians (Alstom Germany);
4. train managers (Alstom Canada).

2.2. Hydrogen delivery truck drivers

Hydrogen delivery truck drivers are responsible for the safe and efficient transport of hydrogen to its destination sites. Their responsibilities include driving the delivery truck, adhering to established schedules, and implementing rigorous safety procedures. Hydrogen delivery truck drivers play a key role in the hydrogen supply chain, contributing to reliable, safe, and regulatory-compliant distribution.

- Additional training for the driver responsible for the project with HTEC and LISOGAZ, in addition to his work experience and previous training in handling diesel fuel.
- Certification for the transport of hazardous materials. No specific hydrogen certification.
- On-site practical training with specific health and safety requirements for drivers working with hydrogen.
- Use of specific personal protective equipment such as antistatic clothing and antistatic gloves.

2.3. Hydrogen filling technician (Harnois Énergies team)

Hydrogen filling technicians play an essential role in the field of hydrogen transport. Their main responsibility is to refill hydrogen gas tanks for transport. They also refill hydrogen storage tanks on the trains, following strict safety and hydrogen handling procedures. These professionals play a crucial role in the logistics of hydrogen transport, helping to ensure operational safety and compliance with regulatory standards.

- Important training for the person responsible for the project with HTEC and LISOGAZ, in addition to their work experience and previous training in handling diesel fuel.
- Practical on-site training with specific health and safety requirements for drivers working with hydrogen.
- Use of specific personal protective equipment such as antistatic clothing and antistatic gloves.

2.4. Train drivers

The train driver plays a central role in rail operations, ensuring that the train runs on time and in accordance with established safety protocols and operating procedures. Before each departure, they carry out checks to ensure the integrity of the train. Regular communication with the control center, crew, and ground teams is essential for effective coordination. Strict compliance with railway regulations is a constant priority. In an emergency, the driver reacts promptly by following established safety protocols, ensuring the safety of passengers and operations.

Train drivers must have in-depth knowledge of railway networks and diesel train operations, in addition to the appropriate training for the job. They must also meet the criteria established by Transport Canada under the Canadian Rail Operating Rules (CROR). As part of the Coradia iLint operation, drivers received specific training in Germany. This training provided them with knowledge about the specific characteristics of the train they were to drive. They greatly appreciated receiving training on hydrogen, which does not directly impact their job, but which answered questions they had about the hydrogen ecosystem.

2.5. Onboard technicians

The hydrogen train's onboard technician plays an essential role in keeping the train operational. Their responsibilities include carrying out scheduled maintenance, detecting and repairing faults, and diagnosing any breakdowns. Whether in the maintenance shop or on the apron, these professionals perform a variety of repairs, including control systems, brake, fuel systems, hydraulic systems, etc. Their primary mission is to ensure that all train systems are functioning properly.

As part of Train de Charlevoix's operation of the train, the technicians are employees of Alstom in Germany. In the case of longer-term commercial operation, Train de Charlevoix's on-board technicians would operate the train. They would then be trained by Alstom during a training program that could last several months. Two technicians took turns throughout the summer 2023 project. These technicians have extensive knowledge and experience with this demonstration train. In addition, as their native language is German, they were able to more easily read and understand the train's error messages displayed on the interface.

As the train is a demonstrator train designed in Germany, it is operated in German. The on-board technician undergoes a three-day training course on explosive atmospheres (ATEX), in addition to specific training on regenerative brakes and the battery system. He supervises the various train system maintenance operations and notes his observations during the various procedures. He uses a foam-type leak detector to identify leaks before any work is carried out on the hydrogen system. Minor leaks were detected and corrected.

Every morning, before rail operations begin, the technician performs thorough checks both inside and outside the train, then issues the departure authorization. Specific checks are carried out, particularly on the condition of the fuel cells or batteries.

As part of the Train de Charlevoix project, the on-board technician only noted problems related to the operation of the air conditioning.

2.6. The conductor/attendant

Conductors or train attendants play a crucial role in the passenger experience and the smooth running of rail operations. They are responsible for assisting passengers during boarding and disembarking. They ensure that luggage is stowed properly, make rounds in the cars to check that everything is in order, announce the name of each station where the train will stop, and provide various other general information. They ensure passenger safety and report any defects that could interfere with the smooth running of operations to the conductor.

They supervise all operations and maintain direct communication with the train driver, whom they guide in the performance of various tasks. They are also in contact with the on-board technician, who informs them of any technical anomalies detected. The conductor is the central point for gathering information and making decisions.

It should also be noted that operating a hydrogen train does not affect the training of the conductor in terms of customer service and emergency evacuation procedures.

Finally, we note that continuous monitoring of the fuel cells was conducted by a Cummins employee during passenger operations. As the train was a demonstrator, more in monitoring of the fuel cell system and greater responsiveness in the event of a problem were required. We did not receive any further information about this operator or his training.

2.7. Firefighters, emergency services, first responders

Firefighters play a vital role in ensuring a rapid and safe response to incidents involving hydrogen. These professionals intervene in the event of leaks or other emergencies that may be related to hydrogen. Their mission includes implementing safety measures, managing evacuations if necessary, and applying specific procedures to contain and eliminate risks. Firefighters are trained to work in collaboration with other emergency services and ensure that all actions taken comply with established safety protocols, aimed at to minimize potential impacts on public and the environment.

As part of the project, the firefighters involved received a briefing on hydrogen from HTEC. In addition, they were given a presentation on Harnois Énergies' hydrogen system. Alstom also presented the hydrogen train to them and provided training on emergency response in the event of a fire.

It should also be noted that firefighters have expertise in managing situations involving explosive gases. They have the skills and knowledge to respond safely and effectively in the event of an incident. Their specialized training and experience give them the skills necessary to manage accident situations and make them key players in the implementation of the hydrogen ecosystem.

3. *Conclusion of Section 5*

Hydrogen train operations have revealed that the impact of the energy source is mainly concentrated in the refuelling process. During these operations, specific measures for hydrogen must be put in place and personnel must receive adequate training on the associated risks. Although experience with other fuels may provide some familiarity with the handling of hazardous materials, a fundamental knowledge of hydrogen remains essential due to its specific characteristics (as with any fuel).

Despite these differences, hydrogen train operations follow broadly the same procedures as those for a diesel-powered train. The staff assigned to the Coradia iLint have expressed their satisfaction at having gained an in-depth understanding of how it works and at having been made aware of this promising new energy source. Finally, it is important to emphasize the importance of the role of the on-board technician. It is necessary for them to have a comprehensive understanding of the train's system, regardless of the power source.

General conclusion

For optimal integration of hydrogen technologies, a comprehensive energy ecosystem is essential to ensure both energy production and distribution. Historically, hydrogen production relied on centralized production, mainly through steam reforming and gasification of fossil fuels. This type of model allows for large-scale production and economies of scale; however it remains dependent on transport infrastructure to serve all consumers and remains vulnerable to failure at the main site. Conversely, the decentralized model promotes flexibility, proximity to the end user, integration of renewable energies, and local resilience, but entails higher investment costs per site and more complex and fragmented management.

In 2019, Québec's first hydrogen station open to the public refuelled 46 Mirai vehicles as part of a Québec government test. Their number has increased to 75 in 2023, and the station has a capacity of 200 kg of H_2 per day (consuming 55 kWh of electricity and 10 L of water to produce 1 kg of H_2). The availability of surplus hydrogen production made it possible to consider refuelling the train in Québec. During the 105 days of the project, Train de Charlevoix sold 9,132 tickets for the Coradia iLint. The train also welcomed project partners, and 34 delegations from North America traveled on it. As a result, more than 10,000 passengers traveled aboard the Coradia iLint.

The data presented in the Table 17 was compiled between the first commercial trip on June 17 and September 30, 2023. The Train de Charlevoix tourist season saw its number of passengers doubled. Indeed, the hydrogen train, presented in commercial form as "the hydrogen experience," attracted more interested travelers.

Table 17 : Coradia iLint performance during the Train de Charlevoix summer season.

Number of days in operation	70
Number of trips between Québec City and Baie-Saint-Paul (round trip)	117
Distance traveled	9,407 km
Maximum speed	50 km/h
Passengers carried	10,000
Mass of hydrogen used	2,514 kg
Number of refills	60
Estimated volume of water produced by fuel cells	11,220 L
Average hydrogen consumption	26.8 kg / 100 km
Average hydrogen consumption per passenger	0.25 kg / passenger
CO_2 reduction equivalent / diesel (train operations only)	22.21 tons

Finally, the North American rail network spans more than 300,000 kilometers, less than 1% of which is electrified. Diesel is still widely used for passenger travel and freight transport. It is in this context that the hydrogen train ran in Québec during the summer of 2023. Various mature electric technologies (catenary, battery, and hydrogen) are already commercially available around the world and adapted to different railway uses, whether for passenger or freight transport. The renewal of train fleets that are reaching the end of their life should be a prime opportunity to consider the most appropriate technology for the application, considering economic and ecological realities. The judicious deployment of new ecosystems, in a context adapted to the public transport needs of populations and freight respectively, can ultimately be considered as an attractive alternative to private cars and trucks in terms of cost, availability, and frequency, while offering a unique experience to users (in terms of comfort and even tourism) and thus contributing even more to the sustainable future of our society.

Appendices

A1: GHG emissions from different types of hydrogen production

Thermochemical methods include methane steam reforming, coal gasification, and partial oxidation of petroleum, which are the most used. These processes are the most intensive, with GHG emission factors ranging from 10 to 13 $kgCO_2$ e/kgH_2 for steam reforming and 22 to 26 $kgCO_2$ e/kgH_2 for coal gasification (seeTable 189). These figures consider emissions from drilling to the finished product, including transportation, and can be significantly reduced by capturing and storing the carbon emitted.

Thermochemical methods using renewable biomass (forestry, agricultural, or municipal) are also possible for hydrogen production, such as pyrolysis and biomass gasification [66]. For example, the use of renewable biomass such as wood chips can significantly reduce the carbon intensity of the gasification process from 1 to 6 $kgCO_2$ e/kgH_2 (compared to 22 to 26 $kgCO_2$ e/kgH_2 for coal) [28] , or even be carbon negative with CO_2 capture and storage.

Electrochemical methods of hydrogen production are characterized using electrical energy to produce hydrogen through electrochemical or electromicrobial processes. The most common process for electrochemical hydrogen production is water electrolysis. This process uses electricity as an energy source to power electrodes where water is oxidized at the anode and the protons from this reaction are reduced to hydrogen at the cathode. PEM (Proton Exchange Membrane) electrolyzer technology is used in Québec by several industrial companies, including Air Liquide [186] and Harnois Énergies [5].

Still in the research stage, electromicrobial processes use organic matter as a source of protons and electrons. The oxidation of organic matter is carried out by microorganisms that have colonized the anode. These microorganisms use organic matter for their metabolism and release the electrons and protons needed to produce hydrogen. These products are transferred to the cathode to be reduced [187]. This process reduces the primary energy input to the system and allows for better tolerance to contaminated water compared to an electrochemical system [188,189].

The carbon intensity of electrolysis (chemical or biological) is low. For a PEM electrolyzer operating 3,000 hours per year, it is around 0.1 $kgCO_2e/kgH_2$ [28]. The most important parameter will be the origin of the electricity used. According to the US Department of Energy [190] , the carbon intensity of electricity can vary greatly depending on how it is produced. As shown in theTable 189, the use of electricity from fossil fuels, except for nuclear power, emits between 486 and 1000 gCO_2e/kWh, while electricity from renewable sources emits between 13 and 52 gCO_2e/kWh. Therefore, despite electrolysis production having very low CO_2 emissions, it is the chosen energy source that will have the greatest impact on the carbon intensity of the hydrogen produced.

Finally, the electricity produced in Québec is mainly supplied by renewable energy sources such as hydroelectricity. Emissions from hydroelectricity are indirect and can result from land flooding and dam construction, both of which lead to increased biogenic GHG emissions due to biomass degradation. The carbon footprint of the electricity distributed is therefore comprehensively quantified at 34.5 gCO_2e/kWh, considering the net biogenic GHG emissions of all hydroelectric reservoirs in the province of Québec (see Appendix A7: Analysis of greenhouse gas emissions).

Table 18 : CO_2 emissions associated with the electricity generation method proposed by the US Department of Energy (adapted from [190]).

Electricity	Production method	Median emissions gCO_2 e/kWh*
Renewable	Biomass	52
	Photovoltaic	43
	Hydroelectricity	21
	Wind	13
Non-renewable	Nuclear	13
	Natural gas	486
	Oil	840
	Coal	1001

*scenario without carbon capture

A2: Summary of international trials and progress of hydrogen trains

Today, hydrogen is playing a role in the transition to greener rail transport. Alstom's Coradia iLint hydrogen train is the first commercially produced train on an international scale. In this summary, we review the testing and progress of this train from 2018 to 2022. The sources presented in this summary are taken from the International Energy Agency's Global Hydrogen Review 2022 [22] , which cites a number of press releases [191–194].

Between 2018 and 2022, trials of the Alstom's Coradia iLint were carried out in Germany, France, the Netherlands, Austria, Italy, Sweden, Spain, and Poland.

In August 2022, Germany inaugurated the first fleet of hydrogen trains consisting of 14 Coradia iLint trains, which will replace diesel locomotives, thereby contributing to the decarbonization of the rail sector [195]. These trains were tested for 18 months on the Buxtehude–Bremervörde–Bremerhaven–Cuxhaven line near Hamburg in northern Germany [192]. They have already covered more than 200,000 km in regular passenger service [191]. The project, which cost tens of millions of euros, has created nearly 80 jobs. Ultimately, Alstom will deliver 41 trains from the Coradia iLint series to Germany [191,194].

France has also formalized agreements and signed the first contracts with Alstom [192]. In 2021, the train underwent its first tests at the Railway Test Center in Valenciennes, and a test of the Coradia iLint on the French rail network was planned for 2022 on the Tours-Loches line in the Centre-Val de Loire region [192].

In the Netherlands in 2020, a pilot project agreement was signed with Alstom to test the Coradia iLint for 10 days on the 65 km line between Groningen and Leeuwarden, with tests carried out at 140 km/h without passengers [176,196]. The tests focused on actual driving, fuel consumption, and refuelling. The trial showed that hydrogen trains can run efficiently with a constant hydrogen consumption of 0.20-0.21 kg of H_2 per km and successful refuelling provided by ENGIE [176,197].

In Japan, East Japan Railway unveiled a hydrogen train called the Hydrogen-Hybrid Advanced Rail Vehicle for Innovation (HYBARI). Testing began in 2022, with service scheduled to begin in 2030. Tests will be conducted on the Nanbu Line and other lines connecting Tachikawa to Kawasaki. The train uses hybrid systems powered by hydrogen fuel cells and storage batteries. With an estimated investment of $34.7 million, the train will have a range of 140 km [198].

In 2021, in China, a hydrogen train project was launched jointly by several companies and began testing on a 627 km line. Designed for various tasks without modification of the existing railway line, the locomotive can produce 700 kW of continuous power for 24.5 hours and reach a speed of 80 km/h. The next goal is to develop a 2000 kW hydrogen fuel cell hybrid locomotive suitable for wider applications in the railway industry [199].

In addition, other companies such as Siemens Mobility and Stadler have also developed hydrogen trains for future testing and commissioning. Siemens Mobility has developed a hydrogen train that will be tested in 2023 [200] and Stadler has unveiled a hydrogen train that is expected to enter service in California in 2024 [22].

The Coradia iLint is a breakthrough in green rail transport that represents a significant step forward in reducing the industry's carbon emissions. The tests conducted prove that hydrogen can be a solution for the sector, even if there are still challenges and obstacles to overcome, such as the lack of infrastructure (production, refuelling, storage, transport, maintenance, and safety), limited production of low-carbon hydrogen, and competition for this fuel versus other industrial sectors.

This is why, in 2022, Alstom and ENGIE signed a partnership agreement whereby the former will supply hydrogen trains and the latter will supply renewable hydrogen via an innovative and green supply chain. The long-term strategic plan is to develop 4 GW of renewable hydrogen production capacity by 2030. Alstom continues to invest in the hydrogen ecosystem, notably through the acquisition of fuel cell manufacturer Helion Hydrogen Power in 2021 and a €6 million investment in the new fuel cell manufacturing platform at the Alstom Hydrogen plant in Aix-en-Provence [193].

A3: Required hydrogen purity

Depending on the process used, varying amounts of contaminants may be formed during hydrogen production [201]. Water electrolysis can be used to produce high-purity hydrogen, greater than 99.8%. However, hydrogen produced by thermochemical processes (gasification, reforming) is the most contaminated, with contaminant levels that can represent up to 75% of the hydrogen-containing gas (see Table 19).

This contaminant load requires a purification step to completely or partially remove the contaminants, leaving only hydrogen. The purification methods commonly used are physicochemical, using adsorption, cryogenic separation, or membrane processes. The most widely used commercial process is PSA (pressure swing adsorption) and its variations. This type of process allows hydrogen with a purity of between 96 and 99.999% to be obtained, with recovery rates of between 71 and 86% [205]. There are also other hydrogen purification technologies, such as palladium alloy metal membranes and dense metal membranes.

Depending on the intended application for hydrogen use, there are purity standards. In the field of fuel cells, the purity of the gas to be used will vary depending on the type chosen. There are various fuel cell technologies, the main ones being: (i) proton exchange membrane fuel cells (PEMFC), (ii) phosphoric acid fuel cells (PAFC), (iii) solid oxide fuel cells (SOFC), and (iv) molten carbonate fuel cells (MCFC) [206]. Depending on the type of cell used, the tolerance for contaminants will vary.

Table 19 : Composition of the gas mixture produced according to the process used to manufacture hydrogen (example: gas produced by coal gasification will be composed of 25 to 35% H_2 , 35 to 45% CO, etc.), adapted from [201].

Compound (%)	H_2	CO	CO_2	CH_4	N_2	Total sulfur	H_2O	O_2	Ref.
Natural gas steam reforming	70-75	10-15	10-15	1-3	0.1-0.5	-	-	-	[202]
Coal gasification	25-35	35-45	15-25	0.1-0.3	0.5-1	0.2-1	15-20	-	[203]
Biomass gasification	25-35	30-40	10-15	10-20	1	0.2–1	-	0.3-1	[204]

The most widely used fuel cells are PEMFCs, which are used in Alstom's hydrogen train, among other applications [207,208]. These fuel cells require very high hydrogen purity to maintain performance and service life, to prevent cathode poisoning [209] and to avoid damaging the membrane [210]. To guarantee a high-quality supply for the operation of PEMFC fuel cells, specific hydrogen purity standards have been published for use in rolling stock and stationary equipment.

Three standards have been identified for these uses, which are becoming increasingly harmonized: the international ISO standard ([211]), the American CGA standard ([212]), and the SAE standard ([201]). The quality of hydrogen gas required for use with PEMFCs is presented in the Table 20.

Table 20 : H_2 specifications for transportation applications (adapted from [201] and [213]).

Compound	ISO 14687:2019	CGA G 5.3	SAE J2719-202003
H_2 (molar fraction)	99.970	99.999	99.970
Total gases excluding hydrogen	-	-	300 ppm
H_2O	5	3.5 ppm	5 ppm
Total hydrocarbons (expressed as methane units)	2 ppm	1 ppm	-
Non-methane hydrocarbons (expressed as C1)	-	-	2 ppm
Methane	-	-	100 ppm
O_2	5 ppm	1 ppm	5 ppm
He	300 ppm	-	300 ppm
N_2	100 ppm	2 ppm	100 ppm
Ar	100 ppm	-	300 ppm
CO_2	2 ppm	2 ppm	2 ppm
CO	0.2 ppm	2 ppm	0.2 ppm
Total sulfur (expressed as H_2S)	0.004 ppm	0.004 ppm	0.004 ppm
HCHO	-	-	0.2 ppm
HCOOH	-	-	0.2 ppm
NH_3	-	-	0.1 ppm
Total halides (expressed as halide ions)	-	1 ppm	0.05 ppm

A4: Track diagram

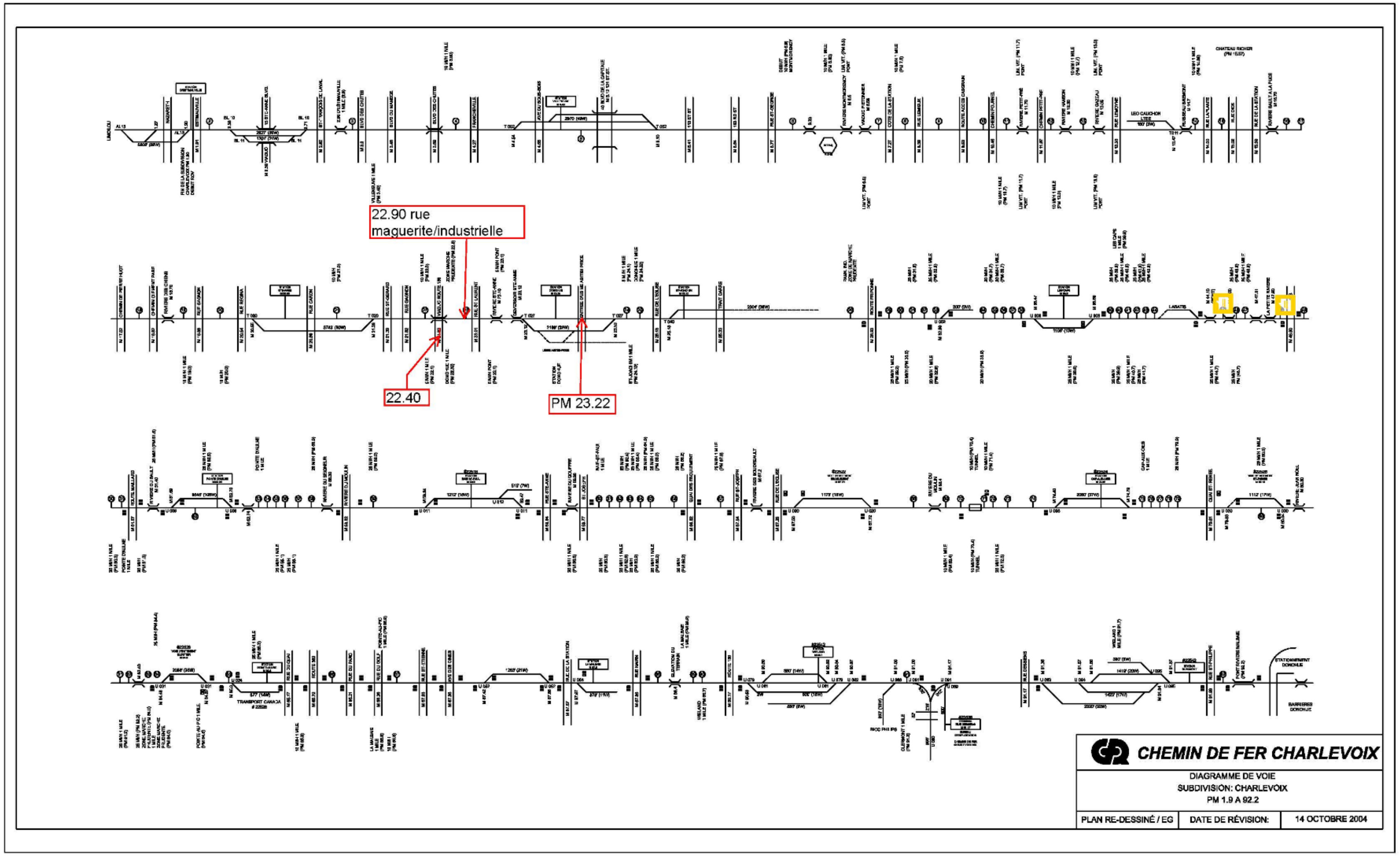


Figure 44 : Track diagram of the Charlevoix Railway.

A5: Functional diagram of the Coradia iLint fuel cell

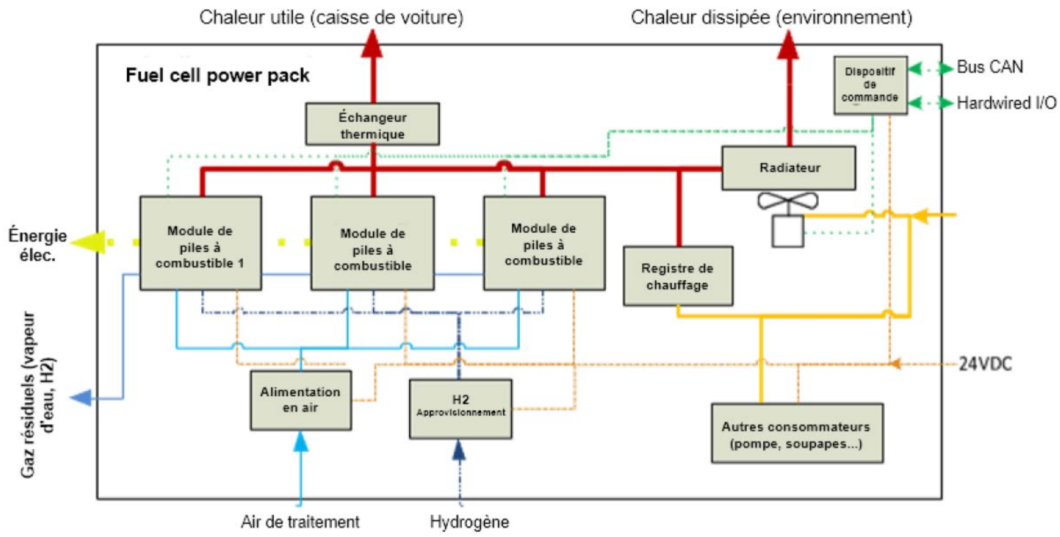


Figure 45 : Functional structure of fuel cell equipment.

A6: GHG measurements and air pollution emissions from a train

Trains are one of the most environmentally friendly modes of motorized transport for goods and people. However, certain environmental problems remain. Exhaust emissions from diesel engines are considered the main source of pollution, particularly nitrogen oxides, particulate matter, and greenhouse gases. Other sources of pollution include particulate matter from the contact between brakes and wheels and the rails, as well as soil resuspension, depending on train weight, driving conditions, and weather conditions. The wear and tear on train components has a definite cost for companies and causes pollution that affects ecosystems and human health [214,215].

PM10, which refers to particles with an aerodynamic diameter of less than 10 µm, is a reliable indicator of the health effects caused by fine particles in ambient air. Many countries have set limit values for PM10, but in densely populated areas these values are often exceeded, causing public concern. Traffic is one of the most discussed sources of fine metal particles [216]. The majority of metals released into the environment come from friction with iron particles, with only a small proportion being dissolved in water. Hydrocarbon emissions can be diffuse or point sources, with wooden sleepers being the main source, followed by lubricants from switches and wheel axles.

In addition to identifying potential emission sources, there is a growing need for information on possible marker substances, concentration ranges, and their fate in the environment. Heavy metals such as Fe, Mn, Cr, Ni, V, As, Mn, Ni, Sn, and Ti emitted by abrasion are mainly trapped in the soil and cannot be degraded by microorganisms. The mobility of heavy metals in the soil is influenced by various properties of the materials and the soil. Weaker bound particles can dissolve in soil water and penetrate into plants or groundwater through deeper soil layers. Due to their persistence and bioaccumulation properties, heavy metals can accumulate from soil and water into the food chain, posing a potential hazard to humans and the environment.

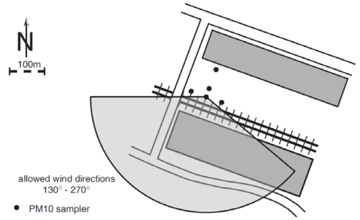
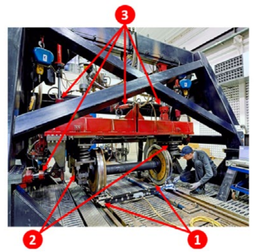
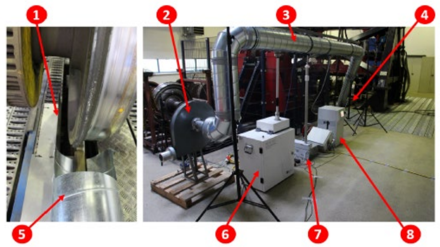
Emissions are influenced by the spatial and temporal characteristics of exposure. This information is useful to regulatory authorities for protecting soil and water, as well as to railway companies for determining their level of protection [214].

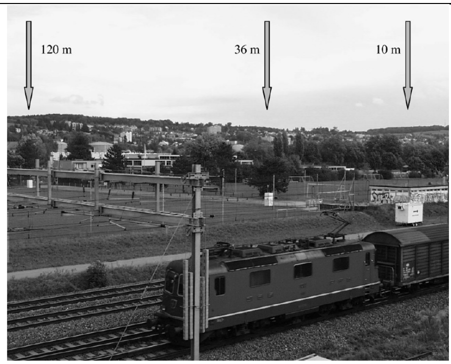
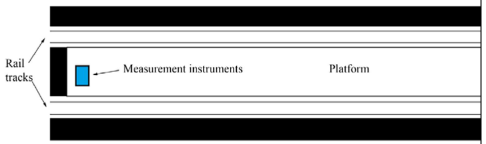
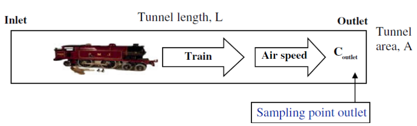
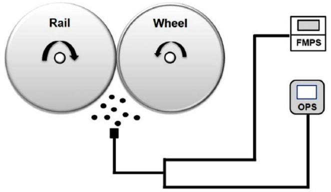
To measure train wear particles, it is necessary to assess particle concentration and air flow. There are different methodologies for measuring particle emissions. The double-disc test bench is a tool used to study the wear behavior of wheel-rail contact and how it relates to train speed. The study considers the impact of rolling and sliding on wear behavior in the laboratory. The results show that an increase in train speed has a significant effect on the rate of wear and particle generation [214]. By comparing the results obtained in wet and dry conditions, it was observed that there was a significant reduction in particle number concentration in wet conditions. In addition, differences in size distribution were also observed. While the maximum concentration of fine particles was observed in dry conditions, ultrafine particles were found to be dominant in wet conditions [217].

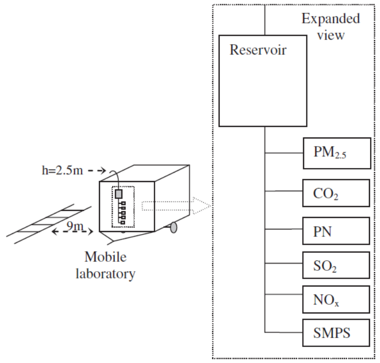
Tunnels are commonly used for road traffic to estimate airflow because they provide a natural volume and cross-section [216]. Tunnels have established themselves as a reliable method for conducting research in various fields. Their reliability makes them an attractive choice for a range of applications [216,218]. Tunnels have been used to measure particle emissions, but they have certain limitations. The main limitation of tunnel measurements is that they only provide information on the emission factor for a specific location, taking into account curvature, weather conditions, and the road, as well as a specific driving pattern, which includes speed and acceleration/deceleration. To supplement these measurements, on-board measurements were taken. These measurements provide information on how particulate emissions vary along a line and how they are affected by driving characteristics [215]. In addition, some rail companies do not have suitable tunnels for measurements due to the unique characteristics of their routes, while tunnels are readily available for other rail companies.

Fruhwirt et al. used a wheel-rail test bench equipped with a light scattering module to determine particle distribution [219]. Their study provided valuable insights into the measurement of particle distribution. The use of advanced equipment such as this can greatly improve our understanding of rail systems and their associated particle emissions [219]. Previous studies have used a variety of methods, presented in Table 21

Table 21 : Different methods for measuring particle emissions from trains (adapted from the references indicated).

Test method	Location	Country / Year	Set up	Equipment	Analyzer	Test duration	Ref.
Detailed analysis of individual particles	On site	Switzerland / 2006	 	Nucleopore filters (0.4 mm pore diameter)	Computer-controlled scanning electron microscopy (CCSEM), environmental scanning electron microscope (ESEM, FEI XL 30 FEG), X-ray spectrometer (EDX, EDAX) attached to the microscope,	1 month	[220]
Wheel-rail test bench	Lab.	Austria / 2023	 Parameter: Wheel diameter — Quantity: 400 – 1,250 mm; Rail profile / slope — 60 E2 / max. 1:40; Axle load — max. 340 kN; Shear force — max. 30 kN; Train speed — max. 300 km/h; Curve radius — min. 300 m  Left - sample inlet, right – sample system (1 – baffle plates, 2 - radial fan, 3 - horizontal air duct, 4 - sample inlet, 5 - sample duct, 6 - PartisolPlus 2025i, 7 - EDM180, 8 - EEPS).	Wheel-rail test bench from DB Systemtechnik GmbH	EDM180 particle analyzer supplied by GRIMM Aerosol Technik, light scattering technology for particle counting, PartisolPlus 2025i sequential air sampler supplied by ThermoFisher Scientific Inc.	Not mentioned	[219]

Not mentioned	On site	Switzerland / 2007		Quartz fiber filters (Schleicher & Schuell QF20, diameter 15 cm)	Scale, wavelength dispersive X-ray (WD-XRF),	14 months	[221]
Principal component analysis (PCA)	On site	Sweden / 2013		Appropriate tunnel	TSI Fast Mobility Particle Sizer Spectrometer (FMPS Model 3091), Electrical Low Pressure Impactor (ELPI+™), scanning electron microscopy (SEM) and energy dispersive spectrometer (EDs)	2 days	[218]
Tunnel measurement	On site	Sweden / 2010		Suitable tunnel	Diode lasers/photo detectors, Portable Aerosol Spectrometer Grimm, Model 1.108	Not mentioned	[216]
Double disc device	Lab	South Korea / 2018		Double disc device	Fast Mobility Particle Size Analyzer (FMPS, TSI 3091, USA), Optical Particle Size Analyzer (OPS, TSI 3330, USA)	Not mentioned	[222]
Onboard measurements	On site	Sweden / 2010		Special equipment: proximity brake, Grimm isokinetic probe	Optical instrument, GPS, plasma mass spectrometry (ICP-MS)	6 weeks	[215]

Mass concentrations measured hourly	On site	Switzerland / 2007		Rotary drum impactor (RDI)	Synchrotron radiation X-ray fluorescence spectrometry (SR-XRF), gravimetry, and wavelength dispersive X-ray fluorescence (WD-XRF)	47 days	[223]
Remote measurement	On site	Australia / 2013		Mobile laboratory	SMPS (TSI 3934) for particle size distribution measurements, condensation particle counter (TSI 3022 CPC), NOx analyzer (Ecotech ML9841A), aerosol photometer (TSI DustTrak) equipped with a PM2.5 impactor and CO_2 sensors (Sable Instruments) and an SO_2 analyzer (Ecotech 9850).	7 days	[224]

A7: Analysis of greenhouse gas emissions

A study of well-to-wheel emissions is being conducted by Zainab Almheiri of McGill University, under the supervision of Professor Sarah Jordaan[38].

A comparative well-to-wheel analysis of hydrogen fuel cell vs. diesel multiple unit trains in Quebec

By

Zainab Almheiri, PhD

A report completed for a Mitacs internship with Alstom

Results of this report will be considered in an academic article supervised by Professor Sarah Jordaan

McGill University, Montreal,

Quebec, Canada

June 2024

[38] Dr. Sarah Jordaan, Associate Professor of Civil Engineering at McGill University, participated in the review of a report including a well-to-wheel analysis prepared by Dr. Zainab Obaid Almheiri as an intern at Alstom. In addition to this review, Dr. Jordaan produced an evaluation report. The report produced by Dr. Almheiri as an intern at Alstom and the evaluation report produced by Dr. Jordaan will be available upon request.

INTRODUCTION

Hydrogen and fuel cell technologies have the potential to play a significant role in reducing energy-related greenhouse gas (GHG) emissions; however, such environmental benefits can only be achieved if hydrogen is produced with low climate impact [1],[2]. These technologies are rapidly emerging as promising alternatives to traditional fossil fuels due to their significant potential in transitioning towards a low-carbon energy system by providing clean and efficient energy for various applications such as grid storage, passenger vehicles, and heavy transport.

The main objective of this study is to quantify the GHG and air pollutant emissions of different train technologies, specifically comparing proton exchange membrane fuel cells (PEMFC) and diesel multiple unit (DMU) passenger trains. The objective of this study is achieved by conducting a comparative analysis to quantify the well-to-wheel (WTW) environmental footprint of these passenger train technologies. The model boundary includes life stages such as fuel extraction, fuel production, transportation, and train operation.

While this study focuses on a WTW approach rather than conducting a complete LCA, it utilizes LCA methods as a guide. The study has yet to undergo the external review required to be ISO 14040 [3] compliant for public comparative assertions (i.e., "an environmental claim regarding the superiority or equivalence of one product versus a competing product which performs the same function"). There are numerous methodological limitations that we identify and must be addressed for alignment with LCA methods. In addition, life cycle impact assessment must be completed for a study meant for comparative assertions made to the public. In this study, impact assessment was completed for global warming potential but not for the other criteria air pollutants in the inventory analysis.

Multiple scenarios for the hydrogen train were considered to explore sustainable solutions to reduce GHG emissions from fuel transportation via diesel trucks. The study also depicts the compensation scenario considered by Alstom for the hydrogen train, where GHG emissions from the diesel trucks have been compensated, thus assumed to be zero. This compensation can be achieved by using zero-emission transport systems for fuel transportation and producing green hydrogen. Alternatively, green hydrogen can be produced at the fueling station. Nonetheless, GHG emissions from the diesel truck are also quantified.

Additionally, the data collection stage is the essence of any life cycle assessment (LCA) based method, and the data quality contributes significantly to the robustness of the results. The data in this study has been collected from various sources, mainly from experts in the field, referred to as primary sources throughout the analysis. Furthermore, data has also been collected from secondary sources such as Ecoinvent [4] (an LCA database), reports, government databases and scientific literature, as explained in the following section.

The remainder of this report is organized as follows. The first section summarizes the methodology employed for the WTW analysis and data collection, including the study goal and scope, and model system boundary. The next section presents the results obtained from the WTW analysis. Following that, the significant findings of the study and the conclusions are presented in the subsequent section.

METHODOLOGY AND DATA COLLECTION

STUDY GOAL AND SCOPE. The main goal of this study is to evaluate GHG emissions and criteria air pollutants from train technologies, including those utilizing PEMFC and diesel propulsion, for passenger trains. The analysis was conducted for Alstom and authored by Almheiri (et al.), is intended for the development of a full life cycle assessment that will be published in a peer reviewed article. As such the notable gap between results presented here and a more complete LCA must be communicated with any public assertions made from the results of this preliminary work.

The goal is achieved by applying a comprehensive WTW method to both trains to evaluate the environmental footprint of hydrogen and diesel fuels throughout the WTW portion of their life cycle, from feedstock extraction for fuel production to their use in trains. In other words, the fuel cycle analysis includes feedstock extraction, fuel production, transportation, and utilization in the train. The fuel cycle supply chain aims to assess GHG emissions (GHGs in carbon dioxide equivalent [CO_2-eq]: carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]) and criteria air pollutants such as nitrogen oxides [NOx] and particulate matters [$PM_{2.5}$, and PM_{10}], referred to as PM in this study.

FUNCTIONAL UNIT. The functional unit for this study is a passenger-km travelled (PKM) accounting for the number of passengers that the hydrogen and diesel trains can accommodate. Although this paper focuses on the results in terms of PKM, the model results can be easily adjusted to represent results based on other units, such as per kilometre, by multiplying per PKM values with the number of passengers per train.

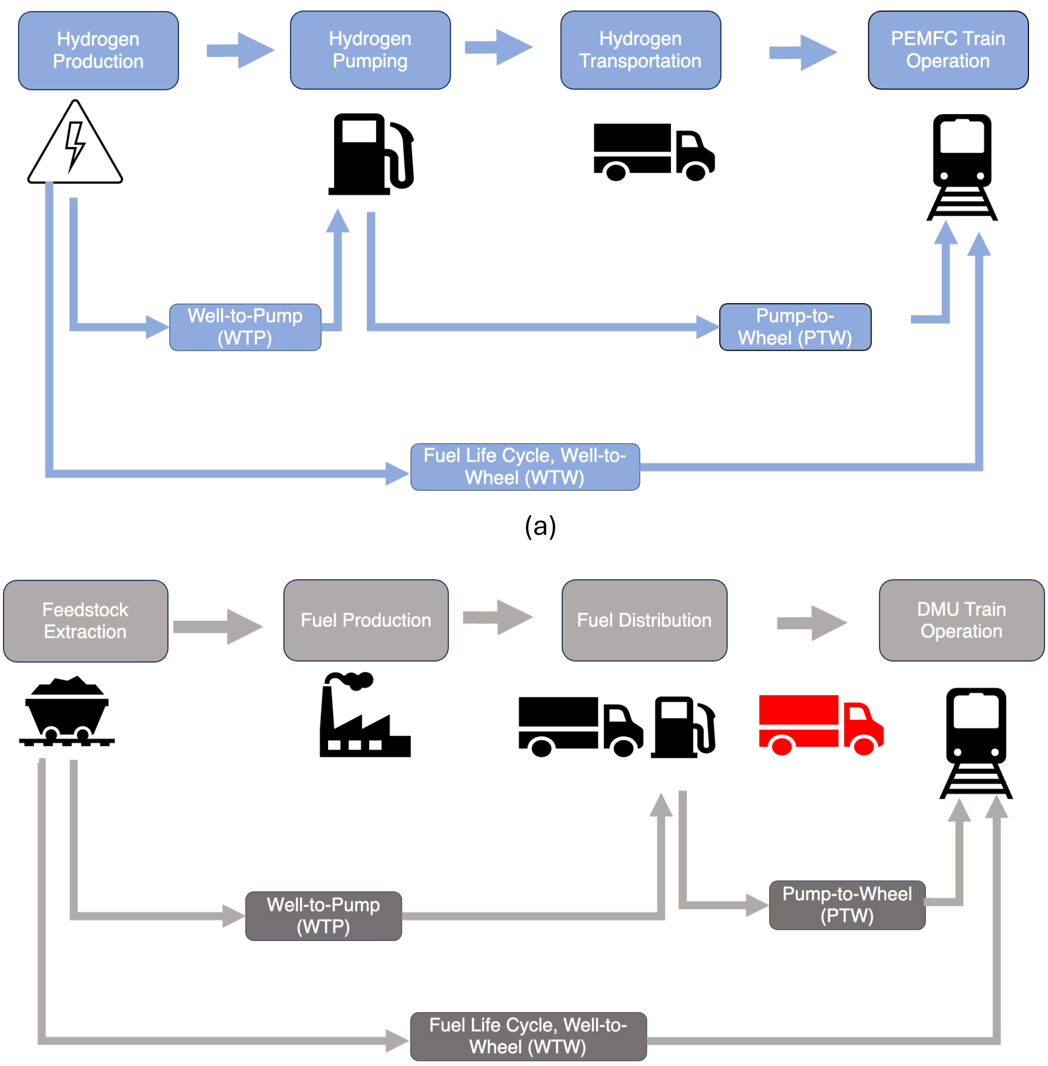
MODEL SYSTEM BOUNDARY.The study identifies two main boundaries for the PEMFC and DMU trains, as illustrated in Figures 1 (a) and (b), respectively. For the PEMFC technology, the system boundary starts with fuel production and ends with the use of hydrogen fuel for the passenger train. The system includes hydrogen production via hydropower, hydrogen pumping, fuel transportation, and train operation. It should be emphasized that the produced gaseous hydrogen in our system is being transported via a diesel truck from the hydrogen production facility to the fueling station. However, a sensitivity analysis of different transportation modes for hydrogen fuel is also investigated in this study. In addition, it should be noted that hydrogen (H2) leakage, specifically when H_2 is released into the atmosphere, has been observed to have secondary impacts on global warming [5]. These impacts can influence the results of LCA, necessitating appropriate measurement when operationalizing the hydrogen train.

Hydrogen has been reported to have a Global Warming Potential (GWP100) of 11.6 ± 2.8 [6]. To ensure a comprehensive analysis, it is essential to examine hydrogen leaks, as research indicates that they can reduce the climate benefits of green hydrogen by up to 25% [5]. By incorporating these findings, we can estimate the amount of hydrogen leakage that would offset the climate advantages, thereby enhancing the robustness of the results.
Future work will include a detailed assessment of hydrogen leaks to refine our analysis further. Additionally, the embodied emissions from train manufacturing will be included in the next steps of this research.

In our analysis of the diesel train, the system boundary encompasses the extraction and transport of crude oil, diesel production, and transportation from the pumping station to the train facility. These steps are included within the well-to-pump (WTP) system boundary of the diesel supply chain, as depicted in Figures 1(a) and

1(b). Similar to the analysis of the hydrogen train, the train operation is included in the pump-to-wheel (PTW) phase of the diesel fuel cycle. Additionally, the diesel trucks used for fuel transportation to operate the DMU train, highlighted in red in Figure 1(b), generate additional emissions beyond those accounted for in the diesel GHG balance reported by the Ministère de l'Environnement du Québec [7]. Specifically, in our current application, the red diesel truck operates twice weekly to transport diesel for the DMU. These supplementary emissions from the red diesel truck are detailed in the Results and Discussion section.

The energy stored in the fuel cell stack is the primary energy source for the hydrogen train and batteries serve as an auxiliary to provide the necessary power to the traction motors in the hydrogen train. The embodied emissions of the fuel cell stack and batteries will be considered in future work. The comparative analysis in this paper will reveal the potential use of hydrogen as an alternative fuel for a passenger train within the specific system boundary outlined in this study.



(a)

(b)

Figure 1. System boundary for the fuel life cycle for the PEMFC (a) and DMU (b) trains. The red diesel truck in Figure 1(b) generates additional emissions beyond those in the diesel GHG balance reported by the Ministère de l'Environnement du Québec.

DATA COLLECTION. Life cycle inventory (LCI) analysis involves the collection of data from primary and secondary sources. The data are compiled into a detailed inventory of input and outputs for various unit processes across life cycle stages. The inputs and outputs include energy balances for all unit processes and activities within the modelling system boundary. The WTW analysis is then implemented to evaluate the potential environmental footprint associated with the inventory data and analyze the global warming potential of the hydrogen and diesel passenger trains.

The primary data related to hydrogen production were collected from Harnois Énergies. The data consist of energy intensity for the hydrogen production (kWh/kg H_2), hydrogen consumption per trip (kg H_2/trip), the distance of hydrogen transportation via a diesel truck (km), and diesel consumption in liter (L) for transporting hydrogen. Nonetheless, data related to PEMFC and DMU trains, such as distance travelled, number of passengers that both trains can accommodate, and fuel consumption (kg/km), were collected from the Alstom train manufacturing company. In addition, secondary data were collected from Ecoinvent LCA database [4] and the Ministère de l'Environnement du Québec [7] which are mainly related to the diesel fuel cycle. These processes include fuel production and transportation.

Furthermore, the electricity generated in Quebec is mainly supplied by renewable energy sources known as hydropower. Emissions related to hydropower are indirect and can result from the flooding of lands and the construction of the dam, which both lead to an increase in biogenic GHG emissions due to biomass degradation. The carbon footprint of electricity distributed, equal to 34.5 gCO_2-eq/kWh, has been comprehensively quantified considering the net biogenic GHG emissions of all hydropower reservoirs in the province of Quebec [8]. Therefore, the authors include this value in the model to quantify emissions related to electricity generation at the upstream level of the hydrogen train. In addition, emission factors for criteria air pollutants emitted by the diesel truck used for fuel transportation in the DMU and PEMFC are reported in [9].

The emission profiles of criteria air pollutants for the DMU train were estimated using fleet emissions data from Germany in 1994 [10]. The DMU train in this study, built in Germany in the 1980s, lacks certification for its specific engine, making it challenging to acquire accurate emissions data. Therefore, emissions estimations were based on a 1994 study of the German Railways [10]. Finally, data necessary for completing the WTW analysis for hydrogen and diesel were collected from previous studies. This includes data on criteria air pollutants from diesel production and hydrogen transportation via fuel cell trucks and pipelines, referenced in studies [4], [11], and [12], respectively.

RESULTS AND DISCUSSION

In this study, the results quantify carbon dioxide equivalent (CO_2-eq) emissions—including CO_2, CH_4, and N_2O—and criteria air pollutants (NOx and PM) for a WTW analysis of the PEMFC and DMU trains. In Figure 2, the results indicate a significant decrease in GHG emissions for the PEMFC train, showing approximately a 33% reduction in CO_2-eq per PKM compared to the DMU train. Moreover, substituting diesel trucks with fuel cell trucks and using pipelines for fuel transportation results in significant reductions in greenhouse gas emissions, achieving 79% and 83% decreases, respectively. Another potential strategy to consider is the onsite production of green hydrogen at the consumption facility, which has the potential to achieve an 84% reduction in GHG emissions.

The PEMFC train produces zero GHG emissions during operation when excluding hydrogen leaks. In contrast, the DMU train significantly contributes to GHG emissions. It is important to note that hydrogen transportation accounts for approximately 76% of the WTW GHG emissions for the PEMFC train, with the remaining 24% arising from fuel production.

To address this, the study proposes potential solutions for eliminating GHG emissions through the use of FC trucks and pipelines for hydrogen transportation. In addition, producing green hydrogen directly at the consumption facility could reduce GHG emissions by 84%, as illustrated in Figure 2.

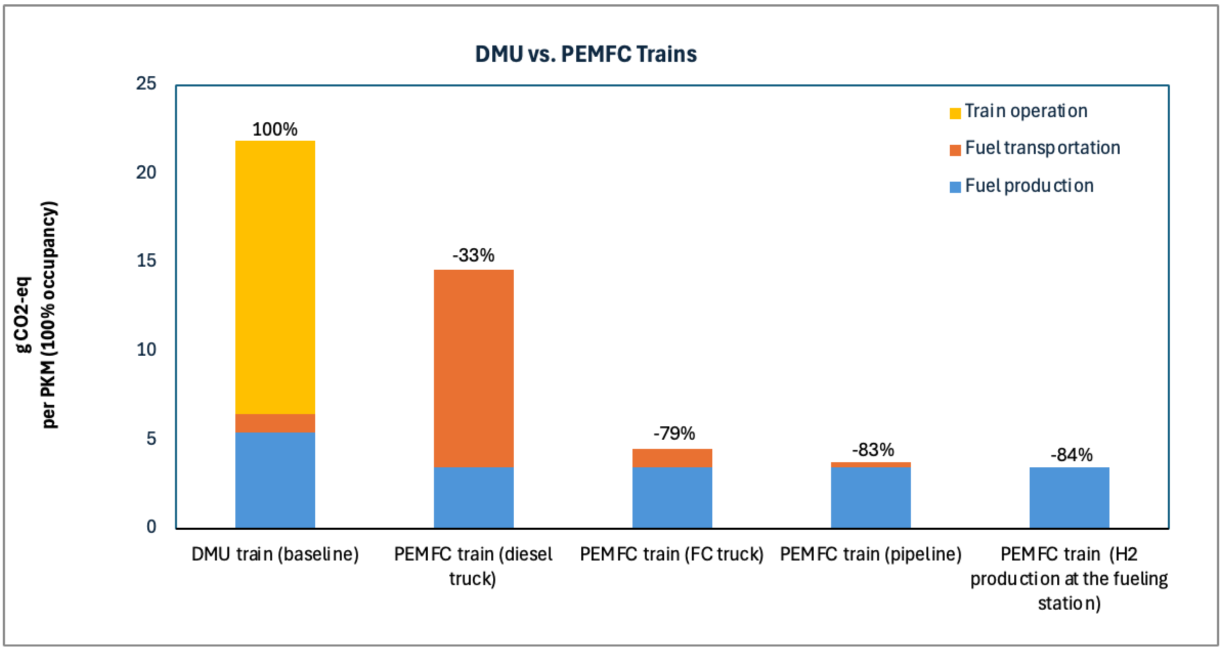
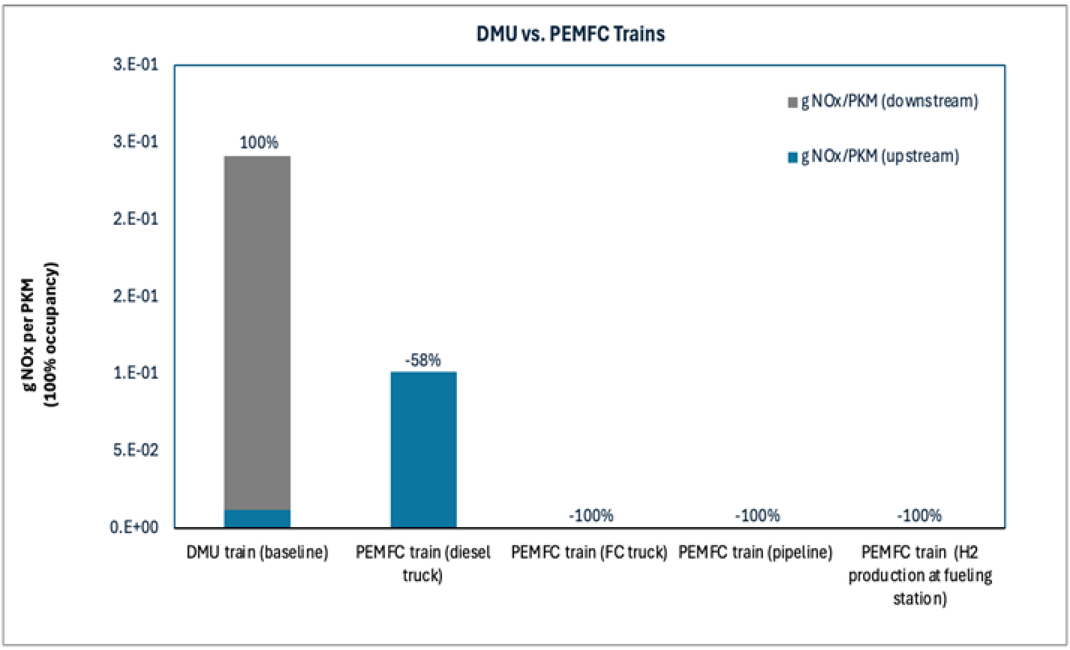
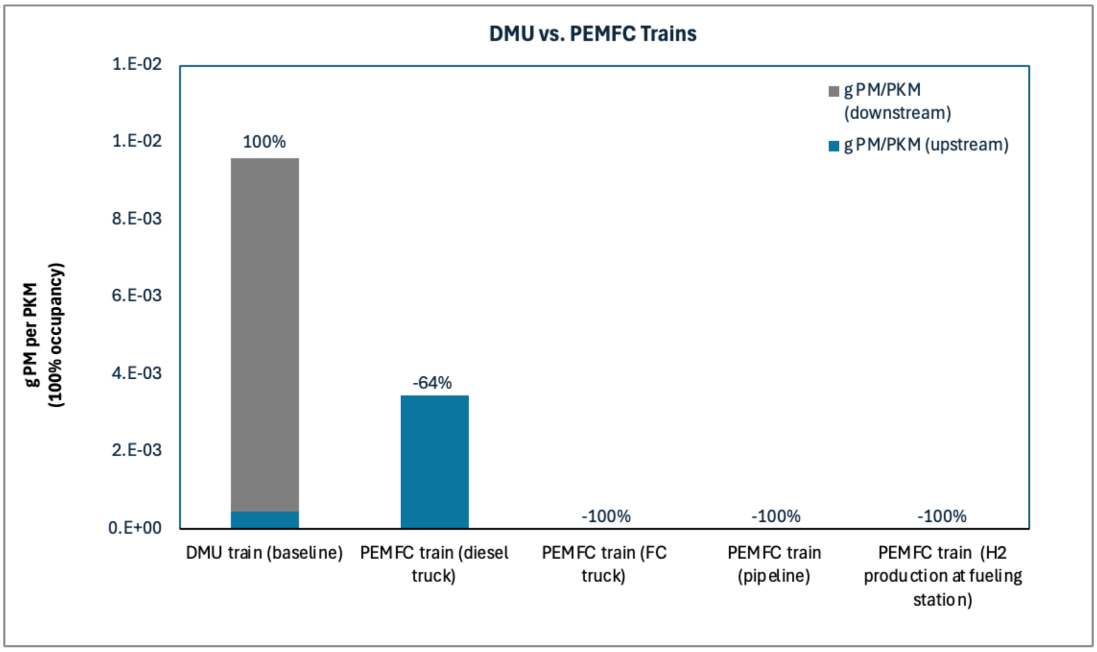


Figure 2. GHG emissions (CO_2-eq /PKM) comparison of PEMFC and DMU passenger trains in Quebec and different hydrogen fuel transportation systems.

Furthermore, the results show that the level of air pollutants, including NOx, and PM in g per PKM, is higher for the diesel train than for the hydrogen train, as can be seen in Figures 3 (a), and 3(b), respectively. Air pollutants throughout the diesel fuel cycle mainly result from diesel production, transportation and train operation. On the other hand, the system boundary of WTW analysis for the hydrogen train considers electricity generation from hydropower, and these air pollutants are the result of hydrogen transportation via a diesel truck from the hydrogen production facility to the fueling pump station. It is noteworthy that transporting hydrogen in the context of fuel cell trucks and pipelines can effectively mitigate criteria air pollutants. Furthermore, the production of green hydrogen at fueling facilities results in zero emissions of NOx and PM, as depicted in Figures 3(a) and 3(b).



(a)



(b)

Figure 3. Criteria air pollutants in g substance per km for PEMFC and DMU for train passengers: (a) NO_x; and (b) PM.

CONCLUSION

This report discovered that:

- Transporting hydrogen via diesel trucks for the PEMFC train operations contributes 76% of the total GHG emissions.
- The PEMFC train can achieve a substantial reduction in GHG (CO_2, CH_4, and N_2O) emissions compared to the DMU train when transporting hydrogen via fuel cell trucks and pipelines, approximately 79% and 83%, respectively.
- The PEMFC train can reach an optimistic reduction in GHG (CO_2, CH_4, and N_2O) emissions as producing green hydrogen at the consumption facility, achieving nearly an 84% reduction.
- The fuel cycle of PEMFC train emits zero-criteria air pollutants (NOx, and PM) when fuel is transported via FC trucks and pipelines. Notably, producing green hydrogen at the fueling station also emits zero-criteria air pollutants.
- The calculations and equations used for estimating the GHG emissions and criteria air pollutants will be included in the appendix in a future version of this report.

This study identified the following limitations:

- The interpretation stage of the present analysis can be further enhanced by including appropriate sensitivity analyses and completeness checks. Section 4.5 of ISO 14044 [13] recommends that the interpretation phase of an LCA should consist of an evaluation that considers completeness, sensitivity, and consistency checks. Specifically, ISO 14044 [13] emphasizes that the interpretation should assess the significant inputs, outputs, and methodological choices to understand the uncertainty of the results. Additionally, section 4.4.4.2 outlines the importance of sensitivity analysis as a procedure to determine how changes in data affect the results of the Life Cycle Impact Assessment.
- To ensure our report meets ISO 14044 [13] requirements for comparative assertions made to the public, comprehensive efforts should be placed on addressing identified gaps. Specifically:
    - Section 4.4.5 emphasizes the importance of including detailed sensitivity analyses to enhance the robustness of our results.
    - Additionally, section 5.1.1 highlights the necessity of complete and unbiased reporting of LCA results, with transparent documentation of methods, assumptions, and limitations.
    - Section 5.3 provides further guidance on ensuring transparency in comparative assertions, including justifications for data inclusion, rigorous sensitivity and uncertainty analyses, and thorough data quality evaluation.
    - Moreover, section 6 underscores the value of a critical review process to maintain consistency, scientific validity, and transparency in our methodologies.

References (McGill)

[1]O. Siddiqui and I. Dincer, "A well to pump life cycle environmental impact assessment of some hydrogen production routes," International journal of hydrogen energy, vol. 44, no. 12, pp. 5773–5786, 2019.

[2]E. Cetinkaya, I. Dincer, and G. F. Naterer, "Life cycle assessment of various hydrogen production methods," International journal of hydrogen energy, vol. 37, no. 3, pp. 2071–2080, 2012.

[3]M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Life cycle assessment, vol. 2018. Springer, 2018.

[4]G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," The International Journal of Life Cycle Assessment, vol. 21, pp. 1218–1230, 2016.

[5]T. Sun, E. Shrestha, S. P. Hamburg, R. Kupers, and I. B. Ocko, "Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales," Environmental Science & Technology, 2024.

[6]M. Sand et al., "A multi-model assessment of the Global Warming Potential of hydrogen," Communications Earth & Environment, vol. 4, no. 1, p. 203, 2023.

[7]"Greenhouse Gas Emissions Quantification Guide".

[8]A. Levasseur, S. Mercier-Blais, Y. Prairie, A. Tremblay, and C. Turpin, "Improving the accuracy of electricity carbon footprint: Estimation of hydroelectric reservoir greenhouse gas emissions," Renewable and Sustainable Energy Reviews, vol. 136, p. 110433, 2021.

[9]X. Zhang, Z. Lin, H. Hao, X. Hao, Z. Wang, and S. Li, "Environment-economic comparison of potential alternative fuel heavy-duty trucks in China," Transportation Research Part D: Transport and Environment, vol. 131, p. 104206, 2024.

[10]W. Knörr and J. Borken, "Erarbeitung von Basisemissionsdaten des dieselbetriebenen Schienenverkehrs unter Einbeziehung möglicher Schadstoffminderungs- technologien," 2003.

[11]D.-Y. Lee, A. Elgowainy, A. Kotz, R. Vijayagopal, and J. Marcinkoski, "Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium-and heavy-duty trucks," Journal of Power Sources, vol. 393, pp. 217–229, 2018.

[12]M. Hermesmann, C. Tsiklios, and T. Müller, "The environmental impact of renewable hydrogen supply chains: Local vs. remote production and long-distance hydrogen transport," Applied Energy, vol. 351, p. 121920, 2023.

[13]I. Standard, "Environmental management-Life cycle assessment-Requirements and guidelines," 2006.

A8: Environmental costs and positive/negative externalities associated with the ecosystem

Mitigating the impact of human activities on the environment is one of the greatest challenges facing humanity today. Several global measures and policies have been implemented to address this challenge, such as the Kyoto Protocol, the Paris Agreement, and the Montreal Protocol. The goal is to reduce greenhouse gas (GHG) emissions in the transportation sector by 50% by 2050 [225]. Rail transportation has long been considered environmentally friendly due to its efficiency, speed, and high load capacity. In the following, several impacts related to rail transportation are analyzed.

Impact on the environment

Diesel locomotives emit various pollutants, including carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrogen oxides (NOx), nitrous oxide (N_2O), sulfur dioxide (SO_2), non-methane volatile organic compounds (NMVOCs), particulate matter (PM), and hydrocarbons (HC) [226,227]. Railway technology has undergone significant changes since its inception, mainly driven by the objectives of reducing costs and improving safety. These changes have been characterized by improved energy efficiency, increased train speeds, and larger train sizes. According to the International Energy Agency and the International Union of Railways, between 1975 and 2012, energy consumption per passenger-kilometer and per ton-kilometer for freight transport fell by a remarkable 62% and 46%, respectively. This improvement in energy efficiency was accompanied by a substantial 60% decrease in CO_2 emissions for passenger transport and a 41% decrease for freight transport during the same period[39] [228].

Combined greenhouse gas (GHG) emissions from short-haul trains and freight in all rail operations in Canada amounted to 6,081 kilotons in 2021. During the same period, emissions of major air contaminants (MACs) from all rail activities decreased, with total nitrogen oxide (NOx) emissions from locomotives decreasing from 70.70 kilotons in 2020 to 66.50 kilotons in 2021—which includes major air contaminants [177].

Canadian railways made a significant investment of $2.3 billion in their Canadian networks in 2021. They also took steps to reduce their emissions, including investing in fleet renewal and modernization, fuel-saving technologies, operational efficiency, and the use of low-carbon fuels. In addition, the railways and their partners have made progress in their various partnerships and pilot projects involving alternative propulsion [177]. Although optimizing existing ecosystems contributes to reducing emissions, this remains limited due to the impact of diesel combustion. Therefore, in order to achieve the decarbonization targets for the rail sector, it is necessary to consider new technological solutions. Hydrogen trains, like battery-powered or catenary trains, offer promising prospects for addressing environmental concerns and justify increased investment in the coming years, in line with Canada's net-zero emissions policy.

Impact of noise and vibration

Noise pollution has many adverse effects on human and animal well-being. Transportation-related noise pollution is particularly bothersome in urban areas. The most common effects on humans are sleep

[39] Countries such as China, India, and Russia, which have extensive rail networks, are prime examples of these achievements. With 60% of the world's high-speed lines, China can boast the lowest energy consumption per passenger-km. India has the lowest CO_2 emissions per passenger-km and the lowest energy consumption per ton-km for freight transport. Russia has the lowest CO_2 emissions per ton-km for freight transport.

disturbances and stress, which can lead to cardiovascular and mental health problems. Sleep, which is sensitive to environmental factors, is often disrupted by ambient noise. Noise pollution is also linked to learning difficulties and reduced work performance, and poses greater problems for students and children, who are more sensitive to noise. In addition, it contributes to physical disorders such as heart disease, high blood pressure, and mental health problems, highlighting the wide range of adverse effects on human life [229,230].

Transportation systems, particularly road traffic, are a major source of noise pollution worldwide. Road traffic noise has a significant impact on the environment, with other modes of transportation such as air, sea, and rail also contributing to noise pollution.

In the European Union, railways are considered the second largest source of noise pollution after road traffic. Railway noise mainly results from the interaction between train wheels and rails, known as rolling noise. This noise varies according to categories such as straight-line rolling noise, extreme rolling noise due to discontinuities, and shrill noise in tight curves. In addition, urban railways contribute to noise pollution through various vehicles and equipment, causing nuisance to residents [229].

Another problem associated with railways is the vibrations emitted when trains are running, which can disturb nearby residents or interfere with sensitive equipment in buildings. Railway vibrations have adverse effects, causing tangible disturbances such as ground vibrations in buildings, shaking windows, and moving objects. Intense train vibrations can cause structural problems such as subsidence and cracking, which can lead to building collapse. In addition, as studies indicate, these vibrations have a negative impact on sleep, contributing to disturbances [229,231].

In 2002, the European Parliament and the Council of the European Union approved Directive 2002/49/EC, which focuses on the assessment and management of environmental noise. The main objectives are to establish a unified approach to preventing or minimizing the adverse effects of exposure to noise, including noise pollution, and to standardize methods for assessing noise-related risks. This directive specifically addresses environmental noise, which includes unwanted sounds from human activities, particularly transport-related noise and industrial noise. All EU Member States must produce strategic noise maps every five years for agglomerations with more than 100,000 inhabitants, including major roads with more than 3 million vehicles per year, major railways with more than 30,000 trains per year, and major airports. These criteria, set in 2011, represent a reduction from 6 million vehicles and 60,000 trains, reflecting an expansion of EU activities [230]. Using the rail noise data described in the directive, Wronty and Bohatkiewicz examined its impact and determined that the number of people affected by this negative factor is lower than that of traffic noise. The noise level depends on factors such as train speed, track type, and noise barriers.

The Federal Transit Authority of the US Department of Transportation has published a guide entitled "Transit Noise and Vibration Impact Assessment" (FTA-VA-90-1003-06, May 2006). This guide helps to predict and assess the effects of noise and vibration from public transport projects, particularly those involving railways. The guide includes three levels of analysis for understanding operational noise and vibration, and also covers construction noise assessment and presentation of results. It provides guidance on predicting noise levels for various rail activities. Keep in mind that using the guide involves equations and technical data, so technical knowledge is required [232].

The Canadian Transportation Agency, authorized by the Canada Transportation Act (CTA), handles disputes related to railway noise and vibration. In 2008, the Agency published guidelines describing the collaborative steps to be taken before investigating a complaint. These guidelines detail the factors taken into account for compliance by railways, such as facilitation and mediation related to noise, followed by the complaint procedure and the information required. The guidelines are available online at [233]. The method for measuring and reporting railway noise, which complements the guidelines, provides guidance to railway companies, citizens, and municipalities in the event of a noise dispute. It provides procedures for assessing noise levels from existing and planned railway facilities and assists the Agency in reviewing noise assessment applications for decision-making purposes at [234].

The noise emitted depends on both the network and the rolling stock. There are three types of noise, the significance of which varies with the speed of the train:

- Equipment noise: this comes from engines, fans, and air conditioning. It is mainly heard at low speeds and when the train is stationary.
- Rolling noise: this results from the contact between the wheels and the rail and from microscopic irregularities on their surfaces. It is most prevalent at normal travel speeds. It is the main source of noise.
- Aerodynamic noise: this is related to air penetration. It is perceived at speeds of 300 km/h and above, but never becomes the main source (this would be the case at speeds above 320 km/h).

To reduce rail noise, action must be taken on various fronts, such as rolling stock, infrastructure, tracks, and operations [235]. In the case of the Coradia iLint, the results of acoustic measurements (see Section 4) indicate a significant reduction in noise compared to a diesel engine, which may enable compliance with current regulations[40].

Soil pollution

The increase in human population and vehicles has made transportation a significant source of heavy metal, polycyclic aromatic hydrocarbon (PAH), and herbicide emissions into the soil. Emissions from fuel combustion, vehicles, road abrasion, and cargo spills release metal-containing particles that settle in the soil and can persist for years due to their low biodegradability [236].

Vehicle emissions, which are resistant to biological and chemical degradation, can impact plant growth and ecosystems. Plants and soil organisms are the main receptors of these pollutants. Ongoing research suggests that absorption by plants varies from species to species. Some have a high translocation capacity for metals such as lead and cadmium, but limited movement from the roots to the aerial tissues, while others show the opposite trend [236,237].

Water pollution

Railway infrastructure has an impact on aquatic ecosystems, particularly due to oil leaks from storage tanks. Levengood et al. [238] found high concentrations of polycyclic aromatic hydrocarbons (PAHs) and heavy metals in waterways crossed or bordered by railways, with PAH levels downstream exceeding concentrations

[40] Under section 95.1 of the Canada Transportation Act (CTA), railway noise and vibration must remain at reasonable levels.

upstream. Some sites had PAH concentrations that posed risks to aquatic life, while chromium (Cr) values remained below levels of concern.

Impact on biodiversity

During operation, railways can impact biodiversity by affecting the variety and number of species [237]. Various emissions such as air, soil, and water pollution, noise, and vibrations are all factors that affect biodiversity. However, railways take up less space than other forms of transport, with land use being a major factor contributing to biodiversity loss worldwide. This is not a minor detail; it is already a significant concern in densely populated areas, and it is becoming a global issue as the human population grows and puts increased pressure on land available for cultivation. Recently, the protection of habitats crossed by railways and their wildlife has become a crucial consideration when designing new railways or maintaining existing ones. This development is linked to increased awareness in society of the importance of biodiversity [239,240]. The impacts of railways on biodiversity can thus be classified into four main categories: mortality, barrier effects, species invasions, and environmental disturbances (including noise and chemical pollution).

A9: Questions related to training

Topic: icebreaker/opening

1. Can you describe your role to me?
2. How have operations been going so far?

Topic: Health and safety issues

3. Have you encountered any problems or emergencies?
    a. If so, how?
4. Have you adjusted/implemented any practices over the summer based on what you have learned in the field?
5. Have you observed or experienced other health and safety issues?
6. If you had to train someone to do your job, what recommendations would you give them?

Topic: Feedback on the training provided by the Hydrogen Research Institute

7. How has the training helped you in your daily work?
8. How did the training help you manage/prevent emergencies?
9. Had you already used other energy sources (diesel, battery, natural gas, etc.) in your work? What specific features are associated with the use of hydrogen?

Topic: improving training

10. Based on your experience over the last few months:
    a. For which situations were you well prepared?
    b. What is missing from the training?
    c. What have you learned in the field that would be relevant to include in future training courses?
    d. Are there any elements of the training that contradict your field experience? Any contradictions?
    e. Any other recommendations for future training courses?

A10: Questions from qualitative interviews with passengers during two trips

Theme: Motivation for taking the train

- Why are you taking the train today?
- How has your experience been so far?
- How did you decide to take this train?

Theme: Passenger experience

- Did you take the diesel train?
    a. If so, can you describe the differences from a passenger's perspective?
- Did you notice any salient or unique features of the hydrogen train?
    a. E.g., less noise, no diesel smell, color of the train and locomotive, etc.
- Did you experience any difficulties or issues with this train?
- Do you feel safe on this train? Do you feel sufficiently informed about this train?

Topic: Understanding hydrogen

- What do you know about hydrogen?
    a. Where did you get this information?
- Do you know how the hydrogen used to power this train is produced?
- How would you explain the impact of trains (and/or hydrogen in general) in the fight against climate change?
- What is your perspective on the energy transition?
- Has this train had an impact on your perception of hydrogen and/or the energy transition?
- Do you have any questions you would like answered?
    a. If no response, explore further:
        i. In terms of safety
        ii. Regarding CO_2
        iii. Regarding governance and the pilot project

A11: Questions from the quantitative survey with passengers during two trips

Theme: Demographics

- *Age
    a. 18-24
    b. 25-31
    c. 32-38
    d. 39-45
    e. 46-51
    f. 52-58
    g. 59-64
    h. 65-71
    i. 72-77
    j. 78
- *Do you identify as
    a. Male
    b. Female
    c. Non-binary
    d. Other
    e. Prefer not to answer
- *Reason for travel
    a. Vacation
    b. Business
    c. Testing the hydrogen train
    d. Other* Define

Topic: Motivation for taking the hydrogen train

- *How many times have you taken the hydrogen train?
    a. 1
    b. 2
    c. 3
    d. 4
    e. 5
    f. 6
    g. 7
- *Have you explicitly chosen hydrogen trains (now or in the past)?
    a. Yes/No
- If yes:
    a. *What motivated you to choose the hydrogen train? Rank from most important to least important.
        i. Innovative experience
        ii. More comfortable experience
        iii. Reducing your environmental footprint
        iv. Encouraging a new product
    b. Is there another factor (or several other factors) that led you to choose the hydrogen train?
        i. Open-ended response
- If no:
    a. *Do you know that you are taking a hydrogen train?
        i. Yes/No
    b. *In general, how do you make a decision to purchase a train ticket like this? (Rank the answer choices in order of priority)
        i. Availability
        ii. Limiting your ecological footprint
        iii. Trying out an innovative experience
        iv. Encouraging a new product
        v. Comfort
        vi. Price
    c. Other factors you consider when purchasing a train ticket like this one
        i. Open response

Passenger experience:

- *Have you taken the diesel train on this same route?
    a. Yes/No
- If yes:
    a. *Do you prefer hydrogen or diesel trains?
        i. Hydrogen
        ii. Diesel
        iii. No preference

Environmental awareness:

- *Is combating climate change an important issue in your life?
    a. Scale from 0 to 5 (5 very important, 0 not important at all)
- *Do you think this hydrogen train has a positive impact on the fight against climate change?
    a. Yes, very positive impact
    b. Yes, small positive impact
    c. No, no impact
    d. No, negative impact
    e. Don't know

- *Do you have any questions about hydrogen trains? Check all that apply:
    a. I would like more details on how the train works
    b. I would like more details about hydrogen
    c. I would like more details on safety issues
    d. I would like more details on its environmental impact
    e. No questions
    f. Other (please specify here)

A12: Quantitative online survey of hydrogen train passengers

Email

[Subject]: You were the first to board Alstom's hydrogen train—your opinion matters!

This summer, you were among the first passengers to ride Alstom's Coradia iLint hydrogen train, a first in North America. This innovative project represents a major step forward in the development of more sustainable and environmentally friendly transportation solutions.

Train de Charlevoix and Alstom are collaborating with the University of Québec at Trois-Rivières to analyze the results of this demonstration project. Your opinion matters! We would like to gather your impressions and feedback in order to understand how to better inform and educate the public about this technology of the future, but also how to make it more accessible in North America in the coming years.
We warmly invite you to take our survey. It will only take a few minutes, and your answers will remain anonymous and confidential.

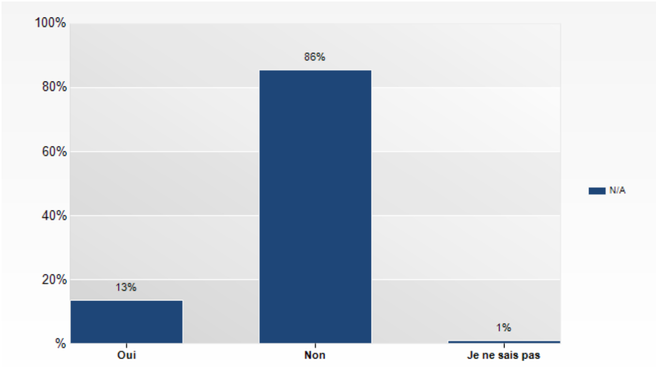
[Link to survey]

Thank you for your time and your commitment to a greener and more innovative future.

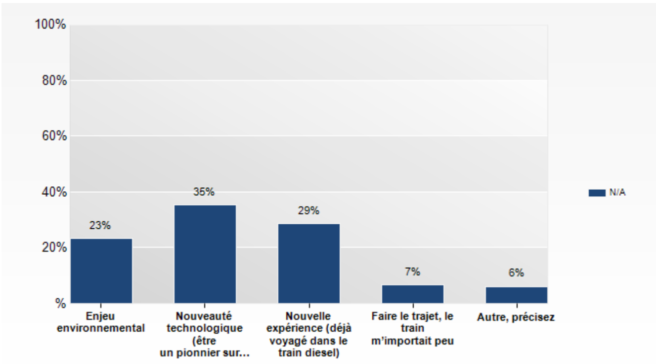
The Train de Charlevoix team

Questions and answers (304 responses by default if no other number is specified)

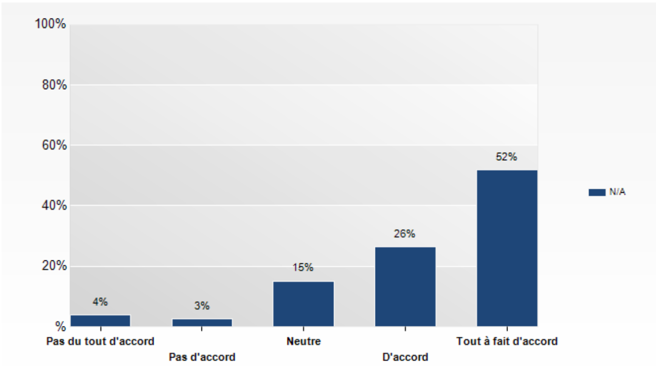
1. **Have you traveled on a hydrogen-powered train? (Yes answer required to continue the questionnaire)**
    a. ( ) **Yes = 304 respondents**
    b. ( ) **No**
    c. ( ) **I don't know**
2. **Have you ever used a hydrogen-powered transport system?**



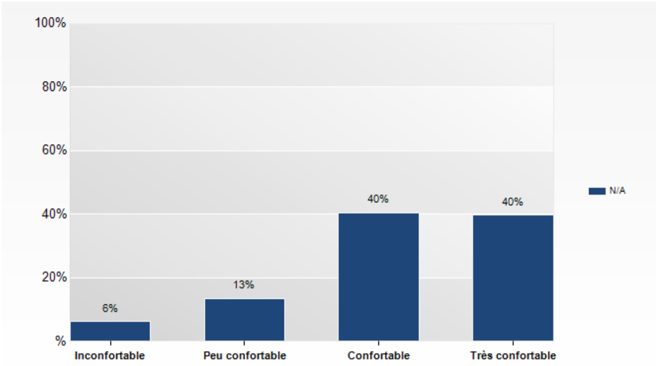
3. **Why did you choose <u>to travel on the hydrogen train</u> rather than the diesel train? (Multiple answers possible, <u>457 responses to this question</u>)**



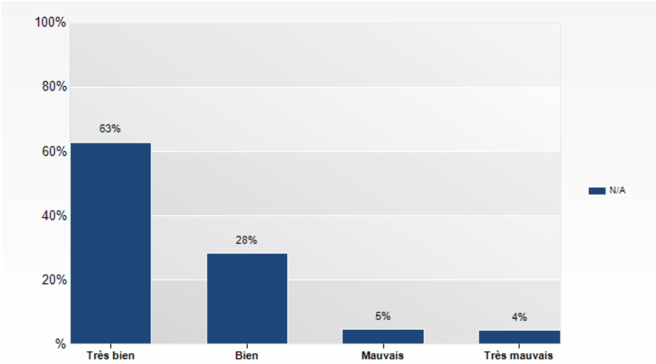
4. **<u>The atmosphere</u> on the hydrogen train is pleasant.** Here we are talking about the atmosphere in terms of design, color, smell, sound, layout, etc.



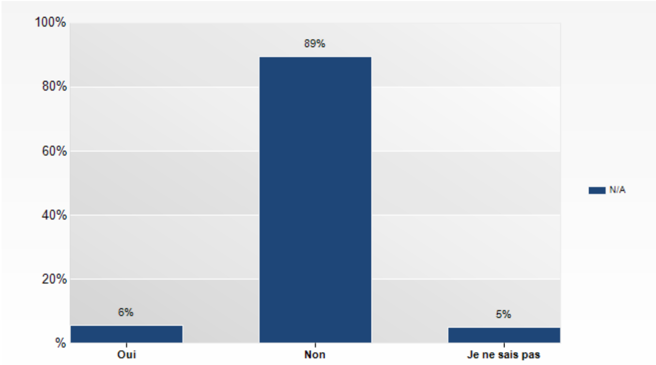
5. **How would you rate the <u>comfort</u> of the hydrogen train?** Here we are talking about the seats, the space between passengers, ease of movement, etc.



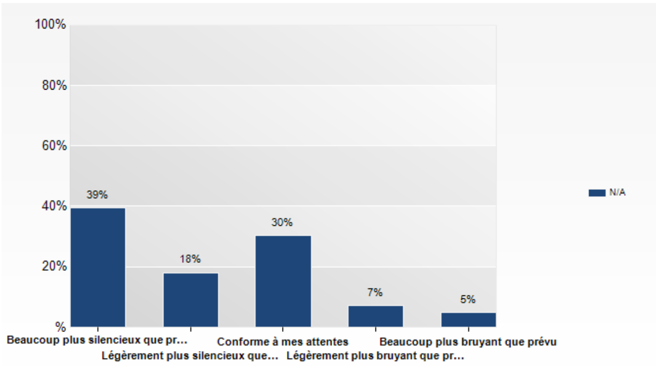
6. **What do you think of the <u>windows</u> on the hydrogen train?** Here we are talking about the views, the windows, and the configuration of the seats in relation to the outside view.



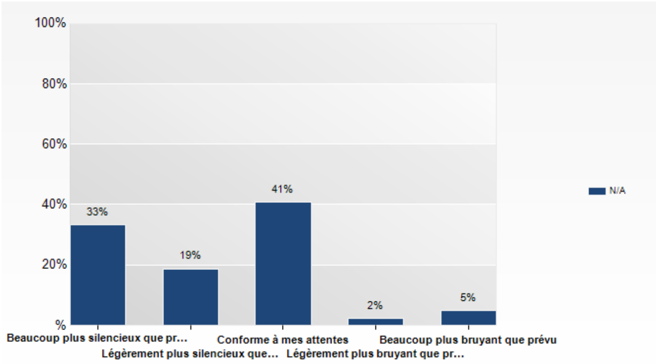
7. **Did you have any questions about <u>safety</u>?**



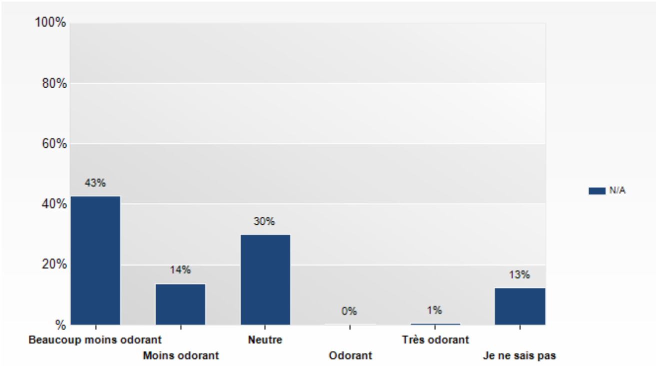
8. **How would you rate <u>the noise level</u> on board the hydrogen train compared to your expectations?**



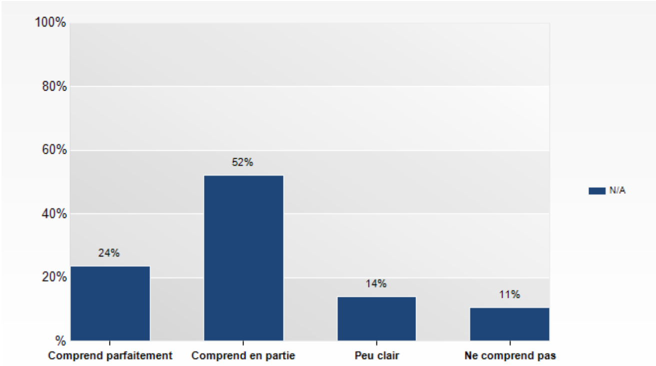
9. **How would you rate <u>the noise level outside,</u> near the hydrogen train, compared to your expectations?**



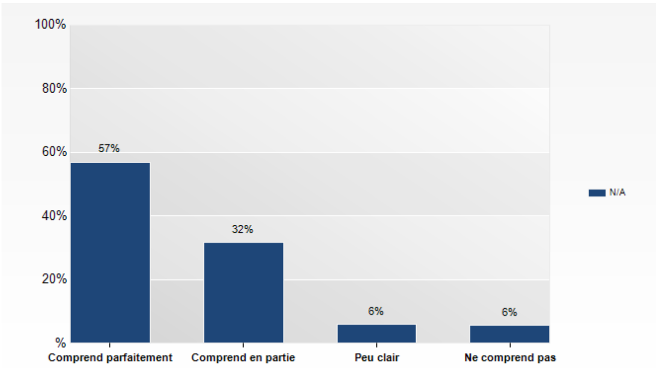
10. **Did you notice any particular smell outside near the hydrogen train?**



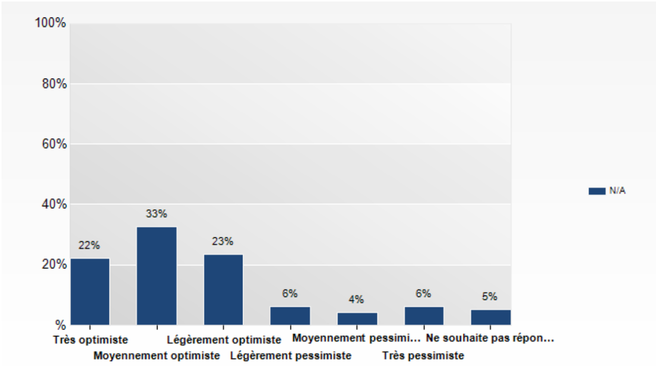
11. **Please indicate your level of understanding of how the hydrogen train works:**



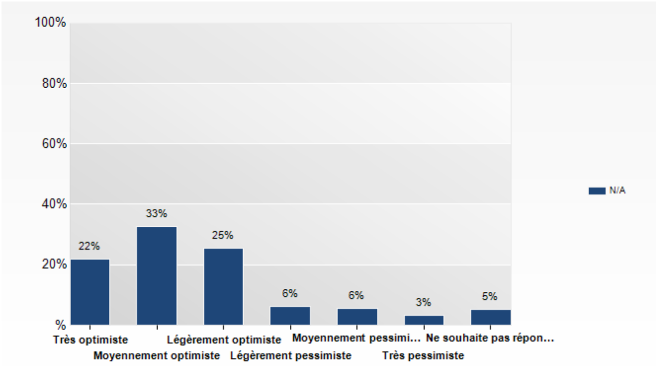
12. **Please indicate your level of understanding of the environmental impact of the hydrogen train.**



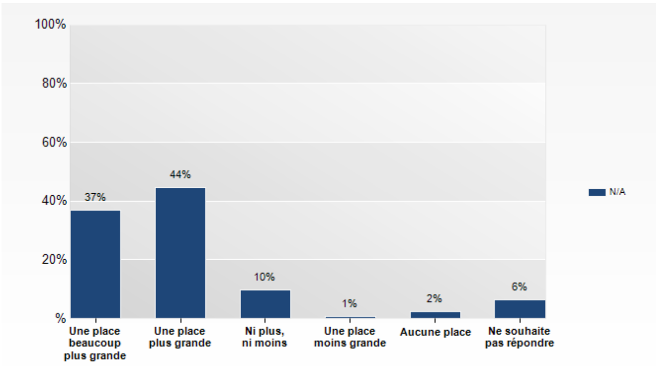
13. **Regarding the deployment of rail transport as an alternative to private cars, are you more inclined to:**



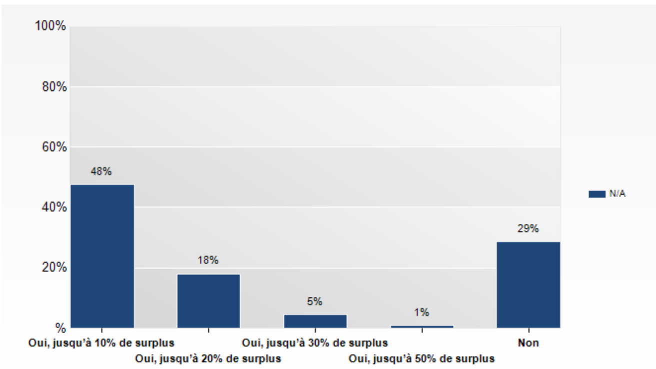
14. **Regarding the deployment of hydrogen-powered transportation, are you more inclined to:**



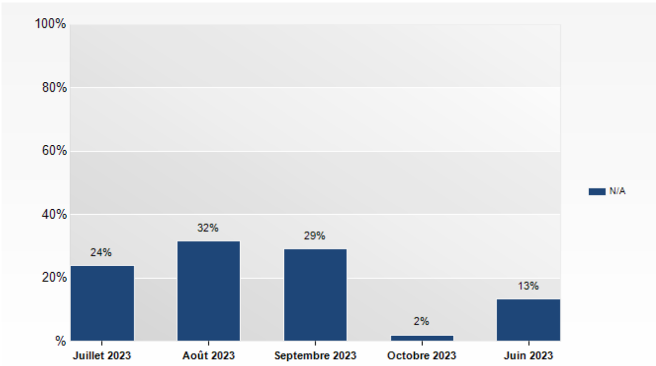
15. **What role do you think hydrogen should play in transportation?**



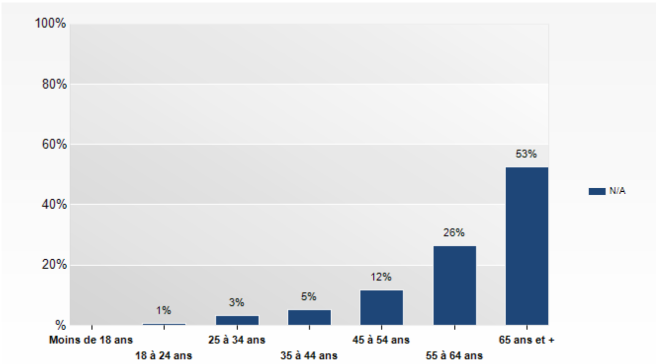
16. **Would you be willing to <u>pay extra</u> to use zero-emission public transportation compared to conventional public transportation?**



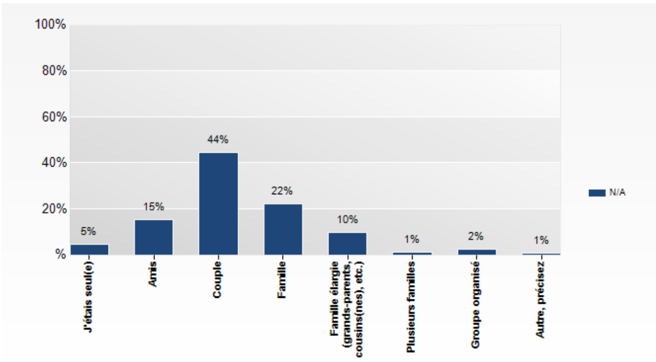
17. **When did you travel on the Charlevoix Train? (<u>301 respondents</u> for this optional question)**



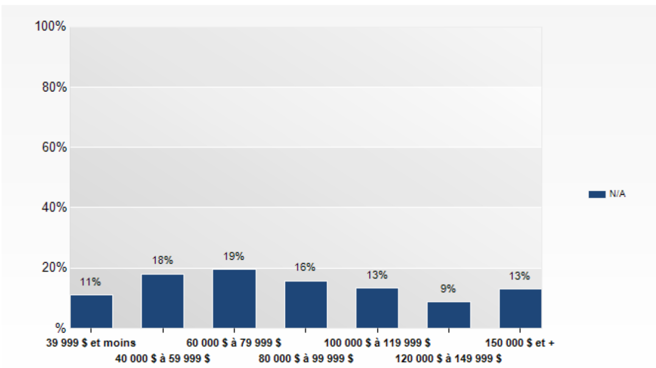
18. **What is your age group?**



19. **What was the composition of your group?**



20. **What is your annual household income bracket?**



References

[1] Gouvernement du Québec. Stratégie québécoise sur l'hydrogène vert et les bioénergies. Gouv Qué n.d. https://www.quebec.ca/gouvernement/politiques-orientations/strategie-hydrogene-vert-bioenergies (accessed March 11, 2024).
[2] GAUTHIER L. Voici le plus puissant électrolyseur d'hydrogène au monde. Révolution Énergétique 2023. https://www.revolution-energetique.com/actus/voici-le-plus-puissant-electrolyseur-dhydrogene-au-monde/ (accessed August 11, 2025).
[3] Tree Energy Solutions (TES). TES présente le Projet Mauricie Un projet essentiel pour la décarbonation du Québec grâce à l'hydrogène vert. TES H2 n.d. https://tes-h2.com/nouvelles/tes-presente-le-projet-mauricie-un-projet-essentiel-pour-la-decarbonation-du-quebec-grace-a-l (accessed March 20, 2024).
[4] H2 Tools. International Hydrogen Fueling Stations 2022. https://h2tools.org/hyarc/hydrogen-data/international-hydrogen-fueling-stations (accessed March 4, 2024).
[5] Harnois Énergies - Hydrogène. Harnois Énerg n.d. https://harnoisenergies.com/fr/produits/hydrogene/ (accessed March 9, 2024).
[6] Banc d'essai gouvernemental sur les véhicules électriques à pile à combustible (VEPC). Gouv Qué n.d. https://www.quebec.ca/agriculture-environnement-et-ressources-naturelles/energie/sources-energie/hydrogene-vert (accessed August 12, 2025).
[7] Ding D, Wu X-Y. Hydrogen fuel cell electric trains: Technologies, current status, and future. Appl Energy Combust Sci 2024;17:100255. https://doi.org/10.1016/j.jaecs.2024.100255.
[8] Martinez AS, Brouwer J, Samuelsen GS. Comparative analysis of SOFC–GT freight locomotive fueled by natural gas and diesel with onboard reformation. Appl Energy 2015;148:421–38. https://doi.org/10.1016/j.apenergy.2015.01.093.
[9] Ahsan N, Hewage K, Razi F, Hussain SA, Sadiq R. A critical review of sustainable rail technologies based on environmental, economic, social, and technical perspectives to achieve net zero emissions. Renew Sustain Energy Rev 2023;185:113621. https://doi.org/10.1016/j.rser.2023.113621.
[10] Rail – analysis - IEA. https://www.iea.org/reports/rail. 2023.
[11] IEA (2019), The Future of Rail, IEA, Paris https://www.iea.org/reports/the-future-of-rail,. n.d.
[12] Zenith F, Isaac R, Hoffrichter A, Thomassen MS, Møller-Holst S. Techno-economic analysis of freight railway electrification by overhead line, hydrogen and batteries: Case studies in Norway and USA. Proc Inst Mech Eng Part F J Rail Rapid Transit 2020;234:791–802. https://doi.org/10.1177/0954409719867495.
[13] Roland Berger. Study on the use of Fuel Cells and Hydrogen in the Railway Environment - Report 1: State of the art & business case and market potential 2019. https://rail-research.europa.eu/wp-content/uploads/2019/04/Report-1.pdf (accessed March 26, 2024).
[14] Hoffrichter A. Hydrogen as an energy carrier for railway traction. d_ph. University of Birmingham, 2013.
[15] Armaroli N, Balzani V. The Hydrogen Issue. ChemSusChem 2011;4:21–36. https://doi.org/10.1002/cssc.201000182.
[16] Mazloomi K, Gomes C. Hydrogen as an energy carrier: Prospects and challenges. Renew Sustain Energy Rev 2012;16:3024–33. https://doi.org/10.1016/j.rser.2012.02.028.
[17] L'hydrogène naturel : curiosité géologique ou source d'énergie majeure dans le futur ? | Connaissances des énergies 2020. https://www.connaissancedesenergies.org/tribune-actualite-energies/lhydrogene-naturel-curiosite-geologique-ou-source-denergie-majeure-dans-le-futur (accessed April 4, 2024).
[18] Howarth RW, Jacobson MZ. How green is blue hydrogen? Energy Sci Eng 2021;9:1676–87. https://doi.org/10.1002/ese3.956.

[19] Osman AI, Mehta N, Elgarahy AM, Hefny M, Al-Hinai A, Al-Muhtaseb AH, et al. Hydrogen production, storage, utilisation and environmental impacts: a review. Environ Chem Lett 2022;20:153–88. https://doi.org/10.1007/s10311-021-01322-8.

[20] Zgonnik V. The occurrence and geoscience of natural hydrogen: A comprehensive review. Earth-Sci Rev 2020;203:103140. https://doi.org/10.1016/j.earscirev.2020.103140.

[21] BNQ - Intensité carbone de l'hydrogène n.d. https://bnq.qc.ca/fr/normalisation/hydrogene-3/intensite-carbone-de-hydrogene.html (accessed August 12, 2025).

[22] Hydrogen Storage. EnergyGov n.d. https://www.energy.gov/eere/fuelcells/hydrogen-storage (accessed February 29, 2024).

[23] International Energy Agency (IEA). Global Hydrogen Review 2022 2022. https://www.iea.org/reports/global-hydrogen-review-2022 (accessed February 24, 2024).

[24] Younas M, Shafique S, Hafeez A, Javed F, Rehman F. An Overview of Hydrogen Production: Current Status, Potential, and Challenges. Fuel 2022;316:123317. https://doi.org/10.1016/j.fuel.2022.123317.

[25] International Energy Agency (IEA). Global Hydrogen Review 2023 2023. https://www.iea.org/reports/global-hydrogen-review-2023 (accessed February 29, 2024).

[26] European Technology and Innovation Platform Bioenergy (ETIP Bioenergy). RENEWABLE HYDROGEN PRODUCTION FROM BIOMASS. ETIP Bioenergy n.d. https://www.etipbioenergy.eu/images/Renewable_Hydrogen_Production_from_Biomass.pdf (accessed February 27, 2024).

[27] Buffi M, Prussi M, Scarlat N. Energy and environmental assessment of hydrogen from biomass sources: Challenges and perspectives. Biomass Bioenergy 2022;165:106556. https://doi.org/10.1016/j.biombioe.2022.106556.

[28] Gouvernement du Canada LR de l'énergie du C. ONÉ - Profils énergétiques des provinces et territoires – Québec 2024. https://www.cer-rec.gc.ca/fr/donnees-analyse/marches-energetiques/profils-energetiques-provinces-territoires/profils-energetiques-provinces-territoires-quebec.html (accessed February 29, 2024).

[29] International Energy Agency (IEA). Towards Hydrogen Definitions Based on their Emissions Intensity 2023. https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity (accessed February 29, 2024).

[30] Salar-García MJ, Ortiz-Martínez VM, Sánchez-Segado S, Valero Sánchez R, Sáez López A, Lozano Blanco LJ, et al. Sustainable Production of Biofuels and Biochemicals via Electro-Fermentation Technology. Molecules 2024;29:834. https://doi.org/10.3390/molecules29040834.

[31] Lee H-S, Xin W, Katakojwala R, Venkata Mohan S, Tabish NMD. Microbial electrolysis cells for the production of biohydrogen in dark fermentation – A review. Bioresour Technol 2022;363:127934. https://doi.org/10.1016/j.biortech.2022.127934.

[32] Zhang Q, Wang Y, Zhang Z, Lee D-J, Zhou X, Jing Y, et al. Photo-fermentative hydrogen production from crop residue: A mini review. Bioresour Technol 2017;229:222–30. https://doi.org/10.1016/j.biortech.2017.01.008.

[33] Khetkorn W, Rastogi RP, Incharoensakdi A, Lindblad P, Madamwar D, Pandey A, et al. Microalgal hydrogen production – A review. Bioresour Technol 2017;243:1194–206. https://doi.org/10.1016/j.biortech.2017.07.085.

[34] Usman MR. Hydrogen storage methods: Review and current status. Renew Sustain Energy Rev 2022;167:112743. https://doi.org/10.1016/j.rser.2022.112743.

[35] Gómez JA, Santos DMF. The Status of On-Board Hydrogen Storage in Fuel Cell Electric Vehicles. Designs 2023;7:97. https://doi.org/10.3390/designs7040097.

[36] Rivard E, Trudeau M, Zaghib K. Hydrogen Storage for Mobility: A Review. Materials 2019;12:1973. https://doi.org/10.3390/ma12121973.

[37] Ghafri SZA, Munro S, Cardella U, Funke T, Notardonato W, Trusler JPM, et al. Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities. Energy Environ Sci 2022;15:2690–731. https://doi.org/10.1039/D2EE00099G.

[38] Hosseini SE. Chapter 5 - Hydrogen storage and delivery challenges. In: Hosseini SE, editor. Fundam. Hydrog. Prod. Util. Fuel Cell Syst., Elsevier; 2023, p. 237–54. https://doi.org/10.1016/B978-0-323-88671-0.00003-6.
[39] Technical Assessment: Cryo-Compressed Hydrogen Storage for Vehicular Applications n.d.
[40] Madadi Avargani V, Zendehboudi S, Cata Saady NM, Dusseault MB. A comprehensive review on hydrogen production and utilization in North America: Prospects and challenges. Energy Convers Manag 2022;269:115927. https://doi.org/10.1016/j.enconman.2022.115927.
[41] Qureshi F, Yusuf M, Arham Khan M, Ibrahim H, Ekeoma BC, Kamyab H, et al. A State-of-The-Art Review on the Latest trends in Hydrogen production, storage, and transportation techniques. Fuel 2023;340:127574. https://doi.org/10.1016/j.fuel.2023.127574.
[42] Transporting the fuel of the future. Roland Berg n.d. https://www.rolandberger.com/en/Insights/Publications/Transporting-the-fuel-of-the-future.html (accessed February 29, 2024).
[43] Riera JA, Lima RM, Knio OM. A review of hydrogen production and supply chain modeling and optimization. Int J Hydrog Energy 2023;48:13731–55. https://doi.org/10.1016/j.ijhydene.2022.12.242.
[44] Röper K, Kunz N, Gast L. Renewable hydrogen in industrial production: A bibliometric analysis of current and future applications. Int J Hydrog Energy 2025;98:687–96. https://doi.org/10.1016/j.ijhydene.2024.12.034.
[45] Pyonnier. Principaux usages de l'hydrogène - Rapport préparé pour le compte du ministère de l'Énergie et des Ressources naturelles 2022. https://transitionenergetique.gouv.qc.ca/fileadmin/medias/pdf/publications/Rapport-MERN-Principaux-usages-hydrogene-2022-05-13-.pdf (accessed March 26, 2024).
[46] Algburi S, Al-Dulaimi O, Fakhruldeen HF, Khalaf DH, Hanoon RN, Jabbar FI, et al. The green hydrogen role in the global energy transformations. Renew Sustain Energy Transit 2025;8:100118. https://doi.org/10.1016/j.rset.2025.100118.
[47] Koneczna R, Cader J. Hydrogen in the Strategies of the European Union Member States. Gospod Surowcami Miner - Miner Resour Manag 2021 Vol 37 No 3 53-74 2021.
[48] H2 Infrastructure Map Europe n.d. https://www.h2inframap.eu/ (accessed February 29, 2024).
[49] International Energy Agency. Global Hydrogen Review 2024 2024.
[50] Ghorbani B, Zendehboudi S, Saady NMC, Dusseault MB. Hydrogen storage in North America: Status, prospects, and challenges. J Environ Chem Eng 2023;11:109957. https://doi.org/10.1016/j.jece.2023.109957.
[51] Alternative Fuels Data Center: Maps and Data - Hydrogen Fueling Station Locations by State n.d. https://afdc.energy.gov/data/10370 (accessed March 4, 2024).
[52] Hydrogen Production and Infrastructure Projects Database - Data product. IEA n.d. https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database (accessed March 4, 2024).
[53] HyPort conçoit des écosystèmes hydrogène et accompagne les collectivités locales et les industries de la région Occitanie. Hyport n.d. https://hyport.fr/ (accessed March 20, 2024).
[54] Lower and Higher Heating Values of Hydrogen and Other Fuels | Hydrogen Tools. H2 Tools n.d. https://h2tools.org/hyarc/hydrogen-data/lower-and-higher-heating-values-hydrogen-and-other-fuels (accessed February 28, 2024).
[55] Tables de conversion d'unités d'énergie - Canada.ca n.d. https://apps.cer-rec.gc.ca/Conversion/conversion-tables.aspx?GoCTemplateCulture=fr-CA#2 (accessed February 28, 2024).
[56] Küchen C, Spitzmüller K. Heating Oil. Ullmanns Encycl. Ind. Chem., John Wiley & Sons, Ltd; 2006. https://doi.org/10.1002/14356007.a12_617.pub2.
[57] Marin GD, Naterer GF, Gabriel K. Rail transportation by hydrogen vs. electrification – Case study for Ontario Canada, I: Propulsion and storage. Int J Hydrog Energy 2010;35:6084–96. https://doi.org/10.1016/j.ijhydene.2010.03.098.

[58] Société Nationale des Chemins de Fer Français (SNCF). Des TER à batteries pour sortir du diesel. SNCF n.d. https://www.sncf.com/fr/innovation-developpement/innovation-recherche/ter-a-batteries (accessed March 27, 2024).
[59] Böhm M, Fernández Del Rey A, Pagenkopf J, Varela M, Herwartz-Polster S, Nieto Calderón B. Review and comparison of worldwide hydrogen activities in the rail sector with special focus on on-board storage and refueling technologies. Int J Hydrog Energy 2022;47:38003–17. https://doi.org/10.1016/j.ijhydene.2022.08.279.
[60] Transports Canada. Lois codifiées, Loi sur les transports au Canada 2023. https://laws-lois.justice.gc.ca/fra/lois/c-10.4/ (accessed March 11, 2024).
[61] Transports Canada. Lois codifiées, Loi sur la sécurité ferroviaire 2022. https://laws-lois.justice.gc.ca/fra/lois/r-4.2/ (accessed March 11, 2024).
[62] Ministère de l’Environnement et du Changement climatique. Lois codifiées, Loi canadienne sur la protection de l’environnement (1999) 2023. https://laws-lois.justice.gc.ca/fra/lois/c-15.31/index.html (accessed March 11, 2024).
[63] Transports Canada. Règlement relatif à l’inspection et à la sécurité des locomotives de chemin de fer. Transp Can 2022. https://tc.canada.ca/fr/transport-ferroviaire/regles/2022-2023/reglement-relatif-inspection-securite-locomotives-chemin-fer (accessed March 11, 2024).
[64] Transports Canada. Règles concernant les périodes de chaleur extrême et l’atténuation des risques d’incendie dans le réseau ferroviaire. ASR 18691630 2022. https://tc.canada.ca/fr/transport-ferroviaire/regles/regles-concernant-periodes-chaleur-extreme-attenuation-risques-incendie-dans-reseau-ferroviaire (accessed March 11, 2024).
[65] Transports Canada. Lois codifiées, Règlement sur les émissions des locomotives (DORS/2017-121) 2017. https://laws-lois.justice.gc.ca/fra/reglements/DORS-2017-121/TexteComplet.html (accessed March 11, 2024).
[66] Environmental Protection Agency (EPA). eCFR :: 40 CFR Part 1033 -- Control of Emissions from Locomotives n.d. https://www.ecfr.gov/current/title-40/part-1033 (accessed March 11, 2024).
[67] Transports Canada. Règlement concernant l’installation, l’inspection et la vérification des réservoirs d’air (autres que ceux des locomotives). 18875464 2014. https://tc.canada.ca/fr/transport-ferroviaire/regles/reglement-concernant-installation-inspection-verification-reservoirs-air-autres-que-ceux-locomotives (accessed March 11, 2024).
[68] Ministère de la Justice. Lois codifiées, Règlement sur l’emmagasinage en vrac des gaz de pétrole liquéfiés (C.R.C., ch. 1152) 2015. https://laws-lois.justice.gc.ca/fra/reglements/C.R.C.,_ch._1152/index.html (accessed March 11, 2024).
[69] Ministère des Transports et de la Mobilité durable. Loi sur la sécurité du transport terrestre guidé n.d. https://www.legisquebec.gouv.qc.ca/fr/document/lc/s-3.3 (accessed March 11, 2024).
[70] Ministère des Transports et Mobilité durable Québec. Partage des responsabilités et secteurs d’activité n.d. https://www.transports.gouv.qc.ca/fr/ministere/role_ministere/partage-responsabilite-activites/Pages/partage-responsabilites.aspx (accessed March 11, 2024).
[71] Ministère des Transports et de la Mobilité durable. chapitre S-3.3, r. 2 - Règlement sur la sécurité ferroviaire n.d. https://www.legisquebec.gouv.qc.ca/fr/document/rc/S-3.3,%20r.%202%20/ (accessed March 11, 2024).
[72] Réseau ferroviaire - Données Québec n.d. https://www.donneesquebec.ca/recherche/dataset/reseau-ferroviaire (accessed March 26, 2024).
[73] U.S. Congress. Federal Railroad Safety Act of 1970 1970. https://www.congress.gov/91/statute/STATUTE-84/STATUTE-84-Pg971.pdf.
[74] Federal Railroad Administration D of T. eCFR :: 49 CFR Chapter II 2023. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-II (accessed March 11, 2024).
[75] U.S. Congress. Clean Air Act 1992. https://nepis.epa.gov/Exe/ZyNET.exe/900L0400.txt?ZyActionD=ZyDocument&Client=EPA&Index=1991%20Thru%201994&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEn

try=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C91THRU94%5CTXT%5C00000019%5C900L0400.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=9 (accessed March 11, 2024).

[76] Parlement Européen. DIRECTIVE 2008/57/CE DU PARLEMENT EUROPÉEN ET DU CONSEIL du 17 juin 2008 relative à l'interopérabilité du système ferroviaire au sein de la Communauté 2008. https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=CELEX:02008L0057-20150101&from=HU.

[77] Parlement Européen. DIRECTIVE 2004/49/CE DU PARLEMENT EUROPÉEN ET DU CONSEIL du 29 avril 2004 concernant la sécurité des chemins de fer communautaires et modifiant la directive 95/18/CE du Conseil concernant les licences des entreprises ferroviaires, ainsi que la directive 2001/14/CE concernant la répartition des capacités d'infrastructure ferroviaire, la tarification de l'infrastructure ferroviaire et la certification en matière de sécurité (directive sur la sécurité ferroviaire) 2004. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:220:0016:0039:fr:PDF.

[78] Directive 2012/34/UE du Parlement européen et du Conseil du 21 novembre 2012 établissant un espace ferroviaire unique européen 2012. https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000027648959/ (accessed March 11, 2024).

[79] Règlement (UE) n ° 1302/2014 de la Commission du 18 novembre 2014 concernant une spécification technique d'interopérabilité relative au sous-système «matériel roulant» — «Locomotives et matériel roulant destiné au transport de passagers» du système ferroviaire dans l'Union européenne Texte présentant de l'intérêt pour l'EEE 2014. http://data.europa.eu/eli/reg/2014/1302/oj/fra (accessed March 11, 2024).

[80] Règlement d'exécution - 2018/545 - EN - EUR-Lex n.d. https://eur-lex.europa.eu/legal-content/fr/ALL/?uri=CELEX%3A32018R0545# (accessed March 11, 2024).

[81] Règlement (UE) n ° 1316/2013 du Parlement européen et du Conseil du 11 décembre 2013 établissant le mécanisme pour l'interconnexion en Europe, modifiant le règlement (UE) n ° 913/2010 et abrogeant les règlements (CE) n ° 680/2007 et (CE) n ° 67/2010 Texte présentant de l'intérêt pour l'EEE 2013. http://data.europa.eu/eli/reg/2013/1316/oj/fra (accessed March 11, 2024).

[82] Règlement (UE) 2016/1628 du Parlement européen et du Conseil du 14 septembre 2016 relatif aux exigences concernant les limites d'émission pour les gaz polluants et les particules polluantes et la réception par type pour les moteurs à combustion interne destinés aux engins mobiles non routiers, modifiant les règlements (UE) n° 1024/2012 et (UE) n° 167/2013 et modifiant et abrogeant la directive 97/68/CE (Texte présentant de l'intérêt pour l'EEE) 2016. http://data.europa.eu/eli/reg/2016/1628/oj/fra (accessed March 11, 2024).

[83] Rheinland T. Hydrogen applications in rail vehicles | TÜV Rheinland n.d. https://www.tuv.com/landingpage/en/hydrogen-technology/wasserstoffanwendungen-in-schienenfahrzeugen.html (accessed March 11, 2024).

[84] Canada G of CNRC. NRCan hydrogen codes and standards gap analysis project (NRCan H2 CSGA) - NRC Publications Archive 2024. https://nrc-publications.canada.ca/eng/view/object/?id=6d14bc19-30b8-4c59-bb26-513dd983d3d7 (accessed March 11, 2024).

[85] CH2M HILL Canada Ltd, Enrst & Young Orenda Corporate Finance Inc., Canadian Nuclear Laboratories, Regional Express Rail Program Hydrail Feasibility Study Report 2018. https://assets.metrolinx.com/image/upload/Documents/Metrolinx/CPG-PGM-RPT-245_HydrailFeasibilityReport_R1.pdf.

[86] Transports Canada. Lois codifiées, Règlement sur les combustibles propres (DORS/2022-140) 2022. https://laws-lois.justice.gc.ca/fra/reglements/DORS-2022-140/page-1.html (accessed March 11, 2024).

[87] Environmental Protection Agency (EPA). eCFR :: 40 CFR Part 80 Subpart M -- Renewable Fuel Standard 2010. https://www.ecfr.gov/current/title-40/part-80/subpart-M (accessed March 11, 2024).

[88] Environmental Protection Agency (EPA). 40 CFR Part 1090 -- Regulation of Fuels, Fuel Additives, and Regulated Blendstocks n.d. https://www.ecfr.gov/current/title-40/part-1090 (accessed March 29, 2024).
[89] Parlement Européen. RÈGLEMENT (UE) 2023/1804 DU PARLEMENT EUROPÉEN ET DU CONSEIL du 13 septembre 2023 sur le déploiement d'une infrastructure pour carburants alternatifs et abrogeant la directive 2014/94/UE 2002. https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=CELEX:32023R1804.
[90] U.S. National Clean Hydrogen Strategy and Roadmap | Hydrogen Program n.d. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap (accessed March 11, 2024).
[91] Commission européenne. REPowerEU - Une énergie abordable, sûre et durable pour l'Europe 2022. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_fr (accessed March 11, 2024).
[92] Ressources naturelles Canada. Stratégie relative à l'hydrogène 2020. https://ressources-naturelles.canada.ca/changements-climatiques/lavenir-vert-canada/strategie-relative-lhydrogene/23134 (accessed March 11, 2024).
[93] Ministry of Energy G of O. Ontario's Low-Carbon Hydrogen Strategy n.d. http://www.ontario.ca/page/ontarios-low-carbon-hydrogen-strategy (accessed March 11, 2024).
[94] Clean Energy and Major Projects Office G of BC. BC Hydrogen Office 2023. https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/renewable-energy/hydrogen-office (accessed March 11, 2024).
[95] Government of Alberta. Alberta Hydrogen Roadmap 2024. https://www.alberta.ca/hydrogen-roadmap (accessed March 11, 2024).
[96] Canada T. Incidence du cycle de conduite et du climat sur la consommation électrique et l'autonomie des véhicules de tourisme entièrement électriques 2018. https://tc.canada.ca/fr/programmes/programmes-financement/programme-ecotechnologie-vehicules/incidence-cycle-conduite-climat-consommation-electrique-autonomie-vehicules-tourisme-entierement-electriques (accessed March 17, 2024).
[97] Environmental Protection Agency (EPA). eCFR :: 40 CFR Part 86 -- Control of Emissions from New and In-Use Highway Vehicles and Engines n.d. https://www.ecfr.gov/current/title-40/part-86 (accessed March 17, 2024).
[98] Règlement (UE) 2023/851 du Parlement européen et du Conseil du 19 avril 2023 modifiant le règlement (UE) 2019/631 en ce qui concerne le renforcement des normes de performance en matière d'émissions de CO2 pour les voitures particulières neuves et les véhicules utilitaires légers neufs conformément à l'ambition accrue de l'Union en matière de climat (Texte présentant de l'intérêt pour l'EEE). vol. 110. 2023.
[99] Frassoldati A, Faravelli T, Ranzi E. A wide range modeling study of NOx formation and nitrogen chemistry in hydrogen combustion. Int J Hydrog Energy 2006;31:2310–28. https://doi.org/10.1016/j.ijhydene.2006.02.014.
[100] Gräber J. D5.8 – Assessment Report of Processes and Procedures Allowing Virtual Certification of Brakes. 2019.
[101] NF EN 14363+A2. Afnor Ed n.d. https://www.boutique.afnor.org/fr-fr/norme/nf-en-14363-a2/applications-ferroviaires-essais-et-simulations-en-vue-de-lhomologation-des/fa205692/333027 (accessed March 18, 2024).
[102] NF EN 15734-2+A1. Afnor Ed n.d. https://www.boutique.afnor.org/fr-fr/norme/nf-en-157342-a1/applications-ferroviaires-systemes-de-freinage-pour-trains-a-grande-vitesse/fa203821/318194 (accessed March 18, 2024).
[103] NF EN 16185-2+A1. Afnor Ed n.d. https://www.boutique.afnor.org/fr-fr/norme/nf-en-161852-a1/applications-ferroviaires-systemes-de-freinage-pour-trains-automoteurs-part/fa198585/84255 (accessed March 18, 2024).

[104] Manual of Standards and Recommended Practices n.d. https://aarpublications.com/msrp.html (accessed March 18, 2024).
[105] L'Usine Nouvelle. Les futurs trains à hydrogène français d'Alstom décortiqués 2019.
[106] Amamou AA, Kelouwani S, Boulon L, Agbossou K. A Comprehensive Review of Solutions and Strategies for Cold Start of Automotive Proton Exchange Membrane Fuel Cells. IEEE Access 2016;4:4989–5002. https://doi.org/10.1109/ACCESS.2016.2597058.
[107] Amamou A, Kandidayeni M, Kelouwani S, Boulon L. An Online Self Cold Startup Methodology for PEM Fuel Cells in Vehicular Applications. IEEE Trans Veh Technol 2020;69:14160–72. https://doi.org/10.1109/TVT.2020.3011381.
[108] Wang Z, Dong B, Wang Y, Li M, Liu H, Han F. Analysis and evaluation of fuel cell technologies for sustainable ship power: Energy efficiency and environmental impact. Energy Convers Manag X 2024;21:100482. https://doi.org/10.1016/j.ecmx.2023.100482.
[109] Sürer MG, Arat HT. Advancements and current technologies on hydrogen fuel cell applications for marine vehicles. Int J Hydrog Energy 2022;47:19865–75. https://doi.org/10.1016/j.ijhydene.2021.12.251.
[110] Züttel A, Remhof A, Borgschulte A, Friedrichs O. Hydrogen: the future energy carrier. Philos Trans R Soc Math Phys Eng Sci 2010;368:3329–42. https://doi.org/10.1098/rsta.2010.0113.
[111] Dräger. Hydrogen: How to meet the safety challenges 2020. https://draeger-mo.com/media/files/hydrogen-safety-challenges-ebk-PDF-11064-en-master.pdf (accessed March 15, 2024).
[112] Crowl DA, Jo Y-D. The hazards and risks of hydrogen. J Loss Prev Process Ind 2007;20:158–64. https://doi.org/10.1016/j.jlp.2007.02.002.
[113] Hall JE, Hooker P, O'Sullivan L, Angers B, Hourri A, Bernard P. Flammability profiles associated with high-pressure hydrogen jets released in close proximity to surfaces. Int J Hydrog Energy 2017;42:7413–21. https://doi.org/10.1016/j.ijhydene.2016.05.113.
[114] Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME), Guide d'information sur les risques et les mesures de sécurité liés à la production décentralisée d'hydrogène 2015. https://www.actu-environnement.com/media/pdf/news-24903-securite-production-decentralisee-hydrogene.pdf (accessed March 13, 2024).
[115] Stefano M de. Explosion d'un mélange hétérogène hydrogène-air dans un milieu clos obstrué. Thèse de doctorat. Institut National des Sciences Appliquées - Centre Val de Loire, 2018.
[116] HyResponder. Cours 2 Propriétés de l'hydrogène pertinentes pour la sécurité NIVEAU I (Pompier) 2021. https://hyresponder.eu/wp-content/uploads/2023/03/Cours2_Niveau-I-HyResponder_FR.pdf.
[117] Abohamzeh E, Salehi F, Sheikholeslami M, Abbassi R, Khan F. Review of hydrogen safety during storage, transmission, and applications processes. J Loss Prev Process Ind 2021;72:104569. https://doi.org/10.1016/j.jlp.2021.104569.
[118] McCay MH, Shafiee S. 22 - Hydrogen: An Energy Carrier. In: Letcher TM, editor. Future Energy Third Ed., Elsevier; 2020, p. 475–93. https://doi.org/10.1016/B978-0-08-102886-5.00022-0.
[119] Nicoletti G, Arcuri N, Nicoletti G, Bruno R. A technical and environmental comparison between hydrogen and some fossil fuels. Energy Convers Manag 2015;89:205–13. https://doi.org/10.1016/j.enconman.2014.09.057.
[120] Molkov V. Fundamentals of Hydrogen Safety Engineering I 2012. https://www.arma.org.au/wp-content/uploads/2017/03/fundamentals-of-hydrogen-safety-engineering-i.pdf (accessed March 13, 2024).
[121] Hourri A, Gomez F, Angers B, Bénard P. Computational study of horizontal subsonic free jets of hydrogen: Validation and classical similarity analysis. Int J Hydrog Energy 2011;36:15913–8. https://doi.org/10.1016/j.ijhydene.2011.09.044.
[122] Détecteurs ultrasoniques de fuite de gaz | Emerson FR n.d. https://www.emerson.com/fr-fr/automation/measurement-instrumentation/flame-gas-detection/about-ultrasonic-gas-leak-detectors (accessed March 26, 2024).

[123] HySafe. Initial Guidance for Using Hydrogen in Confined Spaces - Results from InsHyde 2009. http://www.hysafe.org/download/1710/HYSAFE_D113_version_1.1.pdf.
[124] Royle M, Willoughby D, Udensi J, Grube T, Stolten D, Gummer J, et al. Self Ignition of Hydrogen by Various Mechanisms. Forschungszentrum, Zentralbibliothek; 2010.
[125] Astbury GR, Hawksworth SJ. Spontaneous ignition of hydrogen leaks: A review of postulated mechanisms. Int J Hydrog Energy 2007;32:2178–85. https://doi.org/10.1016/j.ijhydene.2007.04.005.
[126] Molkov V. Fundamentals of Hydrogen Safety Engineering II 2012. https://www.arma.org.au/wp-content/uploads/2017/03/fundamentals-of-hydrogen-safety-engineering-ii.pdf (accessed March 26, 2024).
[127] Barbir F. Safety issues of hydrogen in vehicles 1999. https://courses.engr.illinois.edu/npre470/sp2019/web/readings/Hydrogen%20safety%20issues.pdf (accessed March 16, 2024).
[128] Kovač A, Paranos M, Marciuš D. Hydrogen in energy transition: A review. Int J Hydrog Energy 2021;46:10016–35. https://doi.org/10.1016/j.ijhydene.2020.11.256.
[129] Molnarne M, Schroeder V. Hazardous properties of hydrogen and hydrogen containing fuel gases. Process Saf Environ Prot 2019;130:1–5. https://doi.org/10.1016/j.psep.2019.07.012.
[130] Espaces confinés. Exposition aux risques et effets sur la santé - Risques - INRS n.d. https://www.inrs.fr/risques/espaces-confines/exposition-risques-effets-sante.html (accessed March 19, 2024).
[131] Basic Hydrogen Properties | Hydrogen Tools n.d. https://h2tools.org/hyarc/hydrogen-data/basic-hydrogen-properties (accessed March 30, 2024).
[132] G.S. Manual, Glenn Safety Manual – Chapter 6, (2019) 1–83. n.d. https://www1.grc.nasa.gov/wp-content/uploads/chapter_06.pdf.
[133] Barilo NF. Safety of Hydrogen Systems Installed in Outdoor Enclosures. Pacific Northwest National Lab. (PNNL), Richland, WA (United States); 2013. https://doi.org/10.2172/1115836.
[134] Lowesmith BJ, Hankinson G, Chynoweth S. Safety issues of the liquefaction, storage and transportation of liquid hydrogen: An analysis of incidents and HAZIDS. Int J Hydrog Energy 2014;39:20516–21. https://doi.org/10.1016/j.ijhydene.2014.08.002.
[135] Mirza NR, Degenkolbe S, Witt W. Analysis of hydrogen incidents to support risk assessment. Int J Hydrog Energy 2011;36:12068–77. https://doi.org/10.1016/j.ijhydene.2011.06.080.
[136] Nakayama J, Sakamoto J, Kasai N, Shibutani T, Miyake A. Preliminary hazard identification for qualitative risk assessment on a hybrid gasoline-hydrogen fueling station with an on-site hydrogen production system using organic chemical hydride. Int J Hydrog Energy 2016;41:7518–25. https://doi.org/10.1016/j.ijhydene.2016.03.143.
[137] Hydrogen Safety Panel. Example Safety Plan for Hydrogen and Fuel Cell Projects 2020. https://h2tools.org/sites/default/files/2020-10/Example_Hydrogen_Safety_Plan_September_2020.pdf (accessed March 16, 2024).
[138] Tchouvelev AV, Buttner WJ, Melideo D, Baraldi D, Angers B. Development of risk mitigation guidance for sensor placement inside mechanically ventilated enclosures – Phase 1. Int J Hydrog Energy 2021;46:12439–54. https://doi.org/10.1016/j.ijhydene.2020.09.108.
[139] Gye H-R, Seo S-K, Bach Q-V, Ha D, Lee C-J. Quantitative risk assessment of an urban hydrogen refueling station. Int J Hydrog Energy 2019;44:1288–98. https://doi.org/10.1016/j.ijhydene.2018.11.035.
[140] Hydrogen Incident Examples | Hydrogen Tools n.d. https://h2tools.org/lessons/hydrogen-incident-examples (accessed March 16, 2024).
[141] Gentilhomme O, Weinberger B, Joubert L. Etude de sécurité d'une station de distribution d'hydrogène gazeux, 2020, p. 45.
[142] Moradi R, Groth KM. Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. Int J Hydrog Energy 2019;44:12254–69. https://doi.org/10.1016/j.ijhydene.2019.03.041.
[143] CORADIA TM iLINT TM 54 Manuel du conducteur, 654 n.d.

[144] Ehrhart BD, Brooks DM, Muna AB, LaFleur CB. Risk Assessment of Hydrogen Fuel Cell Electric Vehicles in Tunnels. Fire Technol 2020;56:891–912. https://doi.org/10.1007/s10694-019-00910-z.
[145] Linde. Hydrogène comprimé - fiches de données de sécurité F-4604 2023. https://www.lindecanada.ca/-/media/corporate/praxair-canada/documents-fr/safety-data-sheets-linde-canada-fr/f-4604-hydrogne-comprim-fiche-de-donnes-de-scurit.pdf?la=fr-ca (accessed March 19, 2024).
[146] Canada T. Plans d'intervention d'urgence (PIU). ASDB 14874758 2022. https://tc.canada.ca/fr/marchandises-dangereuses/plans-intervention-urgence-piu (accessed March 16, 2024).
[147] Canada T. Guide pour savoir si vous avez besoin d'un plan d'intervention d'urgence (PIU). ASBD 15207832 2022. https://tc.canada.ca/fr/marchandises-dangereuses/plans-intervention-urgence/guides/savoir-si-vous-avez-besoin-plan-intervention-urgence (accessed March 16, 2024).
[148] Transports Canada. Lois codifiées, Règlement sur le transport des marchandises dangereuses (DORS/2001-286) - ANNEXE 1 2023. https://laws-lois.justice.gc.ca/fra/reglements/DORS-2001-286/page-1.html (accessed March 16, 2024).
[149] Transports Canada. Lois codifiées, Règlement sur le transport des marchandises dangereuses (DORS/2001-286) 2023. https://laws-lois.justice.gc.ca/fra/reglements/DORS-2001-286/page-1.html (accessed March 16, 2024).
[150] Groth KM, Hecht ES. HyRAM: A methodology and toolkit for quantitative risk assessment of hydrogen systems. Int J Hydrog Energy 2017;42:7485–93. https://doi.org/10.1016/j.ijhydene.2016.07.002.
[151] Li X, Han Z, Zhang R, Zhang Y, Zhang L. Risk assessment of hydrogen generation unit considering dependencies using integrated DEMATEL and TOPSIS approach. Int J Hydrog Energy 2020;45:29630–42. https://doi.org/10.1016/j.ijhydene.2020.07.243.
[152] Skjold T, Siccama D, Hisken H, Brambilla A, Middha P, Groth KM, et al. 3D risk management for hydrogen installations. Int J Hydrog Energy 2017;42:7721–30. https://doi.org/10.1016/j.ijhydene.2016.07.006.
[153] Brian Ehrhart. Hydrogen Quantitative Risk Assessment 2020.
[154] Cristina Galassi M, Papanikolaou E, Baraldi D, Funnemark E, Håland E, Engebø A, et al. HIAD – hydrogen incident and accident database. Int J Hydrog Energy 2012;37:17351–7. https://doi.org/10.1016/j.ijhydene.2012.06.018.
[155] H2 Tools. Lessons Learned | Hydrogen Incident Reporting Database n.d. https://h2tools.org/lessons?search_api_fulltext= (accessed March 27, 2024).
[156] Kim W, Burgherr P, Spada M, Lustenberger P, Kalinina A, Hirschberg S. Energy-related Severe Accident Database (ENSAD): cloud-based geospatial platform. Big Earth Data 2018;2:368–94. https://doi.org/10.1080/20964471.2019.1586276.
[157] Annual Report | The High Pressure Gas Safety Institute of Japan n.d. https://www.khk.or.jp/english/report.html (accessed March 30, 2024).
[158] Transport Canada. Risk Assessment of Hydrogen and Battery Power in Locomotives – Part 1 – Literature Review. Transp Can 2023. https://tc.canada.ca/en/innovation-centre/priority-reports/risk-assessment-hydrogen-battery-power-locomotives-part-1-literature-review (accessed March 19, 2024).
[159] Transport Canada. Risk Assessment of Hydrogen and Battery Power in Locomotives – Part 2 – Risks and Hazards Assessment. Transp Can 2023. https://tc.canada.ca/en/innovation-centre/priority-reports/risk-assessment-hydrogen-battery-power-locomotives-part-2-risks-hazards-assessment (accessed March 19, 2024).
[160] Transport Canada. Risk Assessment of Hydrogen and Battery Power in Locomotives – Part 3 – Codes and Standards Review. Transp Can 2023. https://tc.canada.ca/en/innovation-centre/priority-reports/risk-assessment-hydrogen-battery-power-locomotives-part-3-codes-standards-review (accessed March 19, 2024).

[161] Le Coradia iLint, train à hydrogène d'Alstom, a parcouru 1175 kilomètres sans ravitaillement. Alstom n.d. https://www.alstom.com/fr/press-releases-news/2022/9/le-coradia-ilint-train-hydrogene-dalstom-parcouru-1175-kilometres-sans (accessed April 7, 2024).
[162] Reddi K, Elgowainy A, Rustagi N, Gupta E. Impact of hydrogen SAE J2601 fueling methods on fueling time of light-duty fuel cell electric vehicles. Int J Hydrog Energy 2017;42:16675–85. https://doi.org/10.1016/j.ijhydene.2017.04.233.
[163] Office of Energy Efficiency and Renewable Energy (EERE). On-Site and Bulk Hydrogen Storage. EnergyGov n.d. https://www.energy.gov/eere/fuelcells/site-and-bulk-hydrogen-storage (accessed March 19, 2024).
[164] Paul-Robert Raymond. Une première station de ravitaillement à hydrogène au Québec d'ici trois semaines - Le Soleil. Le Soleil 2019. https://www.lesoleil.com/2019/01/17/une-premiere-station-de-ravitaillement-a-hydrogene-au-quebec-dici-trois-semaines-8a60bb093d5652fe5ef9697910378a80/ (accessed March 19, 2024).
[165] Grouset D, Ridart C. Chapter 6 - Lowering Energy Spending Together With Compression, Storage, and Transportation Costs for Hydrogen Distribution in the Early Market. In: Azzaro-Pantel C, editor. Hydrog. Supply Chains, Academic Press; 2018, p. 207–70. https://doi.org/10.1016/B978-0-12-811197-0.00006-3.
[166] FIBA Canning Inc. TUBE TRAILERS. FIBA Cann Inc n.d. https://www.fibacanning.com/tubetrailers (accessed March 19, 2024).
[167] Raymond Drnevich. Hydrogen Delivery Liquefaction & Compression - Praxair 2003. https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/liquefaction_comp_pres_praxair.pdf.
[168] Eudy L, Post M. BC Transit Fuel Cell Bus Project: Evaluation Results Report 2014. https://doi.org/10.2172/1126272.
[169] DB Class 628. Wikipedia 2024.
[170] ISO (International Organization for Standardization). ISO 3381:2021. ISO n.d. https://www.iso.org/fr/standard/77368.html (accessed March 18, 2024).
[171] ISO (International Organization for Standardization). ISO 3095:2013. ISO n.d. https://www.iso.org/fr/standard/55726.html (accessed March 19, 2024).
[172] Groningen. Main Results Test With Hydrogen Train In Groningen 2020. https://www.alstom.com/sites/alstom.com/files/2020/09/30/Rapport Waterstoftrein Groningen_EN.pdf.
[173] Railway Association of Canada (RAC). Locomotive Emissions Monitoring Report - 2021 2021. https://www.railcan.ca/wp-content/uploads/2023/09/SPARK-RAC-21-LEM_REPORT-2023-EN10.pdf (accessed March 19, 2024).
[174] Jia S, Liu M. Embodied GHG emissions of high speed rail stations: Quantification, data-driven prediction and cost-benefit analysis. J Clean Prod 2022;366:133006. https://doi.org/10.1016/j.jclepro.2022.133006.
[175] Greenhouse Gas Emissions Quantification Guide n.d. https://www.environnement.gouv.qc.ca/changements/ges/guide-quantification/index-en.htm (accessed April 25, 2024).
[176] Alstom concludes the successful demonstration of the first commercial service hydrogen-powered train in North America. Alstom n.d. https://www.alstom.com/press-releases-news/2023/10/alstom-concludes-successful-demonstration-first-commercial-service-hydrogen-powered-train-north-america (accessed March 18, 2024).
[177] Hoffrichter A, Miller AR, Hillmansen S, Roberts C. Well-to-wheel analysis for electric, diesel and hydrogen traction for railways. Transp Res Part Transp Environ 2012;17:28–34. https://doi.org/10.1016/j.trd.2011.09.002.
[178] France Hydrogène. Fiche pratique sur la règlementation applicable à la filière hydrogène - Le transport de l'hydrogène 2023. https://s3.production.france-hydrogene.org/uploads/sites/5/2023/02/Fiche-Transport-dhydrogene.pdf (accessed March 26, 2024).

[179] Ministère de l'Emploi et de la Solidarité sociale. S-2.1 - Loi sur la santé et la sécurité du travail 2023. https://www.legisquebec.gouv.qc.ca/fr/document/lc/s-2.1 (accessed March 18, 2024).
[180] Transports Canada. Partie 6 Formation - Lois codifiées, Règlement sur le transport des marchandises dangereuses (DORS/2001-286) 2023. https://laws-lois.justice.gc.ca/fra/reglements/DORS-2001-286/page-21.html (accessed March 18, 2024).
[181] Ministère des Transports et de la Mobilité durable. Transport des matières dangereuses n.d. https://www.transports.gouv.qc.ca/fr/entreprises-partenaires/ent-camionnage/Pages/transport-matieres-dangereuses-vehicules-lourds.aspx (accessed March 20, 2024).
[182] Gouvernement du Canada C canadien d'hygiène et de sécurité au travail. CCHST: Transport des marchandises dangereuses (TMD) - Aperçu (transport routier) 2024. https://www.cchst.ca/oshanswers/legisl/tdg/tdg_overview.html (accessed March 19, 2024).
[183] Air Liquide inaugure la plus grande unité du monde de production d'hydrogène décarboné par électrolyse à membrane au Canada | Air Liquide 2021. https://www.airliquide.com/fr/groupe/communiques-presse-actualites/26-01-2021/air-liquide-inaugure-la-plus-grande-unite-du-monde-de-production-dhydrogene-decarbone-par (accessed March 9, 2024).
[184] Saravanan A, Karishma S, Kumar PS, Yaashikaa PR, Jeevanantham S, Gayathri B. Microbial electrolysis cells and microbial fuel cells for biohydrogen production: current advances and emerging challenges. Biomass Convers Biorefinery 2023;13:8403–23. https://doi.org/10.1007/s13399-020-00973-x.
[185] Parkhey P, Gupta P. Improvisations in structural features of microbial electrolytic cell and process parameters of electrohydrogenesis for efficient biohydrogen production: a review. Renew Sustain Energy Rev 2017;69:1085–99. https://doi.org/10.1016/j.rser.2016.09.101.
[186] Kadier A, Simayi Y, Abdeshahian P, Azman NF, Chandrasekhar K, Kalil MS. A comprehensive review of microbial electrolysis cells (MEC) reactor designs and configurations for sustainable hydrogen gas production. Alex Eng J 2016;55:427–43. https://doi.org/10.1016/j.aej.2015.10.008.
[187] Nicholson S, Heath G. Life Cycle Emissions Factors for Electricity Generation Technologies 2021:1 files. https://doi.org/10.7799/1819907.
[188] Alstom's Coradia iLint hydrogen powered train wins German Sustainability Award. Alstom n.d. https://www.alstom.com/press-releases-news/2021/12/alstoms-coradia-ilint-hydrogen-powered-train-wins-german-sustainability (accessed February 29, 2024).
[189] Alstom's Coradia iLint hydrogen train runs for the first time in France. Alstom n.d. https://www.alstom.com/press-releases-news/2021/9/alstoms-coradia-ilint-hydrogen-train-runs-first-time-france (accessed February 29, 2024).
[190] Alstom and ENGIE sign a partnership to supply a fuel cell system with renewable hydrogen for use in European rail freight. Alstom n.d. https://www.alstom.com/press-releases-news/2022/4/alstom-and-engie-sign-partnership-supply-fuel-cell-system-renewable (accessed February 29, 2024).
[191] Alstom's hydrogen train Coradia iLint completes successful tests in the Netherlands. Alstom n.d. https://www.alstom.com/press-releases-news/2020/3/alstoms-hydrogen-train-coradia-ilint-completes-successful-tests (accessed February 29, 2024).
[192] Whistle blows in Germany for world's first hydrogen train fleet. Fr 24 2022. https://www.france24.com/en/live-news/20220824-whistle-blows-in-germany-for-world-s-first-hydrogen-train-fleet (accessed February 29, 2024).
[193] Trial runs of Alstom's hydrogen train in the Netherlands deemed officially successful. Alstom n.d. https://www.alstom.com/press-releases-news/2020/9/trial-runs-alstoms-hydrogen-train-netherlands-deemed-officially (accessed February 29, 2024).
[194] Alstom et son train à hydrogène ont officiellement réussi les essais aux Pays-Bas. Alstom n.d. https://www.alstom.com/fr/press-releases-news/2020/9/alstom-et-son-train-hydrogene-ont-officiellement-reussi-les-essais-aux (accessed March 9, 2024).
[195] Rani A. East Japan Railway unveils hydrogen-powered train. Railw Technol 2022. https://www.railway-technology.com/news/japan-railway-hydrogen-train/ (accessed March 27, 2024).

[196] First China-developed hydrogen fuel cell locomotive starts trial runs. Green Car Congr n.d. https://www.greencarcongress.com/2021/11/20211102-chinah2loco.html (accessed March 30, 2024).
[197] Frangoul A. Hydrogen-powered train a step closer to passenger service in Germany. CNBC 2022. https://www.cnbc.com/2022/03/16/hydrogen-powered-train-a-step-closer-to-passenger-service-in-germany.html (accessed March 27, 2024).
[198] Du Z, Liu C, Zhai J, Guo X, Xiong Y, Su W, et al. A Review of Hydrogen Purification Technologies for Fuel Cell Vehicles. Catalysts 2021;11:393. https://doi.org/10.3390/catal11030393.
[199] Relvas F, Whitley RD, Silva C, Mendes A. Single-Stage Pressure Swing Adsorption for Producing Fuel Cell Grade Hydrogen. Ind Eng Chem Res 2018;57:5106–18. https://doi.org/10.1021/acs.iecr.7b05410.
[200] Bernardo G, Araújo T, da Silva Lopes T, Sousa J, Mendes A. Recent advances in membrane technologies for hydrogen purification. Int J Hydrog Energy 2020;45:7313–38. https://doi.org/10.1016/j.ijhydene.2019.06.162.
[201] Liszka M, Malik T, Manfrida G. Energy and exergy analysis of hydrogen-oriented coal gasification with CO2 capture. Energy 2012;45:142–50. https://doi.org/10.1016/j.energy.2012.03.054.
[202] Kırtay E. Recent advances in production of hydrogen from biomass. Energy Convers Manag 2011;52:1778–89. https://doi.org/10.1016/j.enconman.2010.11.010.
[203] Zhongfu T, Chen Z, Pingkuo L, Reed B, Jiayao Z. Focus on fuel cell systems in China. Renew Sustain Energy Rev 2015;47:912–23. https://doi.org/10.1016/j.rser.2015.03.057.
[204] Alstom unveils Coradia iLint hydrogen fuel cell powered train for European regional market. Fuel Cells Bull 2016;2016:1. https://doi.org/10.1016/S1464-2859(16)30228-0.
[205] https://www.theinsightpartners.com TIP. Marché des trains à pile à combustible à hydrogène – Analyse des tendances et de la croissance | Année de prévision 2030. Insight Partn n.d. https://www.theinsightpartners.com/fr/reports/hydrogen-fuel-cell-train-market (accessed March 7, 2024).
[206] Manoharan Y, Hosseini SE, Butler B, Alzhahrani H, Senior BTF, Ashuri T, et al. Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect. Appl Sci 2019;9:2296. https://doi.org/10.3390/app9112296.
[207] Madhav D, Wang J, Keloth R, Mus J, Buysschaert F, Vandeginste V. A Review of Proton Exchange Membrane Degradation Pathways, Mechanisms, and Mitigation Strategies in a Fuel Cell. Energies 2024;17:998. https://doi.org/10.3390/en17050998.
[208] ISO (International Organization for Standardization). ISO 14687:2019. ISO n.d. https://www.iso.org/standard/69539.html (accessed March 7, 2024).
[209] Kelechava B. CGA G-5.3-2017: Commodity Specification For Hydrogen - 7th Edition. ANSI Blog 2018. https://blog.ansi.org/2018/01/cga-g-53-2017-commodity-specification-hydrogen/ (accessed February 29, 2024).
[210] Di Serio M, Turco R, Vitiello R, Tesser R. Biofuels Characterization and Standard Methods for Quality Control. In: Riazi MR, Chiaramonti D, editors. Biofuels Prod. Process. Technol., CRC Press; 2017, p. 183–98.
[211] Fruhwirt D, Sturm P, Bucca G, Bode G, Michael S, Rodler J. Emissions from railways: Results of tests on a pantograph-catenary test bench. Transp Res Part Transp Environ 2023;117:103667. https://doi.org/10.1016/j.trd.2023.103667.
[212] Fridell E, Björk A, Ferm M, Ekberg A. On-Board Measurements of Particulate Matter Emissions from a Passenger Train. Proc Inst Mech Eng Part F J Rail Rapid Transit 2011;225:99–106. https://doi.org/10.1177/09544097JRRT407.
[213] Fridell E, Ferm M, Ekberg A. Emissions of particulate matters from railways – Emission factors and condition monitoring. Transp Res Part Transp Environ 2010;15:240–5. https://doi.org/10.1016/j.trd.2010.02.006.
[214] Lee H. Generation of airborne wear particles from the wheel–rail contact under wet conditions using a twin-disk rig. Wear 2020;448–449:203236. https://doi.org/10.1016/j.wear.2020.203236.

[215] Cha Y, Olofsson U, Gustafsson M, Johansson C. On particulate emissions from moving trains in a tunnel environment. Transp Res Part Transp Environ 2018;59:35–45. https://doi.org/10.1016/j.trd.2017.12.016.
[216] Fruhwirt D, Sturm P, Nöst T, Leonhardt P, Bode G, Michael S, et al. PM emissions from railways – Results of tests on a wheel-rail test bench. Transp Res Part Transp Environ 2023;122:103858. https://doi.org/10.1016/j.trd.2023.103858.
[217] Lorenzo R, Kaegi R, Gehrig R, Grobéty B. Particle emissions of a railway line determined by detailed single particle analysis. Atmos Environ 2006;40:7831–41. https://doi.org/10.1016/j.atmosenv.2006.07.026.
[218] Gehrig R, Hill M, Lienemann P, Zwicky CN, Bukowiecki N, Weingartner E, et al. Contribution of railway traffic to local PM10 concentrations in Switzerland. Atmos Environ 2007;41:923–33. https://doi.org/10.1016/j.atmosenv.2006.09.021.
[219] Lee H, Namgung H-G, Kwon S-B. Effect of train velocity on the amount of airborne wear particles generated from wheel–rail contacts. Wear 2018;414–415:296–302. https://doi.org/10.1016/j.wear.2018.08.023.
[220] Bukowiecki N, Gehrig R, Hill M, Lienemann P, Zwicky CN, Buchmann B, et al. Iron, manganese and copper emitted by cargo and passenger trains in Zürich (Switzerland): Size-segregated mass concentrations in ambient air. Atmos Environ 2007;41:878–89. https://doi.org/10.1016/j.atmosenv.2006.07.045.
[221] Johnson GR, Jayaratne ER, Lau J, Thomas V, Juwono AM, Kitchen B, et al. Remote measurement of diesel locomotive emission factors and particle size distributions. Atmos Environ 2013;81:148–57. https://doi.org/10.1016/j.atmosenv.2013.09.019.
[222] Landgraf M, Zeiner M, Knabl D, Corman F. Environmental impacts and associated costs of railway turnouts based on Austrian data. Transp Res Part Transp Environ 2022;103:103168. https://doi.org/10.1016/j.trd.2021.103168.
[223] Park D-U, Ha K-C. Characteristics of PM10, PM2.5, CO2 and CO monitored in interiors and platforms of subway train in Seoul, Korea. Environ Int 2008;34:629–34. https://doi.org/10.1016/j.envint.2007.12.007.
[224] Amarachi N, Emeka O, Christopher A, Lovell A, Conrad E. Emissions of Gasoline Combustion by Products in Automotive Exhausts. Int J Sci Res Publ 2016;6.
[225] International Energy Agency (IEA). Railway Handbook 2015 - Energy Consumption and CO2 Emissions. IEA 2015. https://www.iea.org/reports/railway-handbook-2015 (accessed March 27, 2024).
[226] Maljaee SS, Khadem Sameni M, Ahmadi M. Effects of railway noise and vibrations on dissatisfaction of residents: case study of Iran. Environ Dev Sustain 2024;26:2655–85. https://doi.org/10.1007/s10668-022-02718-4.
[227] Wrótny M, Bohatkiewicz J. Impact of Railway Noise on People Based on Strategic Acoustic Maps. Sustainability 2020;12:5637. https://doi.org/10.3390/su12145637.
[228] Smith MG, Croy I, Hammar O, Persson Waye K. Vibration from freight trains fragments sleep: A polysomnographic study. Sci Rep 2016;6:24717. https://doi.org/10.1038/srep24717.
[229] Carl E. Hanson, David A. Towers, Lance D. Meister. Transit Noise and Vibration Impact Assessment: 2006 - Federal Transit Administration 2006. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/FTA_Noise_and_Vibration_Manual.pdf (accessed March 27, 2024).
[230] Office des transports du Canada. Plaintes et différends en matière de transport ferroviaire 2017. https://otc-cta.gc.ca/fra/plaintes-et-differends-matiere-transport-ferroviaire (accessed March 19, 2024).
[231] Office des transports du Canada. Méthodologie de mesure et de présentation d’un rapport sur le bruit ferroviaire 2011. https://otc-cta.gc.ca/fra/mesure_bruit_ferroviaire (accessed March 19, 2024).
[232] Comment agissons-nous pour réduire le bruit ferroviaire ? | SNCF Réseau n.d. https://www.sncf-reseau.com/fr/developpement-durable/bruit-ferroviaire (accessed March 19, 2024).

[233] Wiłkomirski B, Sudnik-Wójcikowska B, Galera H, Wierzbicka M, Malawska M. Railway transportation as a serious source of organic and inorganic pollution. Water Air Soil Pollut 2011;218:333–45. https://doi.org/10.1007/s11270-010-0645-0.
[234] Lucas PS, de Carvalho RG, Grilo C. Railway Disturbances on Wildlife: Types, Effects, and Mitigation Measures. In: Borda-de-Água L, Barrientos R, Beja P, Pereira HM, editors. Railw. Ecol., Cham: Springer International Publishing; 2017, p. 81–99. https://doi.org/10.1007/978-3-319-57496-7_6.
[235] Levengood JM, Heske EJ, Wilkins PM, Scott JW. Polyaromatic hydrocarbons and elements in sediments associated with a suburban railway. Environ Monit Assess 2015;187:534. https://doi.org/10.1007/s10661-015-4757-2.
[236] Pereira HM, Navarro LM, Martins IS. Global Biodiversity Change: The Bad, the Good, and the Unknown. Annu Rev Environ Resour 2012;37:25–50. https://doi.org/10.1146/annurev-environ-042911-093511.
[237] Maua J. V.A. PROFILLIDIS - RAILWAY MANAGEMENT AND ENGINEERING. n.d.