Hydrogen Fuel Cell Locomotive Retrofit Feasibility Study

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March 21, 2024

Table of Contents

1 Abstract

This study evaluates the practicality of retrofitting existing diesel locomotives with hydrogen fuel cell (HFC) technology in Alberta. It explores the technical feasibility, potential modifications, performance, and efficiency of HFC locomotives, alongside a comprehensive cost analysis. The study includes case studies from Pau, France, and Foshan, China, showcasing successful implementations of HFC technology in public transport. It also examines the environmental benefits, such as significant reductions in greenhouse gas emissions, and the potential for utilizing renewable energy sources in Alberta for hydrogen production. The report further discusses the safety and risk analysis of HFC locomotives, regulatory frameworks, and potential adoption barriers. Concluding with recommendations, the study underscores the importance of developing a supportive policy environment and infrastructure to facilitate the transition to hydrogen-powered rail transport, aiming for a sustainable and zero-emission future in the rail industry.

2 Introduction

Hydrogen fuel cell technology has spurred the interest in sustainable transport solutions as a viable alternative to traditional diesel-powered locomotives. With growing concerns about climate change and the environment, there is a crucial need to explore cleaner and more efficient modes of transportation to achieve net-zero emissions. Hydrogen-powered locomotives offer a promising pathway towards achieving these objectives due to their clean and efficient energy attributes.

The Hydrogen Fuel Cell Retrofitted Locomotive Project is led by Integrated Travel, a non-profit organization dedicated to addressing the needs of regional rail passengers. This report presents an in-depth analysis of the feasibility of integrating hydrogen fuel cell (HFC) technology into rail transport, alongside an assessment of the necessary capital investments for hydrogen-powered locomotives. With a focus on Alberta's rail infrastructure, the project aims to identify and quantify the societal, economic, and environmental benefits associated with retrofitting existing rail infrastructure with hydrogen-powered fuel cells.

3 Evaluation of Technical Feasibility

3.1 Fuel Cell Compatibility in Locomotives

3.1.1 Case Study: Ballard in Pau, France

The Pau-Béarn-Pyrénées urban community in France has had an Air Energy Climate Plan since 2016 that promotes and implements zero-emission public transport opportunities to transform the city's public space (Ballard Power, 2017). Both Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs) were evaluated. A customer analysis determined that fewer FCEBs would service the same bus routes than BEBs, as depot charging 8 FCEBs does the same job as on route fueling 10 BEBs and overnight fueling 14 BEBs. This could provide leads into H_2 fuel cell cost efficiency and engine longevity, giving insight into the practicality of retrofitting H_2 fuel cell-powered engines into diesel engine locomotives.

Table 1 Details on the Zero Emission Project with FCEBs in Pau, France (Ballard Power, 2017)

Site	**Pau-Béarn-Pyrénées, France**
System	100 kW FCveloCity®-HD fuel cell integrated into Van Hool tram-buses
Fuel	Green hydrogen provided by GENVERT (ENGIE subsidiary) using ITM electrolyzer
Objectives	Replace diesel buses with a zero-emission alternative
Refuelling time	Night refuelling, 30 minutes

The case study confirms that the 8 FCEB fleet has travelled over 200,000 km to date, marking it a success. The customer analysis from this case study confirms that H_2 fuel cell-powered engines are more power efficient than battery-electric trams.

3.1.2 Case Study: Ballard in Foshan, China

Foshan, China, has established itself as a trailblazer in the hydrogen industry by introducing the world's first commercial fuel cell-powered tram line (Ballard Power, 2021). This initiative involved a fleet of five trams, four of which are operational and one held in reserve, which underwent approximately two years of research and development. These trams are equipped with Ballard FCveloCity®-XD fuel cell modules, and since their launch, they have been operating successfully.

The technology behind these trams is a synergy between hydrogen fuel cells and large-capacity lithium titanate batteries, which together drive the trams without any emissions.

The only byproducts released during operation are water and heat, making it an environmentally friendly solution. The trams feature an advanced hydrogen storage and heat dissipation system that enhances their hydrogen capacity and extends their cruising range. Remarkably, refuelling the trams is a quick process, taking only fifteen minutes to refill the six 35MPa 140-litre hydrogen storage cylinders, providing twenty kilograms of hydrogen that allow for a range of 125 kilometres. This efficient refuelling process, coupled with the trams' zero-emission operation, marks a significant achievement in sustainable urban transportation.

Table 2. Details on the commercial H_2 fuel cell tram project in Foshan, China (Ballard Power, 2021)

Site	Gaoming District, Foshan City, China
System	Ballard FCveloCity®-XD, 200kW
Hydrogen Consumption	25-30kg/100km

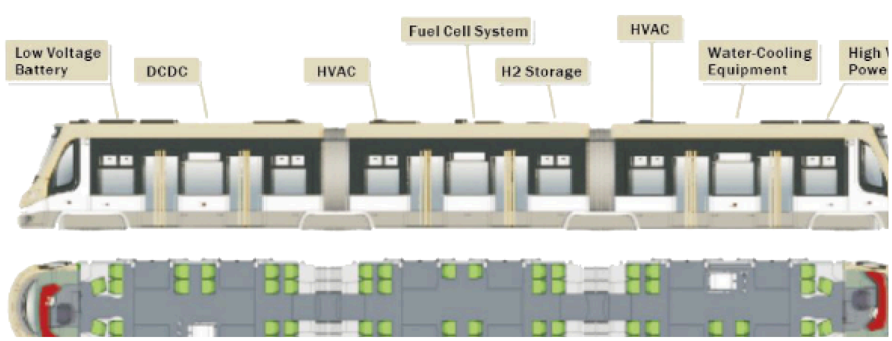


Figure 1. Diagram of the commercial H_2 fuel cell tram project in Foshan, China (Ballard Power, 2021)

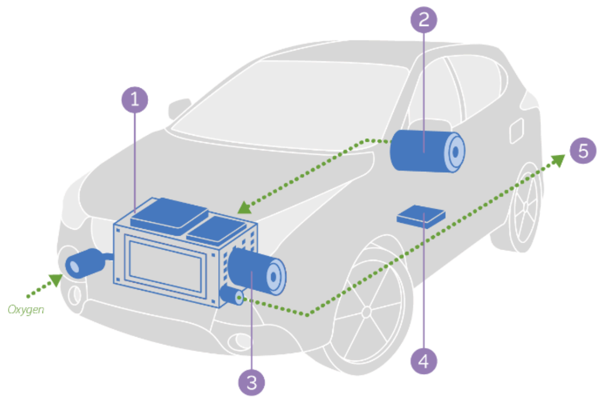
Configuration	3 coaches 2 locomotives	Max Passenger Capacity	360 people	Daily Operation	13 hours
Vehicle Size	35.19m x 2.65m x 3.58m	Max Speed	70km/hour	Refueling Events	2-3 times/day
Vehicle Mass	55 tons	Max Range	125km	Refueling Time	15 minutes

Figure 2. Operational details of the commercial H_2 fuel cell tram project in Foshan, China (Ballard Power, 2021)

Depending on the function, physical and technical requirements of the diesel engine locomotives, operational time, refuelling time and frequency, speed, and max range are all variables dependent on power output.

3.1.3 Understanding the Hydrogen Fuel Cell

The operational capacity of an engine largely depends on engine ‘power’. Thus far, power has been a loosely defined term to describe engines. How ‘powerful’ an engine is depends on the power and torque ratings of the engine. For example, for cars, a horsepower rating is how much power the engine is theoretically capable of outputting. However, every engine has a torque rating as well. The greater the torque an engine is capable of producing, the greater the power it’s able to produce as well (Testbook, 2023). How much torque is produced depends on how much RPM (rotations per minute) the engine can produce. This is the area where engine types differ; electric motors and diesel engines, for example, produce RPMs in fundamentally different ways. As such, for similar production cars with ICE engines, for example, a range between 800 to 7000 RPM can be produced. Electric motors can reach peak torque at zero RPM and around 20,000 RPM safely. Hydrogen fuel cell technology incorporates electric motors, but not in the same way battery-run vehicles use them (DriveClean). The following diagram helps to describe how a hydrogen fuel cell engine works in cars.



1. **Fuel Cell Stack** – An aggregate of numerous fuel cells that combine oxygen and hydrogen to generate electricity and power the electric motor
2. **Fuel Tank** – Hydrogen gas is stored in carbon-fiber reinforced tanks to provide fuel to the fuel-cell stack
3. **Electric Motor** – Powers the car using energy produced in the fuel cell stack
4. **Battery** – Captures energy from regenerative braking and provides additional power to the electric motor
5. **Exhaust** – The byproduct of the reaction occurring in the fuel cell stack is water vapor, which is emitted through the exhaust

Figure 3. How an automobile's hydrogen fuel cell engine operates (DriveClean).

As oxygen gas is abundant in the atmosphere, an electric motor's performance depends on

1. Amount of H_2 stored in the fuel tank; the hydrogen tank empties, and the car would stop running as there's no more hydrogen gas for the fuel cell to generate electricity from. Therefore, how long a hydrogen fuel cell car would run depends on
    a. Fuel cell production rate; the faster the fuel cell consumes hydrogen gas and generates electricity, the faster the fuel tank depletes, reducing the vehicle's operational time.
    b. Motor efficiency; the more efficient the power consumption is of the car, the less hydrogen gas would be consumed, and operational time would increase.
2. Electric motor's power and torque rating; the higher the engine's hp and motor torque rating, the more power it is capable of producing.

A side-by-side engine comparison of gas and diesel engines and electric motors reveals the latter is more capable of producing greater power and torque on less RPM. This makes electric motors a suitable replacement for diesel engines. Hydrogen fuel cell technology incorporates electric motors to power the vehicle. The power requirements of suitable locomotives will dictate hydrogen power consumption, and ultimately determine a suitable size for hydrogen fuel tanks inside the locomotive, as well as operational run time, and refuelling frequency. All engines of the same type can be retrofitted in different vehicles by adjusting power output and consumption settings as required.

3.2 Identifying Potential Modifications Required

3.2.1 Potential Design and Control Issues

A study on the design and control issues of retrofitting H_2 fuel cell technology in diesel locomotives has been conducted (Bartolucci, 2022).

A diesel shunting locomotive serves the purpose of transporting wagons or coaches between different locations within a rail yard. This creates a complete assembly for freight locomotives and for the addition and removal of coaches for travellers at stations. The power consumption for diesel shunting locomotives is less than that of conventional diesel locomotives used for commercial travel. However, this will provide a basis for possible modifications needed to integrate fuel cell technology into locomotives.

The power required by the engine is split between the fuel cells and batteries. The locomotive's powertrain will be analyzed, which consists of all the individual components responsible for operating the locomotive. The diesel engine is a key component of the locomotive's powertrain. Different fuel cell powertrain configurations can affect performance, power output and efficiency, so the best one must be chosen to ensure the project is as financially sustainable as possible.

A key consideration is the hydrogen fuel cell system's operating temperature, as it can greatly impact the powertrain's performance. A cooling system must be designed to size the rest of the powertrain's components and increase the system's efficiency.

A PID controller is a device used in industrial control systems to regulate process variables such as temperature, flow, pressure, and speed (Omega Engineering). This instrument can be used to ensure the fuel cell system's temperature is regulated. Design constraints will be specified by the manufacturer's recommendations/guidelines and for the locomotive corridors of focus.

The lithium-ion battery is a family of high-density rechargeable batteries. This type of accumulator does not require any maintenance activity. It is characterized by high efficiency and relatively low charging time. Hence lithium-ion batteries could be a strong economical battery option for the locomotive's powertrain.

The electric motor that has been selected for the application to work also as an electric generator, thus allowing the implementation of regenerative braking.

With the increasing hybridization of vehicles, the alternative power source typically already includes a second propulsion component as well as an additional energy storage device (Tawadrosi et al, 2014). These components can be configured to store or expend energy, making regenerative braking a ‘free’ addition. Regenerative braking systems are designed to recover energy that would be otherwise dissipated during a braking event. Equipping electric motors with an electric generator as an energy recovery mechanism seems like a strong option for locomotives.

The following images illustrate the design differences between a diesel engine and a fuel cell locomotive.

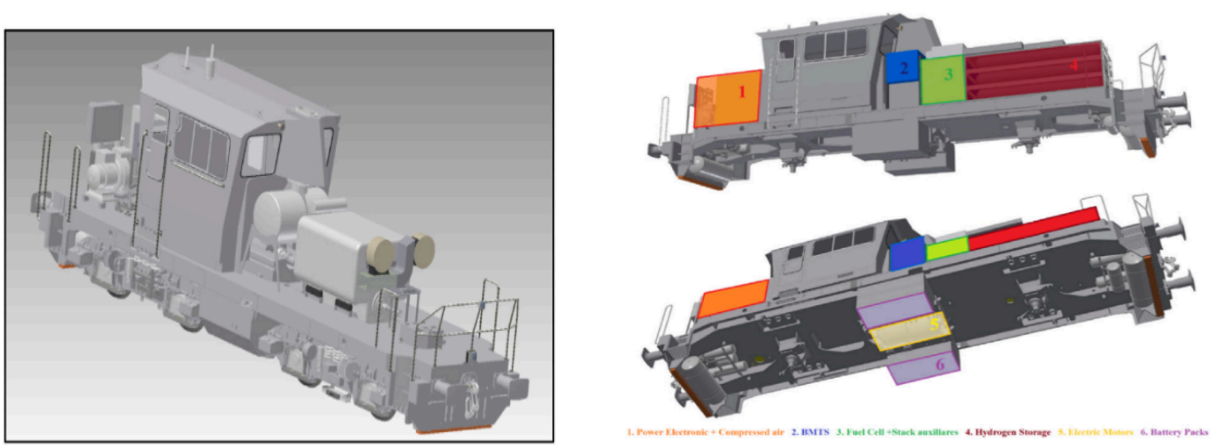


Figure 4. Design differences between a diesel locomotive (left) and HFC locomotive (right) (Bartolucci, 2022).

The two electric motors replace the diesel tank, and the hydrogen storage is located where the diesel engine was situated. The structure does not allow the confinement of leaked hydrogen to decrease the possibility of detonation. Battery packs can be housed under the chassis of the locomotive. The fuel cell stack system with all necessary auxiliaries is placed in the front compartment, while the air compressor as well as the power electronics are housed in the rear of the locomotive. Two separate fuel cell configurations were studied, with the control variable being the number of fuel cell stacks. It was found that fuel cells operated at 100% capacity, increase the amount of fuel cell waste heat emitted, and that is inversely proportional to the fuel stack efficiency. Two fuel cell stacks operating at 50% capacity were found to consume 37% less hydrogen than just one operating at 100%. The amount of greenhouse gas emissions for a hydrogen-fueled powertrain depends on the hydrogen production technology, so the one that produces zero greenhouse gases must be considered in line with this project's zero-emission goal. Water electrolysis, for example, produces hydrogen by applying a direct electric current to water to dissociate it. If the electricity needed is supplied from renewable sources, water electrolysis may obtain large amounts of hydrogen without the emission of greenhouse gases. In this way, the countries with a large excess amount of electrical energy from renewable sources may produce the so-called green hydrogen. As such, barriers to renewable energy in Alberta must be studied.

3.2.2 Optimal Battery and HFC Sizing in Heavy-Haul Locomotives

Data was collected from diesel-electric locomotives operated by Aurizon on Australia's freight rail networks (Knibbe et al, 2023). This study can provide better insight into HFC and battery sizing for heavy-haul locomotives, an analysis better suited for commercial locomotive operation in Alberta's rail network. PEMFCs and SOFCs present the most viable options for use in locomotives. The former, Proton-exchange membrane fuel cells, has been analyzed in the previous paper. PEMFCs operate at low temperatures (~80 ◦C) and require simple manufacturing processes so are currently dominating the HFC market. Among the different lithium-ion battery chemistries available, The NMC battery chemistry is an attractive option from an energy density perspective. However, when considering the battery life cycle costs, NMC is the least favourable due to its relatively short cycle life. Although LTO has excellent cycling stability, the relatively high upfront cost of LTO batteries makes the system very expensive. As a compromise, the LFP battery chemistry was considered the most suitable option, as it combines both relatively good cycling stability and low cost (Knibbe et al, 2022). The degradation aspect of PEMFC should be considered. There isn't conclusive data on the degradation of PEMFCs. A battery with a higher energy density should buffer the PEMFCs' transient operations, but not fully. As such, PEMFCs would have a lifespan.

3.2.3 A Closer Look at Locomotive Battery Considerations

The most popular commercial LIB active materials are lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), lithium nickel cobalt aluminum oxide (NCA), lithium manganese oxide (LMO), graphite and lithium titanium oxide (LTO). The electrodes (cathode and anode) contain active material that stores lithium. These active materials can behave in fundamentally different ways which impact cell energy density, power, lifespan, cost, and safety. Refer to Figure 5 to understand how each battery chemistry performs in different categories. The LFP seems to be the most viable option for lithium-ion batteries in the locomotive.

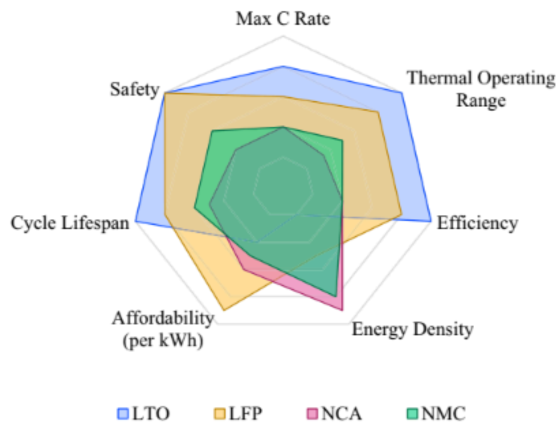


Figure 5. The diagram above shows a comparison of different electrode active materials. The values in each category indicate their performance, with larger values indicating better performance. NCA (pink) and NMC (green) chemistries have similar performance in multiple categories. LTO (blue) performs quite strongly overall but has poor energy density and affordability. On the other hand, LFP (yellow) has good overall performance and is the most affordable per kWh compared to the other chemistries (Knibbe et al, 2022).

3.3 Performance and Efficiency

Fuel cells have a high efficiency; a theoretical efficiency of about 90% and a practical efficiency of less than 60%, which is still greater than combustion engines which have an efficiency of about 40% in optimum conditions. Unlike batteries, fuel cells provide continuous power as long as fuel and oxidant are supplied, without recharging. This uninterrupted power supply is crucial for locomotives, where reliability is essential. The heat produced in fuel cell reactions can be used in combined heat and power (CHP) systems, increasing overall efficiency to over 85%. This is advantageous for locomotive applications where waste heat can be effectively utilized. There are six common types of fuel cells, each with its own efficiency and operating parameters. For instance, Polymer Electrolyte Membrane (PEM) fuel cells operate at around 80°C, offering efficiency between 40-50%, making them suitable for various applications due to their high power density and reliability. Molten Carbonate fuel cells operate at higher temperatures of 650-700°C, with efficiency ranging from 60-80%, but require CO_2 injection, adding to costs. Solid Oxide fuel cells, mostly used in large power plants, have an efficiency of around 60% and operate at temperatures of 1000°C. Alkaline fuel cells operate at temperatures of 150-200°C with an efficiency of about 70% but use expensive platinum electrode catalysts. Phosphoric fuel cells, with an efficiency range of 50-80%, can tolerate carbon monoxide concentrations and use platinum electrode catalysts. Therefore, the best type of fuel cell to use is PEM since they are used in the transport sector and are the leading users of fuel cell technology (Kabeyi & Olanrewaju, 2023).

3.4 Hydrogen Storage

Hydrogen can be stored above ground as a compressed gas in high-pressure cylinders/tanks, but it can also be stored underground in salt caverns, depleted oil/gas reservoirs, and aquifers for technical and economical viability (Hydrogen Strategy for Canada 2020). The most common way to store hydrogen in large quantities is in salt caverns where hydrogen can be stored at extremely high pressures with a sufficient deep salt layer. Currently, Canada does not have underground hydrogen storage facilities but it has been successful in the US (Kauling et al., 2024).

4 Cost Analysis

4.1 Common Canadian Diesel Locomotive Models

The *EMD GP38* is a versatile locomotive model that has been used in various regions, including Alberta, for both freight and passenger service (Bachand, 2006).

- 2000 horsepower
- 65 mph speed
- 800/275 max/min RPM

The *EMD SD40* is another popular model used in Alberta for freight trains (Bachand, 2006).

- 3000 horsepower
- 65 mph speed
- 900/315 max/min RPM

The *GE Dash 8* series, particularly the Dash 8-40CW, has been used by the Canadian National Railway (CN) and Canadian Pacific Railway (CP) in Alberta for freight service (Bachand, 2006).

- 4000 horsepower
- 70 mph speed
- 1050/450 max/min RPM

The GE Dash 9 series is an updated version of the Dash 8 and has also been used in Alberta for freight service (Bachand, 2010).

- 4400 horsepower
- 74 mph speed
- 1050/450 max/min RPM

The GE AC4400CW: This is a more powerful locomotive model that has been used by both CN and CP in Alberta for hauling heavy freight trains (Bachand, 2010).

- 4400 horsepower
- 70 mph speed
- 1050/450 max/min RPM

4.2 Potential Hydrogen Fuel Cell Suppliers

4.2.1 Ballard Power Systems

Based in Vancouver, Canada, Ballard's FCmove™-XD fuel cell power module operates in frigid temperatures as low as -30°C without special start procedures. Safety features include an IP6K9K-rated enclosure, a high-pressure system, and remote diagnostics. The compact design allows engine bay mounting, scalable up to 360kW. With over 25,000 hours of operation, the FCmove™-XD is reliable and ensures low total cost of ownership and high efficiency for extended driving ranges.

Table 3. Details on the different FC power systems available at Ballard (Ballard Power).

Product Series	FCmove®-XD	FCmove®- HD+	FCmove®-HD	FCmove®-MD
Net Power Level	120kW	100kW	70kW	45kW
Application	heavy duty applications	medium & heavy duty applications	medium duty applications	light & medium duty motive applications

4.2.2 Accelera

Formerly known as Hydrogenics, Accelera is a Canadian company based in Mississauga (Accelera). Accelera's fuel cell systems, mounted on train roofs, combine hydrogen and oxygen to power electric motors, emitting only water vapour. This enables 18+ operational hours between refuelling, fast refuelling times, and lower maintenance, transforming non-electrified railway lines into eco-friendly routes without extensive infrastructure changes.

4.2.3 Loop Energy

Table 4. Details of the different FC power systems available at Loop Energy (Loop Energy, 2023).

Model	Net Rated Power (kW)	Net Cruise Mode Operating Efficiency (%)	Combined Heat & Power Output (CHP) (kW)	Net System (CHP) Efficiency at Cruise Mode (%)	Combined Weight (kg)
S300-S	27	53	36	69	200
T505-S	47	50	62	69	290
T605-S	56	52	76	70	305
S1200	100 (peak: 120)	50-60 (across a wide operating range)	125	65-68 (across a wide operating range)	410

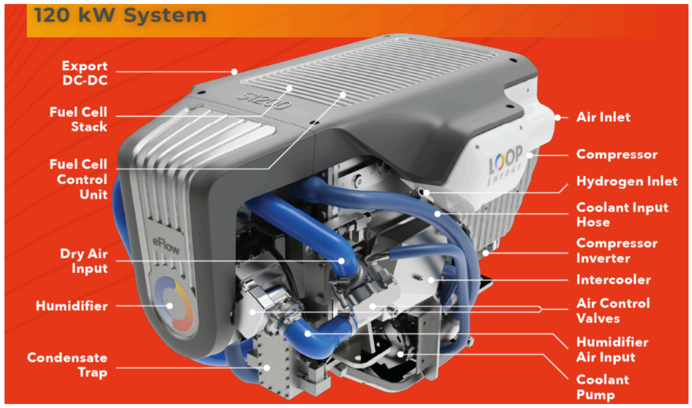


Figure 3. Details on the 120 kW system from Loop Energy (Loop Energy, 2023).

4.2.4 Nuvera Fuel Cells

Nuvera Fuel Cells is a company based in the United States with a great presence on train travel in Canada.

Table 5. Details on the different FC power systems that are available at Nuvera (Nuvera, 2023).

Parameter	Specifications	
Model	E-45-HD	E-60-HD
Gross output power	53 kW	67 kW
Net output power	45 kW	59 kW*
Operating voltage	170–290 VDC	175–290 VDC
Maximum operating current	312.5 A	375 A
Peak efficiency	58%	-

4.3 Maintenance and Capital Costs of Diesel Locomotives

The average maintenance cost for diesel-electric locomotives in 1975 was $30,948 per unit (Ephraim, 1977). Specific railroads may have higher costs due to factors like average distance travelled and the type of operations conducted. A detailed cost breakdown for a typical turbocharged, six-axle 2.24-MW locomotive shows major categories like the engine, lube oil, electrical, and running gear, with the total annual maintenance cost being $42,700. While electric locomotives have higher initial capital costs, their maintenance costs and life expectancy are comparable to diesel-electric locomotives, both expected to be around 25 years.

4.4 PEMFC Fuel Cell Cost Analysis

The cost analysis began with a technology assessment leading to a bill-of-materials (BOM) for the system (Carlson, 2005). Bottom-up costing methods were employed for stack components, while BOP components' costs were obtained from suppliers or estimated based on similar technologies. Sensitivity and Monte Carlo analyses were used to identify key cost drivers and estimate uncertainties. A critical design decision that affects performance, cost, and efficiency. The 2005 project used a cell voltage of 0.65 volts to reduce stack size and cost. The cost of platinum significantly impacts the stack and system cost. The analysis used a baseline platinum price while also exploring the effects of price fluctuations. These parameters drive the cost and size of the stack. Technological advancements have led to reduced platinum loadings and increased power density, resulting in cost reductions. The overall cost for the PEM fuel cell system was assessed at $108/kW, with the stack contributing 63% ($67/kW) and the BOP and assembly contributing 37% ($41/kW). The air management system, particularly the compressor-expander module (CEM), represented the largest share of the BOP cost. The 2005 PEM fuel cell system meets the DOE cost target but falls short of the efficiency targets. The decision to use a lower cell voltage for cost reduction resulted in a slight compromise on efficiency.

The study concludes that while significant progress has been made in reducing costs, further attention to BOP components and system simplification is necessary to meet long-term targets. The balance between platinum supply and demand will be a determining factor in future cost projections.

4.5 Fuel Cell System Production Cost Analysis

The study developed a cost calculation model for PEM fuel cell systems using the Process Based Cost Modeling (PBCM) approach (Kampker et al., 2022). It highlighted that to achieve market penetration, significant cost reductions are necessary, which requires changes in production technologies. The research identified that economies of scale in fuel cell system production are currently only realized at low production volumes. The cost modelling showed a sharp decrease in production costs between 500 and 2,500 systems per year, with costs stabilizing above this level. A detailed analysis using a Mekko diagram and process chain costs was conducted to pinpoint where the highest costs occur and which technologies need changes. Material costs, particularly for the Membrane Electrode Assembly (MEA) and system production, were found to be the dominant factors in overall fuel cell system costs. The paper also presented a sensitivity analysis to determine the influence of various production parameters on the list price. This analysis helps in identifying the most impactful parameters for cost reduction and guides the optimization or redesign of the fuel cell system production.

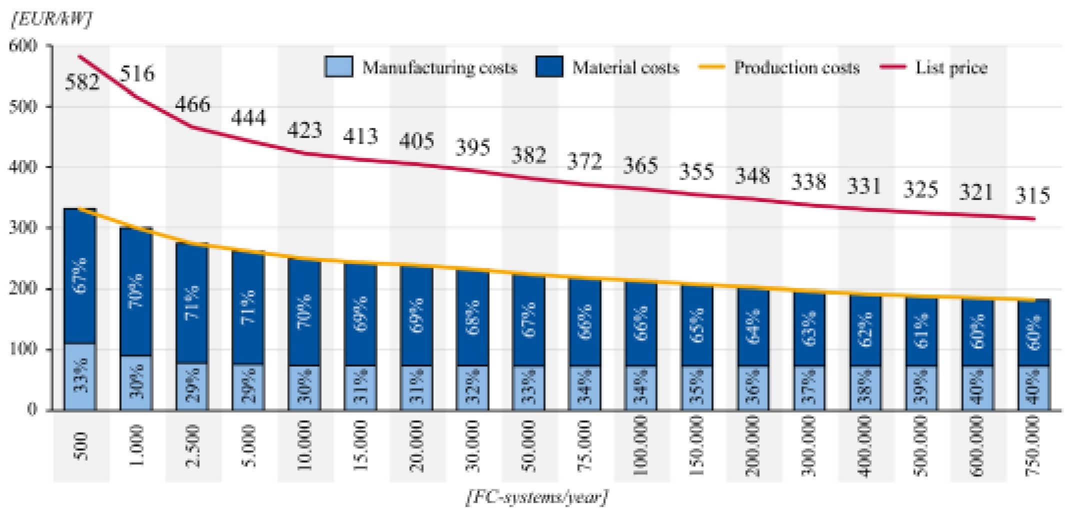


Figure 4. The cost of FC systems depends on the annual number of units produced. (Kampker et al., 2022)

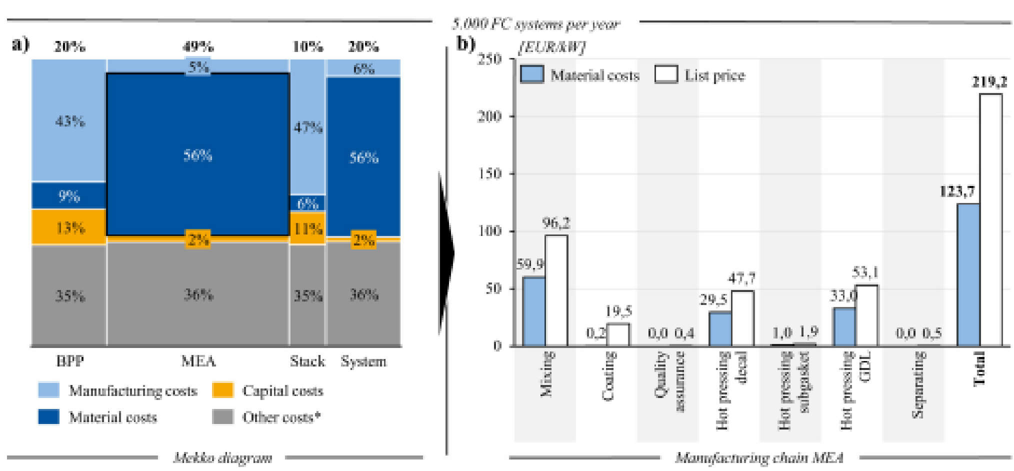


Figure 5. Mekko diagram showing cost distribution along fuel cell components and cost types (left), distribution of list price and material costs along the fuel cell value chain (right) (Kampker et al., 2022)

5 Greenhouse Gas Emissions Analysis

5.1 Hydrogen-Powered Trains vs Diesel-Powered Trains

The comparison between retrofitted trains powered by hydrogen fuel cells and traditional diesel-powered trains were compared using the Coradia iLint which is a hydrogen-powered version of the Coradia Lint 54 as an example. This is shown in the table below (Kumbhar, 2023):

Table 6. Comparison between hydrogen-powered trains and diesel-powered trains

	Coradia iLint (Hydrogen Fuel Cell)	**Coradia Lint 54 (Diesel Engine)**
Maximum Power output	400 kW (per trainset)	315-390 kW (per trainset)
Energy storage	Lithium-ion batteries	Direct power from diesel
Emissions	No carbon emissions, water vapour is a by-product since hydrogen fuel cell technology generates electrical power through an electrochemical oxidation process.	Carbon emissions which impact climate change

	Positive impact on air quality by eliminating emissions of air pollutants	
Noise pollution	Quiet during operations	It is deafening and leads to noise pollution
Greenhouse gas emissions	Zero emissions	CO2 emissions
Air pollution	Zero emissions	NOx, PM, SO2 emissions
Sustainability	Lower carbon footprints and zero carbon footprint during operation	High carbon footprints
Overall environmental impact	Low to zero impact on the environment	High negative impact on the environment

5.2 Hydrogen Gas Production Life Cycle Assessment

5.2.1 SMR Using Natural Gas Hydrogen Production Pathway

The steam methane reforming (SMR) process is a widely used hydrogen production method (Gonzales-Calienes et al., 2022). In the life cycle impact assessment (LCIA) phase, ISO:14067:2018 (ISO, 2018) and ISO:14044:2006 (ISO, 2006b) methods are applied. These methods help to calculate the potential carbon intensity of each hydrogen production pathway chosen. To determine the impact of each GHG emitted and removed by the hydrogen production system, the mass of GHG released or taken out is multiplied by the 100-year GWP. The sum of these calculated climate change impacts gives us the carbon intensity. Open-source software openLCA 1.11.0 © developed by Green Delta is used to calculate the aggregated climate change impacts related to SMR hydrogen production using natural gas. IPCC 2013 is the impact method used to calculate the individual emission flows. The carbon intensity of the SMR pathway is calculated to be 12.08 kgCO2e/kg hydrogen. Figure 6 shows the life cycle GHG emissions of the steam methane reforming pathway from the main input flows to the SMR system boundary. The direct GHG emissions from off-gases of LO_CAT© and PSA processes contribute 86.5% of the total CI of the SMR pathway. The life cycle GHG emissions from the electricity consumption in the SMR process and utility natural gas demand as SMR feedstock and input flow for steam production represent 7.3% and 6.2% of the total life cycle emissions, respectively.

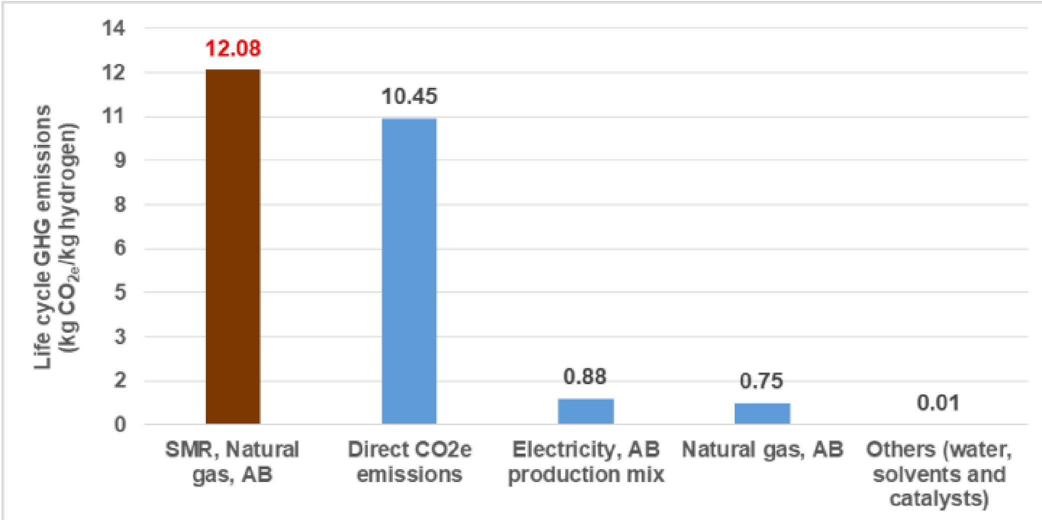


Figure 6. Life cycle climate change impacts of hydrogen production using steam methane reforming process with natural gas as feedstock. (Gonzales-Calienes et al., 2022)

Emissions resulting from electricity production and transmission in the Alberta electricity system account for emissions from a generation mix that depends mostly on fossil fuel sources. Electricity production from lignite, natural gas, and oil represents 4.1%, 2.5%, and 0.4% of total life cycle GHG emissions of the SMR pathways in Alberta, respectively (as shown in Figure 7). The shares of electricity technologies in this market are valid for the year 2020. Carbon dioxide equivalent emissions from natural gas extraction, production, and transportation represent 1.1%, 1.6%, and 2.8% of the total CI of the SMR pathway in Alberta, respectively (Figure 7).

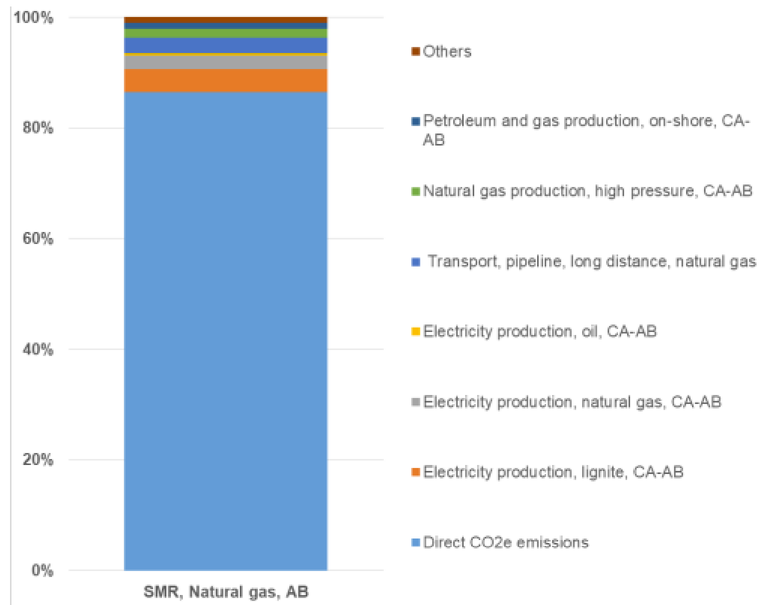


Figure 7. Share of life cycle climate change impacts for SMR pathway, natural gas, AB. (Hardman et al., 2017)

5.2.2 Alkaline Electrolysis Hydrogen Production Pathway

To shift from traditional steam methane reforming (SMR) generated hydrogen to low carbon intensity hydrogen, a hypothetical alkaline electrolysis (AEC) plant is needed. This plant must have a large hydrogen production unit that can scale up to hundreds of MW. This is much larger than most existing industrial electrolyzer demonstration plants, which are typically at kW or a few MW. The electrolysis unit in a large-scale plant is commonly installed in modular configurations. This enables easy installation and flexible operation according to demand. The hypothetical AEC plant in this study has a hydrogen production rate of 146.8 tonne/day, which is the same as that from the SMR process shown in Section 6, providing 24-hour operation per day.

The same criteria used for the SMR case are applied to perform LCIA. The carbon intensity of the alkaline electrolysis hydrogen production pathway is calculated as 1.37 kg

$CO2e$/kg H_2. Figure 8 indicates the life cycle GHG emissions of the alkaline electrolysis pathway from the main input flows to the AEC system boundary. Figure 9 illustrates the contribution of feedstock and other materials input flows to the overall life cycle climate change impact of the AEC pathway. Life cycle GHG emissions of electricity from the QC electricity grid system represent 99% of the total CI of the AEC pathway. The remaining 1% is mostly related to the steam and KOH electrolyte solution input flows. Electricity demand for the electrolyzer stack usage represents 97% of total electricity input. Emissions due to the consumption of electricity production and transmission in the Quebec electricity system account for emissions from the Quebec electricity generation mix, electricity imports, and electricity transmission. Greenhouse gas nitrous oxide formation due to ionization of air molecules and transmission grid losses represent 53% and 12%, respectively. Meanwhile, electricity imports account for 34% of the total emissions. The shares of electricity technologies in this market are valid for the year 2019.

Figure 10 shows the breakdown of carbon intensities from renewable sources in the AEC pathway in QC. Emissions from renewable sources represent 86% of the total carbon intensity of the alkaline electrolysis pathway to produce hydrogen in Quebec, Canada. Emissions from hydroelectricity, wind, and biomass production represent 68%, 6%, and 1.35%, respectively.

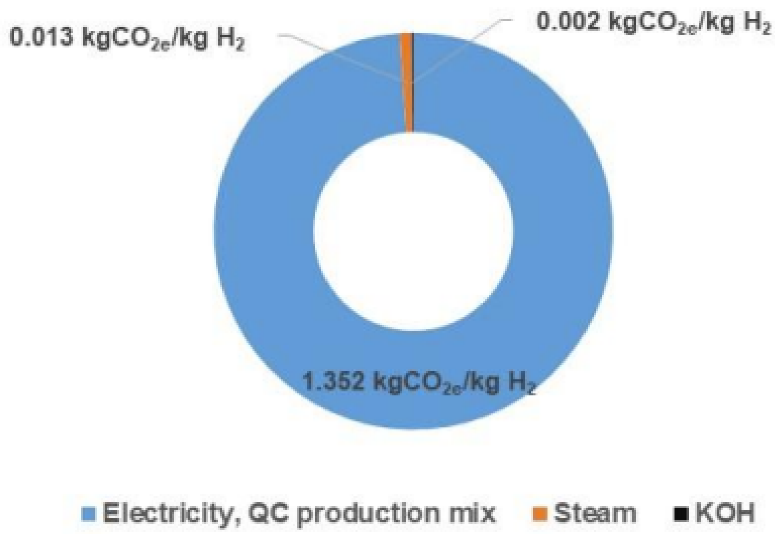


Figure 8. Life cycle climate change impacts hydrogen production using alkaline electrolysis and QC grid electricity as feedstock. (Gonzales-Calienes et al., 2022)

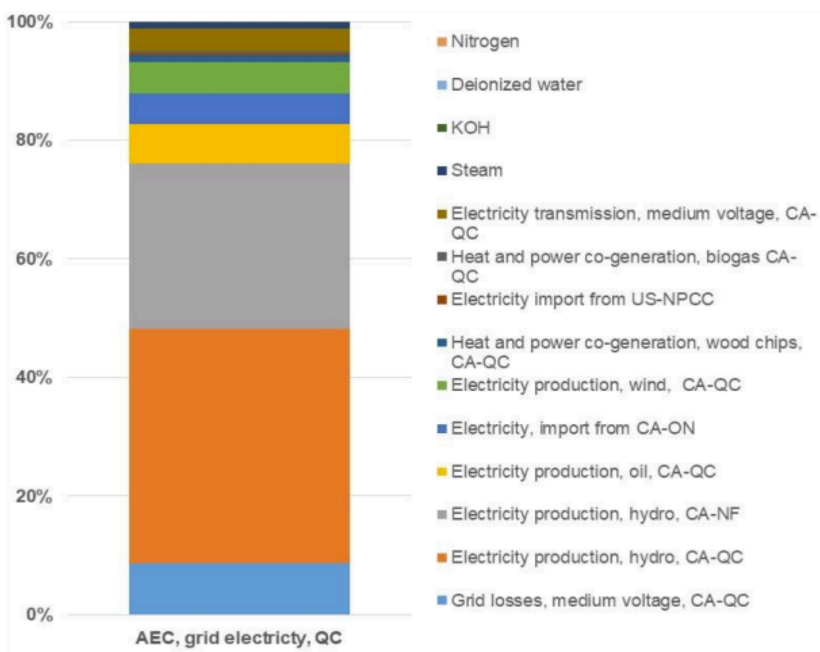


Figure 9. Share of life cycle climate change impacts for AEC pathway, grid electricity, QC. (Hardman et al., 2017)

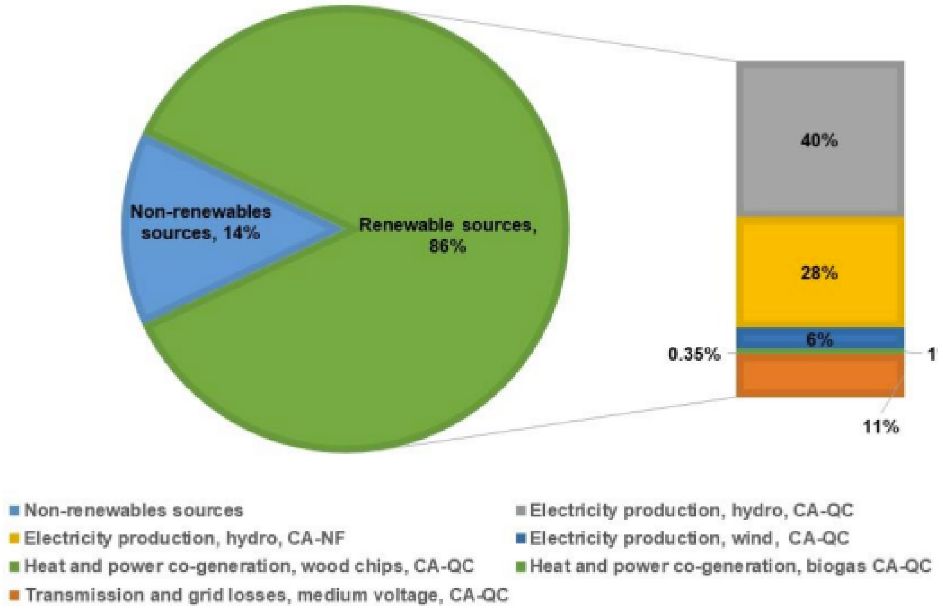


Figure 10. Breakdown of carbon intensities from renewable sources in the AEC pathway in QC. (Hardman et al., 2017)

5.3 Environmental Benefits

The environmental benefits of replacing diesel engines with hydrogen fuel cell technology are that there is a significant reduction of greenhouse gas emissions compared to diesel engines since hydrogen fuel cells produce only water as a byproduct. Switching to hydrogen fuel cells helps lower emissions of criteria air containments which overall improves air quality. Fuel cells have no moving parts so they are quieter and vibration free.

According to the Locomotive Emissions Monitoring report from the Railway Association of Canada, there has been a decrease in greenhouse gas emissions intensity by 17.99% from 2020 to 2021, implying that trains are becoming more environmentally friendly per passenger-km. Trains, particularly those with improved emissions standards, generally have lower emissions per passenger-kilometre than personal vehicles and short-haul flights, making them more sustainable travel options. Investments in locomotive modernization programs have improved fuel efficiency and reduced carbon dioxide emissions by 2810 tonnes with Canadian Pacific reporting a minimum of 2.7% improvement in locomotive fuel efficiency. Intercity passenger rail emissions intensity increased significantly due to reduced ridership during the COVID-19 pandemic, highlighting the importance of passenger volume in achieving low emissions per passenger-km. However, initiatives like VIA Rail's development of a new Corridor fleet powered by Tier 4 locomotives are expected to contribute to future emissions reductions (RailCan, 2023).

Rail transport has the highest energy efficiency as compared to air and road transportation. It enhances sustainability and reduces negative environmental effects, including greenhouse gas emissions (GHG) and pollution. Rail transport has the lowest emissions per passenger-km of 19g $CO_{2,\ eq}$ /passenger-km. This value is ⅓ of those for buses and ⅙ for air transport. Trains only account for 2% of the total GHG emissions from the transport industry, therefore much less air pollution as compared to road transport (Ding & Wu, 2024).

5.4 Renewable Energy Sources in Alberta

Renewable energy is generated from sources that can be restored indefinitely while complementing, reducing or replacing conventional fossil fuel energy sources which lower carbon dioxide (CO_2) emissions (Alberta Government, 2024). Adaptation to changing climates is increased by diversifying from traditional, centralized energy sources. Wind, solar and small-scale hydro systems have zero greenhouse gas (GHG) emissions while generating power.

Biomass sources of energy are considered GHG neutral because the CO_2 generated by producing the energy is offset by the growing crop.

Table 7. Estimated emissions by technology in Alberta (Alberta Government, 2024)

Technology	Tonnes CO2e /MWh*
Coal, with Carbon Capture and Storage (CCS)	0.11
Coal, without CCS	0.76
Natural gas, simple cycle	0.37
Natural gas, combined cycle	0.37
Cogeneration	0.37
Wind	0
Hydro	0
Solar PV	0

5.4.1 Electrolysis

This method uses electricity to split water into hydrogen and oxygen. Renewable energy sources such as wind, solar, or hydropower can be used to provide the electricity needed for electrolysis (Alberta Innovates, 2023).

5.4.2 Biological Processes

Some microorganisms can produce hydrogen gas through biological processes, such as the fermentation of organic matter. Renewable biomass sources can be used as feedstock for these processes (Dinh, 2022)

5.4.3 Thermochemical Processes

Renewable biomass or waste materials can be used in thermochemical processes, such as gasification, to produce hydrogen gas (Alberta Innovates, 2023).

5.4.4 Photoelectrochemical Processes

These processes use solar energy to directly split water into hydrogen and oxygen. They typically involve semiconductor materials that can absorb sunlight and catalyze the water-splitting reaction.

6 Project Schedule Development

6.1 Details on the CP Hydrogen Locomotive Project

According to CP Rail, the hydrogen infrastructure at CP's Edmonton and Calgary sites will include a 1MW electrolyzer, compression, storage, and dispensing for locomotive refuelling (Canadian Pacific Rail). Construction of facilities is expected to begin later this year with production and supply of hydrogen being provided to locomotives in 2023. CP will also be converting three diesel-electric powertrains to hydrogen-electric powertrains as part of the project. ATCO Group (ATCO) was awarded an engineering, procurement, and construction services contract from CP. WSP is providing detailed design. Emissions Reduction Alberta has provided $15M in funding for the project.

Table 8. Details on the CP locomotive project. (Canadian Pacific Rail)

Municipality:	Calgary, Edmonton
Sector:	Infrastructure
Type:	Other
Schedule:	2021 - 2022
Estimated Cost:	$33.2M
Stage:	Completed
Developer:	Canadian Pacific Railway
Contractor:	ATCO Ltd.
Architect:	WSP

The timeline of this HFC retrofit project is dependent on factors such as:

- Labour and resources available to accelerate the development of the hydrogen locomotive infrastructure
- Hydrogen locomotive fleet quantity
- Specific power requirement demands for the locomotives operating on specific corridors. For example, different diesel locomotive models specialize in freight transportation, while others specialize in passenger transport.

- Adequate funding must be provided to accommodate the crucial assets of this infrastructure (for example, electrolyzers and hydrogen storage and refilling provisions)

When specific information becomes available, the CP hydrogen locomotive project timeline can be scaled to estimate a project completion date.

7 Safety and Risk Analysis

The hazards associated with hydrogen-powered locomotives are hydrogen gas, hydrogen storage, hydrogen fuel cells, and lithium batteries. Mitigation measures are also included to reduce these risks in the locomotives.

7.1 Hazards with Hydrogen

Hydrogen is the most abundant element that must be handled safely with other fuels due to its unique properties. It has low density and viscosity so it is susceptible to leak which could lead to an asphyxiation risk in confined spaces. Hydrogen has an autoignition temperature of 585℃ and a burning speed between 2.65m/s - 3.25m/s. This indicates that hydrogen fires ignite quickly, heightening the likelihood of explosions due to their high flame velocity. These flames are difficult to extinguish, therefore, special flame arrestors are required. Hydrogen has a flammability range of 4 - 75% in the air by volume. In a pure oxygen environment, an explosive mixture with hydrogen can occur in a range between 4 - 94% concentration of oxygen. Given this flammability range, leaks are a major concern (Hernandez et al., 2023).

The engineering controls to reduce the risks with hydrogen include adding ventilation, leak detection sensors, flame sensors, pressure relief devices, segregation from ignition sources, and an adequate storage container design.

7.2 Hydrogen Storage Hazards

Hydrogen has a low density at atmospheric pressure, so hydrogen has the potential to leak in gas storage systems due to mechanical failure. If this leak is ignited, then the consequence severity would be ‘Damage’. The most hazardous event would be a complete tank failure due to a crash resulting in an uncontrolled hydrogen release leading to a blast wave. The consequence severity for this event would be ‘Severe/Catastrophic’. Hydrogen tanks are equipped with TPRDs which are designed to release hydrogen safely when it exceeds a specific temperature. If TPRDs fail to operate, it can lead to an uncontrolled release of hydrogen with a consequence severity of ‘Severe/Catastrophic’ (Hernandez et al., 2023).

Some mitigating factors include no ignition sources, ventilation, fire detection system, multiple TPRDs, pre-purge before startup, tanks not placed in vehicle crushing zone, tank and piping connection are protected, controlling sources of sparks and ignition, and simulation/crash testing should be conducted. These factors would reduce the risk likelihood to ‘Low’ for mechanical failure and ‘Medium’ for crash damage.

7.3 Fuel Cells Hazards

Fuel cells have electric motors that operate at voltages exceeding 350V. This poses risks of electrocution hazards and an ignition source for the fuel. Fuel cells are also prone to leaking hydrogen gas due to mechanical failure. This poses the risk of hydrogen buildup that causes jet fire which has a consequence severity of 'Minor Damage'. If the fire leads to an ignition or explosion, it would have a consequence severity of 'Damage' and 'Major Damage' respectively.

Mitigating factors include redundant ventilation systems, hydrogen sensors connected to alarms and fuel shutoff systems, impact protection, and adequate equipment used in classified areas. These factors would reduce the likelihood of these risks to 'Low'(Hernandez et al., 2023).

7.4 Lithium Battery Hazards

Lithium batteries comprise highly flammable materials such as electrolytes, combustible materials like carbon, and highly oxidizing cathode materials. It has a higher energy density as compared to lead-acid batteries commonly found in locomotives, and it has flammable organic solvents within the electrolyte. Lithium batteries risk igniting, exploding, or catching fire due to overheating or gas generation. These cells operate within a limiting temperature and operating voltage ranges to function properly. Otherwise, deviation beyond this range may trigger undesirable side effects, including exothermic reactions, and internal electric shorts leading to self-heating. This heating can lead to a thermal runaway which can cause uncontrollable increases in temperature and pressure. Thermal runaway can cause the potential risks of catastrophic cell failure, overpressure, and combustion of flammable electrolytic solvent vapours

(Hernandez et al., 2023).

There are several safety design considerations when manufacturing lithium batteries to mitigate these risks. These include an adequate battery thermal management system, cell spacing and thermal path for heat dissipation, high flash point organic electrolyte, safer anode and cathode material, and internal safety design such as shutdown separator and safety vents.

8 Regulatory and Policy

8.1 Codes and Standards Applicable to Hydrogen Installations

There are some codes and standards that are relevant for hydrail locomotives. The common standards for general hydrogen safety guidelines are ANSI/AIAA G-095A-2017 and ISO/TR 15916. These standards are for system designers, manufacturers and installers. The standard used for hydrogen quality is CGA PS-31 which is required for the proton exchange membrane hydrogen piping/components. The standard for the hydrogen venting system is CGA G-5.5 which allows hydrogen to disperse into the atmosphere (Hernandez et al., 2023).

8.1.1 Standard for Hydrogen Storage

The important standard for ground hydrogen storage is the BNQ 1784-000 which is the Canadian hydrogen installation code that specifies the installation requirements for hydrogen storage, hydrogen-powered equipment, and hydrogen dispensing equipment. Another important code/standard is the CSA SPE-2.1.3 which is a guide for the best practices for the disposal and decommissioning of compressed hydrogen gas vehicle fuel containers. A safety code used in Canada is the CSA B51 part 3 which is for hydrogen refuelling station pressure piping systems and ground storage vessels (Hernandez et al., 2023).

The standards for hydrogen storage systems are CSA/ANSI HGV 2 which is used for rail applications, CSA/ANSI HGV 3.1 which covers gas valve train components, and CSA/ANSI HPRD 1 which addresses pressure relief valves for compressed hydrogen vehicle fuel containers.

8.1.2 Fuel Cell Power Standards

The standard that can be used for safety to cover hazards for fuel cell technologies is the CSA/ANSI FC 1 and the standard for fuel cell modules is the CAN/CSA C22.2 to ensure that the module meets the minimum safety requirements.

8.2 Incentives, Subsidies and Policies

Currently, in Canada, there is a lack of comprehensive, long-term policy and regulatory framework that encompasses hydrogen. The measures promoting the adoption of hydrogen technologies include various policies and regulations, such as low carbon fuel regulations, carbon pollution pricing, vehicle emissions standards, zero-emission vehicle mandates, the establishment of emission-free zones, and mandates for renewable gas integration within natural gas networks (Hydrogen Strategy for Canada 2020).

The Government of Canada established federal targets for zero-emission vehicles (ZEV) to reach 30% of light-duty vehicle sales per year by 2030. Canada classifies fuel-cell electric vehicles (FCEVs) as zero-emission vehicles. British Columbia and Quebec have taken a provincial lead by implementing consumer purchase incentives for ZEVs and sales regulations. Both of these provinces have initiated the deployment of hydrogen fueling infrastructure and FCEVs (Hydrogen Strategy for Canada 2020).

The Canadian government offers an investment tax credit of up to 30% on clean hydrogen. This incentive encourages private sector investment in hydrogen production and distribution infrastructure, including hydrogen refuelling stations for vehicles. Another subsidy is the Zero Emission Transport Infrastructure which includes hydrogen refueling infrastructure. This funding stimulates the adoption of clean and cost-effective hydrogen fuel for transportation users (CHFCA, 2022).

9 Potential Adoption Barriers

9.1 Fuel Cell Technology Adoption Barriers, Nordic Companies

The barriers to the large-scale adoption and implementation of fuel cell technology by Nordic companies were analyzed (Latapí et al., 2022). Nordic shipping companies are front-runners in the adoption of hydrogen fuel cells. This study is based on 38 interviews conducted with high-level managers and experts from the Nordic shipping industry.

9.1.1 Behavioural barriers

Based on the notion that certain factors can influence the behaviour of individuals and organizations, four behavioural barriers were identified within the shipping industry. While resistance to change was mentioned as a barrier in only 11 interviews, individuals in this industry were found to be hesitant about operating new technologies due to their long-term relationships with partners and suppliers, and their familiarity with certain types of engines and fuel. This creates a certain organizational inertia that can lead to a technological lock-in. Additionally, fossil fuel companies and conventional engine manufacturers and suppliers were found to be making it difficult for HFC (hydrogen fuel cell) providers to enter the market through lobbying with institutions such as the IMO, as well as directly with shipowners and ship operators. The lack of knowledge of the technology represents another relevant barrier, with three key aspects being identified: 1) the technology is not commonly known around the world, which makes people skeptical about its use; 2) shipowners and ship operators do not have the knowledge and experience to operate this technology; and 3) the overall lack of experience with the technology raises questions about its safety for maritime applications. Another barrier mentioned in the interviews was the lack of a systemic view from the authorities. Interviewees explained that the overall efforts to reduce emissions of the shipping industry follow a vessel-by-vessel approach and not a fleet or system approach that considers the complete value chain. It was highlighted that the lack of a systemic view has a close relation to the lack of knowledge of the technology. The negative public perception towards hydrogen was identified as a barrier, mainly due to a lack of knowledge of the fuel and technology, as well as an increasing negative attitude towards it due to accidents involving hydrogen.

9.1.2 Economic Barriers

Economic barriers can hurt the decision to adopt hydrogen fuel cell (HFC) technology. Five economic barriers were identified, including high costs associated with HFC. Interviewees mentioned that the capital expenses (CAPEX), operational expenses (OPEX), and total cost of ownership (TCO) of using HFC are still too high to consider its adoption. They also explained that the access to capital for adopting HFC is limited, and even with financial support for CAPEX, OPEX and TCO are still too high. Additionally, interviewees noted that the OPEX of using hydrogen as a fuel is too high compared to other alternatives. A CO_2 tax on fossil fuels is needed to make HFC cost-competitive. Furthermore, interviewees explained that using HFC includes additional costs such as replacement and/or retraining of staff and costs related to the installation of equipment and infrastructure, including bunkering facilities.

The lack of regulations and standards was mentioned as a key barrier in 31 interviews, and interviewees explained that they prefer to wait until there are clear regulations and standards before investing in expensive technology. They pointed out that the current approval process through the IMO-IGF Code for Alternative Ship Design using HFC is too complex and expensive, particularly for smaller organizations. Regulations are essential not only for the operation of the technology onboard vessels but also for building the infrastructure needed to deliver the fuel to the harbours and for bunkering.

The lack of infrastructure and the supply of green hydrogen were also mentioned as barriers. Interviewees explained that these are mainly due to a lack of demand for green hydrogen for the shipping industry, and vice versa. Although the demand might increase in the following decade, interviewees emphasized that shipping would compete with other industries for the supply of green hydrogen. This could delay investments in specific infrastructure for the use of hydrogen for maritime transportation.

Interviewees explained that adopting HFC represents uncertainty and high risk. They pointed out that no available supply of green hydrogen can be purchased and delivered with the same guarantees as traditional fuels. While they mentioned the option of using swap containers with hydrogen to get the fuel onboard, they stressed that this is only a transitional solution. It should not become permanent as it represents uncertainty and higher risks than using other fuels. These aspects, along with the costs associated with HFC, translate into risks for their organizations. Although the cost of hydrogen is expected to decrease, it was explained that adopting HFC would translate into operating the vessel without profit for several years, which represents a financial risk for the organization.

9.1.3 Organizational Barriers

During the interviews, organizational barriers were identified as the aspects that are directly related to the organizational culture, power, and structure. One major barrier that was pointed out by 11 interviewees is the inflexible and bureaucratic structure that many organizations have. These interviewees explained that some companies have outdated structures that limit their ability to adapt to the market they operate. According to them, these structures are inefficient for today's competitive environment and can prevent effective internal communication, as well as affect the company's relations with its stakeholders.

9.1.4 Technological Barriers

Based on interviews with 33 individuals, one of the technological barriers identified is related to the handling and operation of hydrogen fuel cells (HFC). The interviewees explained that significant operational challenges are involved in operating HFC and identified bunkering and storage of hydrogen as two key issues. Regarding bunkering, interviewees stated that traditional fuels are easier to handle than hydrogen, and switching to hydrogen would make the bunkering process more complicated. In terms of storage, interviewees pointed out that hydrogen's characteristics make it more challenging to store onboard than other fuels. They identified two critical aspects of this challenge - firstly, hydrogen needs to be stored above deck due to safety concerns for passenger transportation, and secondly, hydrogen requires more storage space than traditional fuels. Interviewees explained that these aspects make ship design and operation more complex, particularly for passenger vessels.

10 Conclusions and Recommendations

From the current research findings, it is evident that the integration of hydrogen fuel cell (HFC) technology into locomotive retrofitting presents a viable path toward sustainable rail transport. The technical feasibility, as demonstrated through case studies and evaluations, indicates that HFCs can be compatible with existing locomotive infrastructures, offering enhanced power efficiency and engine longevity. The economic analysis underscores the potential for cost savings over time, despite the initial investment required for the transition.

The environmental benefits, particularly the significant reduction in greenhouse gas emissions compared to traditional diesel engines, align with global efforts to mitigate climate change impacts. The adoption of HFC technology in locomotives not only supports environmental sustainability but also contributes to the advancement of clean energy transportation solutions.

This research underscores HFC technology's potential to revolutionize the rail transport industry. The environmental benefits of HFC technology are particularly noteworthy, offering a significant reduction in greenhouse gas emissions compared to traditional diesel engines. The uninterrupted power supply and high efficiency of fuel cells, coupled with the utilization of renewable energy sources in Alberta, present a compelling case for the adoption of this technology.

The project schedule development outlined in section 7 highlights the strategic planning and resource allocation required to facilitate the transition to hydrogen-powered locomotives. The involvement of key stakeholders, such as CP Rail and ATCO Group, and the support from Emissions Reduction Alberta, are critical to the project's success.

The safety and risk analysis provides a thorough examination of the potential hazards associated with HFC technology and the necessary mitigation measures. The implementation of robust safety protocols and engineering controls is essential to ensure the safe operation of hydrogen-powered locomotives.

This research outlines the regulatory framework and standards pertinent to hydrogen fuel cell installations. It emphasizes the importance of adhering to established safety guidelines such as ANSI/AIAA G-095A-2017 and ISO/TR 15916, which are crucial for system designers, manufacturers, and installers. The section also highlights the significance of hydrogen quality standards like CGA PS-31 and the necessity for robust hydrogen venting systems as per CGA G-5.5.

Furthermore, the document underscores the criticality of specific standards for hydrogen storage, particularly BNQ 1784-000, which is the Canadian hydrogen installation code. This code delineates the installation requirements for hydrogen storage and dispensing equipment, ensuring safety and efficiency. Additionally, the CSA SPE-2.1.3 guides the disposal and decommissioning of hydrogen gas vehicle fuel containers, reflecting a comprehensive approach to safety and sustainability.

The section also delves into the standards for fuel cell power systems, advocating for the adoption of CSA/ANSI FC 1 for fuel cell technologies and CAN/CSA C22.2 for fuel cell modules, to meet minimum safety requirements.

Recommendations for further research into the feasibility of hydrogen fuel cell retrofitting in existing diesel locomotives include a focus on advancing the technology behind hydrogen fuel cells to improve efficiency, reduce costs, and enhance safety measures. This includes exploring new materials for fuel cells that can operate at higher temperatures and pressures and developing more robust systems that can withstand the rigours of rail transport.

Future studies should investigate the necessary infrastructure for the widespread adoption of hydrogen fuel cell locomotives. This encompasses the development of hydrogen production facilities, refuelling stations, and maintenance hubs strategically located along rail networks.

Conducting a detailed economic analysis is crucial. This should include the life-cycle cost assessment of hydrogen fuel cell locomotives compared to traditional diesel engines, considering factors such as initial investment, operational costs, maintenance, and potential subsidies or incentives.

It is essential to perform a thorough environmental impact assessment of hydrogen fuel cell locomotives. Research should quantify the reduction in greenhouse gas emissions and other pollutants, and evaluate the overall environmental benefits of transitioning to hydrogen power.

Policy and Regulatory Framework: Research should also address the policy and regulatory aspects of implementing hydrogen fuel cell technology in the rail industry. This includes identifying gaps in current regulations, proposing new standards for safety and performance, and examining the role of government policies in supporting the transition to cleaner energy sources.

Understanding the market dynamics and consumer behaviour is important for the adoption of hydrogen fuel cell locomotives. Future research should explore the willingness of rail operators to invest in this technology and the potential demand from passengers and freight customers for greener transportation options.

Finally, conducting pilot programs and in-depth case studies of existing hydrogen fuel cell locomotive projects can provide valuable insights. These studies can help identify best practices, common challenges, and strategies for successful implementation and scaling up of the technology.

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