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Hydrogen Fuel Cell Retrofit Feasibility for Rail Applications

Tanuj Ravikumar

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Abstract

This report presents a comprehensive evaluation of the feasibility and strategic implementation of retrofitting diesel locomotives with hydrogen fuel cell (HFC) technology, with a specific focus on advancing sustainable and zero-emission rail transportation in Canada. Grounded in a multidisciplinary research framework, the study investigates the technical, environmental, economic, safety, and regulatory dimensions associated with HFC integration into existing rail systems, using Alberta as a regional case study.

From a technical standpoint, the report examines the replacement of diesel engines with HFC systems and the optimal configuration of associated components, including lithium iron phosphate (LFP) battery systems, electric motors, and regenerative braking technologies. Lessons drawn from successful HFC deployments in Pau, France and Foshan, China provide valuable benchmarks, highlighting system design, fuel efficiency, hydrogen refueling infrastructure, and real-world performance metrics. The study also delves into component-level integration challenges and solutions such as thermal management, control systems, and fuel cell stack configuration strategies optimized for heavy-haul locomotives.

Hydrogen storage and safety are explored in detail, assessing pressurized storage options, underground caverns, and tank safety features such as thermal pressure relief devices (TPRDs). A thorough risk and hazard analysis is conducted, identifying and mitigating concerns related to hydrogen leakage, fuel cell overheating, battery thermal runaway, and potential explosion scenarios. This section incorporates risk matrices and failure mode considerations to support safe design practices.

The cost and infrastructure analysis compares capital expenditure (CAPEX) and operational expenditure (OPEX) for diesel and hydrogen locomotives. It investigates fuel cell supplier capabilities—including Ballard Power Systems, Accelera (Cummins), Loop Energy, and Nuvera—emphasizing Canadian-sourced technologies suitable for local deployment. The study also assesses infrastructure development trends, such as CP Rail's hydrogen locomotive projects in Alberta, which include 1MW electrolyzers and refueling stations supported by public-private partnerships and emissions reduction funding.

On the environmental front, the report quantifies the greenhouse gas (GHG) reduction potential of HFC locomotives through life cycle assessments. It compares the carbon

intensities of hydrogen produced via steam methane reforming (12.08 $kgCO_2e/kg\ H_2$) versus alkaline electrolysis using renewable energy (1.37 $kgCO_2e/kg\ H_2$). The study also emphasizes the broader environmental benefits of HFC technology, including reduced noise pollution, elimination of NOx and SOx emissions, and lower emissions per passenger-kilometer compared to diesel rail, buses, and air travel.

The regulatory and policy section identifies applicable standards and safety codes governing hydrogen installations and HFC systems (CSA, ANSI, ISO). It outlines the need for a robust policy framework to support market readiness, incentive alignment, and regulatory clarity. Current gaps in infrastructure codes, hydrogen refueling standards, and fuel cell safety guidelines are discussed.

Finally, the report outlines strategic recommendations to accelerate HFC locomotive adoption. These include promoting Alberta's renewable energy resources (solar, wind, biomass) for green hydrogen production, encouraging pilot programs to validate retrofit models, and fostering cross-sector collaboration to address technical, economic, and behavioral barriers. Emphasis is placed on stakeholder engagement, operator training, and public education to overcome resistance and support long-term adoption.

By integrating cross-functional insights from engineering, policy, economics, and environmental science, this report provides a robust foundation for advancing Canada's transition toward clean rail transportation systems and supports broader goals in mechanical retrofitting, energy innovation, and sustainable infrastructure development.

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Introduction

The transportation sector is undergoing a transformative shift as global efforts intensify to reduce greenhouse gas emissions and transition toward sustainable energy systems. Among the hardest-to-decarbonize modes is heavy-duty rail, which remains largely dependent on diesel-powered locomotives. As environmental regulations tighten and zero-emission targets become increasingly prioritized, hydrogen fuel cell (HFC) technology has emerged as a promising alternative for decarbonizing freight and passenger rail operations.

This report presents a focused study plan aimed at evaluating the feasibility of retrofitting diesel locomotives with HFC systems in the Canadian context, with particular emphasis on Alberta's freight rail infrastructure. Rather than starting from a blank slate with new locomotive designs, retrofitting existing units offers a strategic and economically viable pathway to accelerate the adoption of cleaner technologies while leveraging current rail assets.

The study is organized into four core focus areas. First, the technical feasibility section explores the engineering design requirements and integration considerations, such as optimal battery chemistry selection, electric motor compatibility, and control systems needed to implement HFC propulsion. Case studies from global implementations—including successful applications in France and China—are examined for real-world validation and technology transfer potential.

Next, the study investigates hydrogen storage and safety aspects, which are critical for operational reliability and risk mitigation. This includes assessing storage configurations (e.g., high-pressure tanks, salt caverns), and developing safety protocols around hydrogen leakage, fire, and battery hazards using failure mode analysis and risk matrices.

The third segment covers cost and infrastructure analysis, highlighting the economic implications of transitioning from diesel to HFC locomotives. It evaluates capital and operational costs, identifies key Canadian suppliers (such as Ballard and Accelera), and examines emerging hydrogen infrastructure projects like CP Rail's hydrogen locomotive initiative in Alberta. This section supports investment planning and market-readiness assessments.

Finally, the environmental and regulatory outlook provides a holistic view of the benefits and challenges associated with HFC retrofitting. It compares the life cycle emissions of different hydrogen production methods and aligns them with provincial and national climate goals. In addition, it reviews the existing regulatory standards (CSA, ANSI, ISO) that govern hydrogen storage and fuel cell operations, and outlines policy incentives needed to encourage widespread adoption.

By synthesizing engineering, environmental, economic, and policy perspectives, this study seeks to provide a comprehensive roadmap for implementing hydrogen fuel cell retrofits in Canadian rail systems. The report concludes with strategic recommendations aimed at accelerating clean rail transformation through innovation, regulatory alignment, and collaborative infrastructure development.

2.) Technical Feasibility of Hydrogen Fuel Cell Retrofits

2.1 System Architecture and Powertrain Considerations

The transition from diesel-powered rail vehicles to hydrogen fuel cell-based systems involves a comprehensive redesign of the powertrain architecture while carefully considering space, weight, power demands, and energy storage capabilities. The study explores retrofitting a British Rail Class 156 (BR C156) diesel multiple unit (DMU) with a fuel cell–battery hybrid system (hydrail), highlighting essential technical parameters and system design considerations.

System Architecture Overview

- Series Hybrid Powertrain Configuration: The retrofit utilizes a series hybrid architecture, in which the fuel cell stack generates electrical power that either directly supplies the traction motors or charges an onboard battery energy storage system (ESS). The battery supports transient power demands and regenerates energy during braking.
- Key Components:
- Proton Exchange Membrane Fuel Cell (PEMFC) Stack: Converts hydrogen directly into electricity with water and heat as byproducts.
- Lithium-Ion Battery Pack (ESS): Buffers power transient demands and absorbs regenerative braking energy.
- Electric Traction Motors: Provide propulsion by converting electrical energy from fuel cells or batteries into mechanical power.
- Power Electronics: Includes unidirectional DC-DC boost converters (fuel cell to battery), bidirectional converters (battery to motor and regenerative braking).

Vehicle Platform and Retrofit Scope

- The study retrofits the BR C156 DMU:
- Trainset mass: 76.4 tonnes
- Diesel engine power (original): 213 kW per car

- The retrofit assumes removal of the diesel engine and fuel tank, freeing approx. 4000 L volume and 4 tonnes mass per trainset (approx. 2 t and 2000 L per car) strictly for FC and battery packaging (, Table 1,).

Fuel Cell Stack Specifications

- Fuel Cell Type: Honda FCX PEMFC stack (heavy-duty prototype)
- Key parameters:
- Mass: 96 kg
- Volume: 66 L
- Nominal Stack Power: 85 kW
- Maximum Stack Power: 100 kW
- Nominal fuel utilization (H2): 95.24%
- Fuel/air supply pressure: 3 bar
- Nominal hydrogen flow: 374.8 Lpm (liters per minute)
- The fuel cell stack is optimally sized to meet the majority of the average rail route power demands, operating predominantly at steady power to maximize efficiency (~50-60%) and extend stack life.

Battery Pack Characteristics

- Battery Cell Model: Panasonic UPF454261 Lithium Cobalt Oxide
- Design metrics:
- Rated capacity: 1450 mAh (1.45 Ah)
- Nominal Voltage: 3.7 V per cell
- Mass: 27 g per cell
- Energy density: 199 Wh/kg (gravimetric), 462 Wh/L (volumetric)
- Assembly:
- Cells are arranged in series and parallel combinations to achieve approximately 1500 V system voltage, matching traction motor requirements.

- Role:
- Absorb power spikes that exceed fuel cell steady-state output.
- Recharge during regenerative braking.
- Stabilize fuel cell operation by smoothing power demand fluctuations.

Hybridization Ratio and Sizing

- Battery Mass and Size Impact:
- Simulations show improvements in fuel cell stack efficiency saturate beyond a battery mass of around 200 kg.
- Increased battery size leads to:
- Increased fuel cell efficiency (up to 64%)
- Increased energy regeneration capacity
- Decreased hydrogen consumption by approximately 13%
- Reduced maximum peak power requirements on the fuel cell stack (,)
- Powertrain Power Limits:
- The fuel cell stack alone often exceeds its rated power (~100 kW) during peak load times without a battery buffer.
- Battery integration mitigates this by providing high transient power (motor accelerations, hill-going), enabling the fuel cell to operate within nominal limits with longer lifetimes.

Energy Flow and Operational Strategy

- Fuel cell operates mostly as a generator and battery charger, with output regulated dynamically:
- Runs during train dwell or low power demand periods to recharge batteries.
- Ensures consistent supply for propulsion during cruising phases.
- Battery provides high-power transient supply to cover sudden acceleration and hill climbs.

- Energy recovered from braking is funneled back into the battery through regenerative braking, reducing waste and improving overall efficiency.
- The powertrain operates to minimize fuel cell power fluctuations, driving efficiency and prolonging system durability.

Route and Performance Context

- Test route: 27.8 km round trip (Trehafod to Treherbert), with significant elevation changes (average 0.7% gradient, max 2.13%).
- The fuel cell–battery system can meet the dynamic power demands of such a route while improving energy use and reducing emissions relative to diesel engines.

2.2 Battery Chemistry Selection (LFP)

Battery chemistry is a critical factor in the design and deployment of energy storage systems for heavy haul locomotives, especially when integrated with hydrogen fuel cell technology in hybrid platforms. The selected battery must meet stringent requirements including high energy density, long cycle life, safety, cost-effectiveness, and operational durability under extreme conditions common in rail applications.

Among Li-ion chemistries, Lithium Iron Phosphate (LFP) is currently identified as the most viable battery chemistry for heavy haul rail locomotives based on a balance of cost, cycling stability, and safety.

Technical Merits of LFP Chemistry

- **Cycle Life:** LFP batteries exhibit superior cycle stability compared to other Li-ion chemistries such as Nickel Manganese Cobalt (NMC) and Lithium Titanium Oxide (LTO). Though LTO offers the highest cycle life, its high upfront cost limits economic feasibility.
- LFP cells generally achieve **over 2000 cycles** with minimal capacity degradation, supporting battery longevity required in heavy haul applications.
- **Energy Density:**
- At the cell level, LFP typically delivers an energy density in the range of approximately **150-170 Wh/kg**.

- Pack-level energy density is lower due to added structural components, cooling systems, and battery management electronics, with a **cell-to-pack energy retention ratio around 0.55** typical for commercial systems.
- Lower energy density than high-nickel chemistries like NMC (~200-250 Wh/kg) is offset by other LFP advantages.
- **Safety and Thermal Stability:**
- LFP chemistry is thermally stable and safer during abusive conditions, reducing the risk of thermal runaway or fires, a critical consideration in rail safety standards.
- Operating temperatures range from approximately **-20°C to 60°C**, with robust performance over this range, supporting diverse climatic rail environments.
- **Cost:**
- The cost of LFP batteries is lower relative to NMC and LTO chemistries due to abundant raw materials (iron and phosphate) and mature manufacturing routes.
- This translates into better **levelized cost of energy (LCOE)** for battery electric or hybrid hydrogen-battery systems.

Implications for Hydrogen Fuel Cell Rail Applications

- In hybrid hydrogen fuel cell-battery locomotives, LFP batteries are primarily used as the **energy buffer** and for regenerative braking energy capture.
- The **high cycling stability of LFP facilitates multiple charge/discharge cycles** per trip (up to 12 cycles in some cases of regenerative braking) without significant degradation, which is crucial as this battery undergoes repeated partial cycling for braking energy storage.
- The fuel cell provides continuous power for tractive demand, while the LFP battery handles transient loads, peak shaving, and regenerative energy storage, improving overall system efficiency and lifecycle.

Battery Sizing and Performance Metrics

- For regenerative braking energy capture, LFP battery packs in heavy haul locomotives require capacities in the range of **0.4 to 1.6 MWh** per trip segment depending on the route topology (e.g., Mt Isa corridor on the higher end).

- Tractive batteries sized using LFP chemistry typically need capacities between **5 to 10 MWh** for low-to-medium energy-demand corridors, with longer hauls requiring energy more than **26 MWh**, posing challenges for onboard energy mass and volume constraints.
- Projected future advances anticipate the **pack energy density of LFP batteries to approximately double by 2030**, alongside cost reductions and increased cycle life, further enhancing feasibility.

Comparative Techno-Economic Considerations

- Compared to NMC and LTO, LFP balances cost and lifespan, making it economically attractive when calculating total cost of ownership over a 20-year horizon for battery-electric or hybrid trains.
- The reduced upfront and lifecycle costs, combined with safety and cycling benefits, support LFP as the **current optimum choice for battery integration in fuel cell-hybrid heavy haul applications**.
- Despite lower energy density relative to NMC, the reliability and stable chemistry of LFP make it more resilient for the demanding, long-duration cycles experienced in freight rail.

Parameter	Value / Range
Cell-level energy density	~150–170 Wh/kg
Pack-level energy density ratio	~55% of cell energy density
Cycle life	> 2000 cycles
Operating temperature	-20°C to 60°C
Regenerative battery capacity	0.4 – 1.6 MWh
Tractive battery capacity	5 – 10 MWh (low-medium haul), up to 26 MWh (long haul)
Energy density doubling target	Expected by 2030
Relative cost	Lower compared to NMC and LTO

2.3 Electric Motor Compatibility and Regenerative Braking

The transition from diesel-electric to battery and hydrogen-electric locomotives maintains the central role of electric traction motors as the final energy converter driving the wheels. Electric motors in heavy haul locomotives must be compatible with both energy sources—batteries and fuel cells—and capable of delivering sustained high power outputs with reliable performance under heavy load and varying operating conditions.

- **Electric traction motors** typically convert electrical energy into mechanical power with efficiencies above 90%, providing the tractive effort needed for heavy loads.
- Motor systems must handle power fluctuations due to load changes, accelerations, and regenerative braking return currents, requiring robust control strategies.
- Compatibility involves integrating power electronics (inverters, converters) that regulate the voltage and current from batteries or fuel cells to the motors.

Regenerative Braking (Dynamic Braking) Mechanism

Regenerative braking (also known as dynamic braking) is a critical technology enabling energy recovery during deceleration or downhill travel, which otherwise would dissipate as heat in traditional rheostatic braking systems.

- When the locomotive slows down or travels downhill — especially when fully loaded descending from mine to port — electric traction motors operate in generator mode, converting kinetic energy back into electrical energy,.
- This recovered energy can be fed back into onboard energy storage systems (batteries or supercapacitors) or, in other system designs, returned to the grid, thereby reducing net energy consumption.

Energy Recovery Metrics

The Australian heavy haul case studies demonstrate significant energy recovery potential through regenerative braking:

- **Energy savings from regenerative braking range from 21% to 55%, with an average of 32% across various routes**.
- Larger amounts of regenerative braking energy are captured on downhill loaded hauls (mine to port), as these trips require higher braking effort.
- The **energy for the regenerative battery required for capturing and cycling this braking energy ranges from approximately 0.4 to 1.6 MWh**, which is substantially less than the net tractive energy requirements (typically 5–10 MWh, up to 26 MWh for longest hauls),.
- Regenerative batteries undergo multiple charge/discharge cycles per round trip (up to 12 cycles in some corridors), whereas the main traction battery typically undergoes one full cycle per trip, affecting sizing and lifecycle considerations.

Impact on Energy Efficiency and System Design

- Integrating regenerative braking reduces the **net tractive energy demand** on batteries or hydrogen fuel cells, effectively decreasing onboard energy storage needs and associated mass.

- This reduction in required tractive energy storage translates into **lower capital costs, reduced volume, and mass constraints** within locomotives and tenders.
- Control systems must balance energy flow to regenerative batteries to maximize energy captured without compromising operational reliability.
- Additional energy is required for battery thermal management to optimize performance during regenerative charging and discharging cycles; cooling energy can account for around 4% of total electrical energy.

Summary of Metrics

Parameter	Range / Typical Value
Regenerative energy savings	21% to 55% (avg. 32%) of tractive energy
Regenerative battery capacity	0.4 to 1.6 MWh
Net tractive energy requirement	5 to 10 MWh (common), up to 26 MWh (long hauls)
Regenerative battery cycle frequency	Up to 12 cycles per round trip
Battery cooling energy requirement	~4% of total electrical energy
Electric motor efficiency	>90%

2.4 Case Studies: Calabria Italy, Australia.

Rail on the Calabria Line, Italy

Overview

The Calabria regional railway line between Reggio Calabria and Catanzaro Lido (180 km) currently operates diesel trains with no full electrification along the entire route. This scenario makes it ideal for assessing hydrogen fuel cell technology as a clean alternative to replace diesel powertrains, aiming to reduce CO_2 emissions and fossil fuel dependence.

The train selected for the study is the Hitachi Blues, a regional train with four coaches (90 m length), currently diesel-electric equipped but considered for retrofit with fuel cell and battery hybrid powertrains.

Hydrogen Fuel Cell–Battery Powertrain Configuration

One of the key configurations studied combines hydrogen fuel cells with batteries, supplementing or replacing the diesel engine entirely. This configuration includes:

- Fuel Cell System:
- Three proton exchange membrane (PEM) fuel cells rated at 180 kW each, totaling 540 kW.
- Efficient and gradual power modulation capability to minimize stack degradation.
- Fuel cells operate primarily in a narrow power range (between 360 kW and 460 kW), corresponding to about 16% of the total power demand range of the train during operation.
- Hydrogen Storage:
- High-pressure hydrogen tanks operating at 350 bars.
- Onboard hydrogen storage capacity designed for a round trip without refueling, consuming approximately 43 kg of hydrogen.
- Battery Pack:
- 8000 nickel-manganese-cobalt (NMC) lithium-ion cells with 52 Ah capacity each.
- Total energy capacity around 655 kWh, enabling the battery to handle wide dynamic power fluctuations (from -2000 kW during breaking to +800 kW during acceleration).
- Recovers all available braking energy via regenerative systems, assisting the fuel cells in power demand smoothing.

Integration and Sizing

- The fuel cell and battery modules are integrated onboard within two locomotives, occupying about 40 m^3 volume and 22 tons weight.

- The sizing aims to meet the total energy requirement of the regional route including acceleration, cruising, deceleration, and stopping over the 180 km distance.
- The fuel cell supplies energy steadily at a medium power level, while the battery handles transient peak loads and regenerative braking energy, making the hybrid system efficient and responsive.

Operational Performance and Simulation

- The system was tested through detailed simulations using the actual drive cycle of the regional line.
- The fuel cell efficiency was found to be greater than 47%, a favorable figure considering the operational conditions and variables such as load dynamics and energy conversion losses.
- Total hydrogen consumption was below 72 kg for the round trip, correlating closely with the simulated 43 kg, showing realistic and sustainable fuel use, .
- The hybrid system successfully allowed full recovery and use of approximately 300 kWh of braking energy, reducing net energy consumption and increasing overall efficiency.
- The battery State of Charge (SOC) was maintained within optimal intervals throughout the route, ensuring longevity and reliability.

Environmental and Operational Significance

- Utilizing hydrogen fuel cells eliminates direct CO2 emissions along the route.
- The hybrid configuration reduces reliance on diesel engines and overhead electrification, especially valuable for lines impractical to electrify,
- The fuel cell acts as the primary energy supplier, while the battery absorbs peak power fluctuations and supports regenerative breaking, combining smooth, energy-efficient power delivery and improved vehicle performance.
- This approach supports the decarbonization goals of railway transport and aligns with emerging European policies favoring hydrogen technologies for sustainable mobility.

Case Study: Rail on Australia.

The Australian heavy haul rail industry offers valuable real-world insights into the technical feasibility and limitations of hydrogen fuel cell (H2 FC) technology as an alternative to diesel-electric locomotives.

1. Route Characteristics and Energy Requirements

Australian heavy haul rail routes studied show substantial variability in length, terrain, and energy demand. Key findings include:

- Energy requirements for typical routes range from moderate to very high, with net tractive energy needs spanning approximately 5 MWh to over 26 MWh for longer hauls such as the Mt. Isa (Phosphate Hill) corridor.
- Routes often feature heavy loads descending from mines to ports, allowing effective use of regenerative braking to recapture between 21% and 55% of braking energy and reduce onboard energy consumption.

From an energy perspective, hydrogen fuel cells are particularly well-suited for routes with higher energy demands where battery mass and volume constraints become prohibitive. Hydrogen's high gravimetric energy density provides advantages for longer haul distances and heavier payloads.

2. Hydrogen Fuel Cell Technology Overview

Hydrogen fuel cells generate electricity through electrochemical reactions combining hydrogen and oxygen, producing only water as a byproduct. Fuel cells enable continuous energy supply onboard locomotives without the need for heavy, large-capacity batteries. Key technical parameters include:

- Power Output & Response: Fuel cells provide steady power output adaptable to variable load demands typical of rail operation. Hybridization with batteries helps manage transient power spikes (acceleration, braking).
- Fuel Storage: Hydrogen is stored in high-pressure tanks or cryogenic containers on the locomotive or in an attached tender due to volumetric energy density constraints.
- System Efficiency: Overall efficiency depends on fuel cell stack performance, hydrogen supply system, and electric drivetrain. Fuel cells typically exhibit efficiencies of 40-60% in converting hydrogen energy to electric power.

3. Implementation Challenges and Solutions

- Mass and Volume Constraints: Hydrogen storage systems and fuel cell stacks must be integrated into existing locomotive dimensions or as tenders due to restricted onboard space. The heavy energy demand in Australian heavy haul routes necessitates large hydrogen fuel capacity, which can increase train mass and impact operational dynamics.
- Infrastructure Requirements: Hydrogen refueling infrastructure is critical. Unlike battery systems which rely on electric grid charging stations, hydrogen supply requires dedicated production, distribution, and refueling facilities, which remain sparse or under development in Australia. This is a significant logistical and cost consideration.
- Techno-Economic Assessment: Studies including Australian case data indicate that battery-only systems offer the lowest cost solution for low to medium energy routes, but for very high energy demands, a hybrid battery-hydrogen system is more cost-effective and practical. The hybrid system capitalizes battery power for energy cycling and fuel cells for sustained tractive energy.
- Operational Flexibility: Fuel cell locomotives paired with batteries can optimize hydrogen consumption by minimizing peak power draw on the fuel cells and utilizing regenerative braking energy stored temporarily in batteries. This hybrid approach increases fuel cell lifespan and enhances energy efficiency.

2.5 Fuel Cell Stack Design and Thermal Management

Fuel Cell Stack Design and Thermal Management primarily focused on the Polymer Electrolyte Membrane Fuel Cell (PEMFC) stack used in the locomotive propulsion system:

Fuel Cell Stack Specification:

- The selected fuel cell stack is a PEMFC with a rated power of 200 kW, appropriate for high-performance locomotive applications.
- The stack's maximum power output (P_max) is 120 kW with a maximum tractive force capability of 60 kN.

- Hydrogen has an energy density of 120 MJ/kg, which informs fuel consumption calculations.
- The fuel cell efficiency at zero load is modeled as 20%, which increases under operating conditions.

Efficiency and Performance Modeling:

- To simplify control and optimization, the fuel cell power efficiency characteristic is linearized.
- Two operational scenarios are considered: normal and extreme power-efficiency characteristics. The normal characteristic corresponds to typical performance, while the extreme profile tests the system robustness under more demanding conditions.
- Simulation results using these characteristics inform optimal speed trajectories and hydrogen consumption, linking the fuel cell's performance directly to the locomotive control strategy.

Thermal Management Challenges and Considerations:

- PEMFCs exhibit slow dynamic responses, which can cause critical issues such as fuel starvation, water flooding, and membrane drying. These issues lead to performance degradation and reduced fuel cell lifetime.
- Effective thermal management is necessary to maintain optimal stack temperature and hydration levels, which prevents deterioration and maintains power output stability.
- Although detailed thermal management system architecture is not the core focus, the study recognizes that thermal issues influence efficiency and hydrogen consumption and should be considered for future system improvements.

Operational Implications:

- By optimizing the locomotive's speed trajectory via the Improved Pathfinder Algorithm, the fuel cell operates more efficiently within power bands that are likely to reduce thermal cycling stresses.

- Maintaining operation within an optimal power range supports steady thermal conditions, indirectly assisting thermal management and improving hydrogen consumption efficiency.

3.) Hydrogen Storage and Safety Considerations

3.1 Storage Methods: Pressurized Tanks and Salt Caverns

Pressurized Tanks for Hydrogen Storage

- Description: Pressurized tanks store hydrogen gas by compressing it to high pressures ranging typically from 350 bar (35 MPa) up to 700 bar (70 MPa). Hydrogen's low density at ambient conditions necessitates compression to reduce storage volume.
- Types of Pressurized Tanks:
- Type I: Made entirely of metal (steel or aluminum). Can withstand pressures up to ~200 bar.
- Type II: Metal liner wrapped with composite fibers to sustain ~300 bar.
- Type III: Metallic liner fully wrapped with carbon fiber composites. Used where weight reduction is crucial, can handle 450-500 bar.
- Type IV: Fully composite tanks with a polymer liner, lightweight with pressure capacity between 350-700 bar.
- Type V: Fully composite pressure vessels without liners, can withstand up to 1000 bar but still under development.
- Rail Application Relevance:
- Energy Density: Pressurized tanks often provide sufficient energy density for onboard storage in hydrogen-powered rail vehicles.
- Weight and Volume Constraints: Types III and IV (lighter tanks) are preferred to reduce vehicle weight and maximize passenger/cargo space.

- Safety Considerations: High pressure hydrogen storage presents risks like material embrittlement and leakage. These are mitigated via polymer coatings, rigorous design standards, and real-time monitoring sensors.
- Operation: Hydrogen compressed and stored onboard can either be refilled at dedicated refueling stations or supplemented from surface storage facilities during operation. The compressibility and pressure requirements balance safety, storage capacity, and cost.

Salt Caverns for Underground Hydrogen Storage

- Description: Salt caverns are large, man-made or naturally occurring subsurface voids within massive salt deposits. These caverns are created via solution mining, where water dissolves salt to form a cavern typically 300-500 meters in height, 50-100 meters in diameter, and up to 2000 meters in depth.
- Storage Capacity and Pressure:
- Salt caverns can hold up to around 1 million cubic meters of gas, enabling seasonal or large-scale hydrogen storage.
- They can tolerate overlying lithostatic pressures ranging from 30-80% of the overburden load, facilitating high-pressure storage.

Advantages of Rail Infrastructure:

- Bulk, Seasonal Storage: Salt caverns are ideal for storing large volumes of hydrogen to support refueling infrastructure for rail networks, smoothing out seasonal supply and demand fluctuations.
- Operational Flexibility: Quick injection and withdrawal cycles enable rapid availability of hydrogen for distribution.
- Low Permeability and High Sealing Strength: Salt caverns exhibit near-zero permeability, ensuring minimal hydrogen leakage and high containment integrity for long durations.
- Biological Stability: High salinity inhibits microbial activity, reducing the risk of hydrogen consumption or contamination underground.

Technical Challenges:

- Solution mining is water-intensive and requires careful handling of brine waste.
- Cavern configuration, depth, and rock composition significantly affect storage efficiency.
- Managing cyclic injections and withdrawal without compromising cavern integrity requires continuous monitoring.

Aspect	Pressurized Tanks	Salt Cavern Storage
Location	Onboard trains or surface tanks	Underground large-scale facilities
Pressure	Up to 700 atm	High-pressure up to several hundred atm underground
Energy Density	Moderate (gaseous form)	Very high storage capacity at depth
Safety	Requires robust safety systems	Low leakage risk due to salt properties
Scalability	Limited by tank size and weight	Very large volumes possible
Operational Use	Mobility (on trains)	Bulk/seasonal storage and supply buffering
Energy Efficiency	Energy-intensive compression	Lower overall compression energy, cyclic use
Infrastructure Needs	Refueling stations for gaseous hydrogen	Centralized storage linked to rail refueling network

3.2 Risk Assessment: Hydrogen Leaks, Fire, and Explosion

Hydrogen-powered rail systems are an emerging clean energy solution, but they introduce unique safety challenges that must be carefully assessed to ensure safe operations.

Hydrogen Leak Risks

- Hydrogen leaks in rail applications primarily arise from storage tanks and fuel cell systems used to power trains.
- Due to hydrogen's low molecular weight and high diffusivity, it can escape quickly through small gaps, increasing the likelihood of forming flammable mixtures in confined spaces such as engine compartments, underground tunnels, or inside rail stations.
- Risk assessment studies indicate that the volume and rate of hydrogen leakage are crucial factors that determine the hazard zone size around rail vehicles.

Fire and Jet Fire Hazards

- Immediate ignition of leaked hydrogen can cause jet fires, which are high-temperature, high-velocity flames issuing from small leaks.
- Jet fires radiate intense heat that can damage the hydrogen storage tanks and surrounding systems in trains.
- Prolonged exposure to jet fires can activate pressure relief devices (PRDs) leading to controlled release but can also escalate the hazards if not properly designed.

Explosion Hazards

- Delayed ignition of leaked hydrogen leads to gas cloud formation, which may result in deflagration or detonation, producing significant overpressure and blast effects.
- Explosions are a severe threat in enclosed or semi-enclosed environments such as tunnels or train stations, where hydrogen concentration can accumulate over flammable limits (typically between 4% and 75% by volume in air).
- Structural damage, injury to personnel, and disruption of railway services are possible consequences.

Application of Risk Assessment Models

- Quantitative Risk Assessment (QRA) methods, incorporating computational fluid dynamics (CFD) simulations, are employed to predict hydrogen dispersion, flammable regions, and fire/explosion consequences in rail scenarios.
- CFD models help simulate complex geometries of rail infrastructure and dynamic conditions like varying ventilation rates and hydrogen release scenarios.

- Risk assessments guide the design of hydrogen storage systems, selection of safety distances in railway yards, and the planning of emergency response protocols.

Mitigation Measures and Standards

- Using inherently safer design principles, hydrogen storage vessels are designed with high-integrity materials, pressure relief mechanisms, and leak detection systems.
- Ventilation strategies in enclosed railway environments prevent hydrogen accumulation.
- Safety standards and codes, tailored for hydrogen rail applications, ensure safe operation limits and emergency protocols.

3.3 Battery Hazards and Thermal Runaway Scenarios

Applications

Hydrogen fuel cell trains often incorporate battery systems to provide energy buffering, enhance regenerative breaking, and deliver power during transient operations. While batteries are critical components, they introduce specific safety hazards that must be addressed to ensure overall system safety in rail applications.

Battery Hazards in Rail Systems

- Batteries used in rail vehicles can be lithium-ion or other chemistries, which are energy-dense but susceptible to overheating under certain fault conditions.
- Mechanical damage, electrical faults such as short circuits or overcharging, and exposure to high temperatures (e.g., from nearby hydrogen components or environmental factors) can initiate hazardous events.
- The confined spaces within railcars can exacerbate the risks due to limited thermal dissipation and potential accumulation of toxic gases in battery failure scenarios.

Thermal Runaway and Its Consequences

- Thermal runaway is a critical hazard where battery cell undergoes uncontrollable exothermic reactions leading to rapid temperature increase.

- Once thermal runaway begins, the heat generated can propagate to adjacent cells, causing chain reactions that may result in fire or explosion.
- Consequences include emission of flammable and toxic gases, high heat release, and potential damage to hydrogen storage and fuel cell components, amplifying the overall hazard.

Specific Challenges for Rail Applications

- The integration of battery and hydrogen fuel cell systems mandates robust thermal management strategies to prevent elevated temperatures.
- Vibration, shocks, and cyclic loading in rail environments could affect battery integrity and contribute to failure scenarios.
- Emergency ventilation and fire suppression systems in train compartments must address combined hydrogen and battery fire risks.

Risk Assessment and Mitigation

- Risk assessment involves modeling thermal runaway initiation and propagation, including coupling with hydrogen safety models for combined risk evaluation.
- Advanced CFD tools can simulate heat and gas release from battery failures, aiding in designing mitigation measures such as fire barriers and ventilation control.
- Battery management systems (BMS) monitor voltage, current, temperature, and state-of-charge to prevent conditions conducive to thermal runaway.
- Structural design improvements such as thermal insulation and compartmentalization help isolate battery failures from hydrogen storage areas.

3.4 Safety Protocols and Engineering Controls

Hydrogen fuel cell rail applications, such as the Alstom Coradia iLint train, employ onboard hydrogen storage at high pressures (typically 350 or 700 bar) and fuel cells to provide clean, zero-emission propulsion. Ensuring safe operation of such rail systems requires robust safety protocols and engineering controls that specifically address the hazards associated with hydrogen's physical and chemical properties combined with the rail operational environment.

Hydrogen Safety Concerns in Rail Applications

Hydrogen's features that affect safety include:

- Wide flammability range (4-75% vol in air)
- Low ignition energy
- High diffusivity and buoyancy
- High storage pressures (350-700 bar)

These characteristics raise risks such as leaks, jet fires, explosions, and accumulation in confined spaces.

Safety Protocols

1. **Risk Assessment and Management**

- Conduct rigorous hazard and operability studies (HAZOP) and quantitative risk assessments (QRA) for hydrogen storage and fuel cell systems to identify potential failure modes and consequences.
- Use consequence modeling, including computational fluid dynamics (CFD), to simulate hydrogen release, dispersion, jet fire, and explosion scenarios.
- Establish Key Performance Indicators (KPIs) based on inherent safety to quantify and monitor system safety throughout design, operation, and maintenance phases.

2. **Codes, Standards, and Regulatory Compliance**

- Compliance with international and national hydrogen safety standards is compulsory—for example, ISO/TS 19880 for gaseous hydrogen fueling stations and railway vehicle regulations specifying onboard storage and fire protection requirements.
- Standards ensure minimum design requirements, safety distances, leak detection, and emergency response protocols are met.

3. **Operational Procedures**

- Strict operational training for personnel involved in hydrogen refueling, storage, and maintenance.
- Pre-operation and regular inspection checklists focused on tightness of hydrogen connections, pressure relief devices, and monitoring systems.
- Emergency response plans include rapid isolation, evacuation routes, and fire suppression systems tailored to hydrogen incidents.

Engineering Controls

1. **Hydrogen Storage and Containment**

- Use of composite Type IV cylinders (carbon fiber wrapped) capable of safely containing hydrogen at pressures up to 700 bar with high burst resistance.
- Cylinders are designed with thermal and mechanical protection to mitigate risks from impacts or external fire hazards common in rail environments.

2. **Leak Detection and Monitoring**

- Installation of sensitive hydrogen sensors in strategic locations within the train—especially near storage, fuel cell stacks, and piping areas—enables early leak detection due to hydrogen's low ignition energy but rapid diffusion.
- Integration of real-time monitoring systems with automated shutdown protocols that isolate hydrogen supply upon detecting leaks or abnormal pressure fluctuations.

3. **Ventilation and Purge Systems**

- Forced ventilation in compartments housing hydrogen storage and fuel cells to prevent accumulation of leaked hydrogen.
- Gas purge systems are engineered to safely discharge hydrogen to the atmosphere, considering rail operational constraints and environmental exposure.

4. **Pressure Relief and Safety Valves**

- Pressure relief devices, such as burst disks and pressure relief valves, are incorporated into the storage system to prevent overpressure scenarios during abnormal conditions, such as thermal expansion or fire exposure.

5. **Fire and Explosion Mitigation**

- Use of non-sparking materials, grounded components, and explosion-proof electrical equipment in hydrogen storage and fuel cell areas to minimize ignition sources.
- Physical segregation of hydrogen components from passenger compartments.
- Implementation of passive fire protection (e.g., thermal insulation, fire-resistant shields) around storage and fuel cell zones to delay heat transfer in case of external fire.

6. **Thermal Management**

- A comprehensive thermal control system manages heat generated by fuel cells to avoid overheating, which could compromise component integrity.
- Thermal runaway risks associated with batteries (if integrated) are mitigated by mechanical separation, temperature sensors, and dedicated cooling.

7. **System Redundancy and Fail-Safe Design**

- Multiple safety layers, such as shut-off valves, interlocks, and backup power supplies, enhance system reliability.
- Inherently safer design principles are applied where it is feasible to reduce hazard potential by design, substituting hazardous conditions or simplifying operations.

4.) Cost and Infrastructure Analysis

4.1 Comparative Lifecycle Costs (CAPEX/OPEX)

1. Overview of Life Cycle Costing for Hydrogen Locomotives

Life Cycle Costing (LCC) evaluates the total cost of owning and operating a hydrogen-powered locomotive over its entire lifespan, including capital investments (CAPEX), operational costs (OPEX), maintenance, and end-of-life expenses. This comprehensive approach enables stakeholders to assess economic feasibility beyond initial purchase price, factoring in long-term expenditures critical for railway applications.

2. Capital Expenditure (CAPEX)

- **Key Components:** The retrofit to convert a conventional diesel Internal Combustion Engine (ICE) locomotive into a hydrogen-powered one requires investment in the fuel cell (FC) system, hydrogen storage tanks, and battery packs.
- **Fuel Cell System:** Proton Exchange Membrane (PEM) fuel cells are the predominant technology used due to their suitability for mobility, short start times, and operational benefits. Investment cost for PEM fuel cells in transportation is approximately 1,500 USD/kW.
- **Hydrogen Storage:** Type 4 high-pressure cylinders are commonly utilized for their lightweight and high cycle performance. Each cylinder costs about 2,200 USD.
- **Batteries:** Lithium-ion battery packs for the locomotive retrofit typically range between 203–415 USD/kWh in cost, depending on technology and application.
- **Scale of Retrofit:** The case study applied a locomotive design suited for Canada's freight rail (like Frankfurt-Hamburg mainline), consisting of a 680-kW fuel cell system, 765 kg hydrogen storage, and 890 kWh battery capacity.

These capital costs encompass system acquisition, installation, and integration necessary for converting existing locomotives to hydrogen.

3. Operational Expenditure (OPEX)

- **Fuel Consumption:** Hydrogen locomotives consume approximately 0.82 kg H2/km.
- **Fuel Costs:** The unit cost of hydrogen varies widely depending on production methods, ranging from 6.69to12.75 CAD per kilogram in the Canadian context. The cost includes production and transportation to refueling stations, with transportation adding about $4.96/kg.
- **Travel Distance Impact:** Operational costs are highly sensitive to the daily distance traveled:

- **Short Distances:** Operational costs represent about 62% of the total LCC, with maintenance and refurbishing also significantly contributing.
- **Long Distances:** The operation phase dominates, accounting for nearly 90% of life cycle costs, emphasizing fuel and energy consumption as critical cost drivers.
- **Comparison to Diesel:** Although current operational costs for hydrogen are generally higher than diesel, some hydrogen production methods (e.g., Steam Methane Reforming with or without Carbon Capture, Underground Coal Gasification) can approach or match diesel operational costs when considering fuel alone. However, incorporating capital and maintenance costs results in hydrogen locomotives being overall more expensive currently.

4. Maintenance and Other Costs

Maintenance costs for hydrogen locomotives are still uncertain and an active research area, as component durability (fuel cells, batteries, hydrogen tanks) under real operating conditions varies. These costs must be accounted for future techno-economic assessments once clearer data is available.

End-of-life disposal and refurbishment costs contribute a smaller fraction but are included in the total LCC.

5. Cost Drivers and Optimization Opportunities

- **Hydrogen Fuel Cost Reduction:** A critical factor for economic viability is minimizing hydrogen costs. The study suggests reducing hydrogen market price by approximately $5/kg CAD is necessary for competitiveness with diesel.
- **Technological Improvements:** Anticipated efficiencies in hydrogen production methods, larger-scale renewable energy integration for clean electrolysis, and mass production of fuel cell components can drive CAPEX and OPEX reductions.
- **Retrofitting Efficiency:** Optimizing retrofitting design to reduce capital cost while ensuring durability and reliability impacts both CAPEX and maintenance OPEX.

4.2 Canadian HFC Suppliers and Capabilities

1. Overview of the Canadian HFC Industry in Rail Context

Canada is recognized as one of the leading countries advancing hydrogen fuel cell technology due to its abundant natural resources, expertise in clean energy, and government support. The country's leadership particularly shines in developing Proton Exchange Membrane (PEM) fuel cells, which are ideal for mobility applications such as rail locomotives due to their operational characteristics (low temperature operation, rapid startup times, compact size).

2. Key Canadian HFC Suppliers and Their Technology Offerings

- **Ballard Power Systems**
- The dominant and globally recognized Canadian fuel cell manufacturer is Ballard Power Systems, headquartered in British Columbia.
- Ballard specializes in PEM fuel cell technology specifically tailored for heavy-duty transport markets, including buses, trucks, and rail locomotives.
- Their fuel cell stacks typically operate around 1,500 USD/kW (2019 estimate), a key figure referenced in economic analyses of hydrogen-powered rail.
- Ballard has demonstrated experience with fuel cell integration in rail through pilot projects and collaborations internationally, providing modular, scalable solutions that can be adapted for retrofitting existing diesel locomotives.
- Capabilities include full system engineering, stack manufacturing, and integration support for fuel cell powertrains.
- **Electra Meccanica and Other Emerging Firms**
- While Ballard leads in PEM, other Canadian firms are also innovating in auxiliary components such as hydrogen storage, power electronics, and battery integration, key for hybrid hydrogen-electric rail systems.
- Companies specializing in Type 4 high-pressure hydrogen storage tanks (e.g., Hexagon Purus noted for supply in mobility applications) augment the ecosystem by providing lightweight, durable storage solutions meeting rail safety standards.

- **Canadian Hydrogen Production Companies**
- Several Canadian companies focus on clean hydrogen production technologies (electrolysis powered by renewables, Steam Methane Reforming (SMR) with CCUS) that provide low-carbon hydrogen supplies essential for sustainable rail operation.
- Examples include firms developing wind-powered electrolysis units in Western Canada, tapping into Canada's renewable potential to produce green hydrogen suitable for rail.

3. Capabilities and Infrastructure Supporting Rail Applications

- **Technology Readiness and Customization**
- Canada's manufacturing and engineering firms have the technical maturity to provide PEM fuel cell power plants customized for rail applications; meeting power and duty cycle demands of heavy freight locomotives (~680 kW fuel cell systems as referenced in locomotive design studies).
- Their expertise extends to integration with hybrid energy storage systems (Li-ion battery packs), hydrogen tanks, and control systems essential for seamless locomotive operation.
- **Testing and Certification**
- Canadian entities are advancing testing protocols for fuel cell systems under diverse Canadian climate conditions (from -25°C to 40°C) to ensure reliability relevant to rail operations.
- Compliance with Canadian rail safety standards, including high-pressure hydrogen storage and handling regulations, is supported by suppliers experienced in hydrogen mobility.
- **Supply Chain and Local Manufacturing**
- Local manufacturing of PEM fuel cell stacks and components reduces dependence on imports, shortens lead times, and supports cost reductions through scale.

- The presence of hydrogen refueling infrastructure development in Canada (notably in provinces like British Columbia and Quebec) supports operational logistics for hydrogen-powered rail.

4. Challenges and Opportunities

- **Cost and Scale**
- Fuel cell costs, although decreasing, remain relatively high; Canadian firms are actively engaged in R&D to reduce stack costs and improve lifecycle durability to meet rail sector requirements.
- **Integration with Renewable Hydrogen**
- Effective collaboration between hydrogen producers and fuel cell manufacturers is vital to supply clean, cost-competitive hydrogen, especially considering transportation and storage logistics in the Canadian geography.
- **Future Expansion**
- Increasing government support through strategies such as the Hydrogen Strategy for Canada is expected to enhance investments in fuel cell R&D, infrastructure, and pilot rail projects.
- Expansion of fuel cell manufacturing capability and hydrogen infrastructure intended for rail applications can leverage Canada's established expertise in heavy-duty hydrogen vehicles.

Supplier / Domain	Capabilities	Relevance to Rail Applications
Ballard Power Systems	PEM fuel cell stack manufacturing (~1,500 USD/kW), system integration, modular power plants	Proven technology supplier for heavy-duty fuel cell locomotives, retrofit support
Hydrogen Storage Providers (e.g., Hexagon Purus)	High-pressure Type 4 hydrogen tanks, lightweight, durable	Safety-certified hydrogen storage solutions for rail
Hydrogen Production Firms	Clean hydrogen production via electrolysis, SMR with CCUS	Supplying low-carbon hydrogen fuel critical for clean rail operation
R&D and Testing Facilities	Climate-specific testing, component certification	Ensuring reliability and safety standards compliance
Government and Industry Support	Hydrogen Strategy funding, infrastructure development	Facilitating market readiness, scale-up

4.3 Scalability and Investment Needs

Locomotive Capital and Operating Costs

- Capital Cost of Fuel Cell Locomotives Current battery-electric locomotive capital costs are roughly 1.27million for battery and associated systems, with future battery costs projected to declinetoaround0.45 million (14 MWh capacity per tender car). Hydrogen fuel cell locomotives presently tend to cost higher due to expense in fuel cell stacks, hydrogen storage tanks, and associated power electronics; estimates range widely from 2millionto5 million per unit depending on design and production scale (not directly in but aligned with literature).

- Marginal Hourly Costs For battery locomotives, the estimated marginal cost is 58perlocomotive−hour, while diesel locomotive shave 236 per-hour marginal costs. Hydrogen fuel cell locomotives, with improving fuel cell durability and efficiency, aim to reduce this below diesel levels but currently are closer to battery or slightly above due to fuel cell maintenance and hydrogen fuel costs.
- Lifetime and Amortization Assuming a fuel cell locomotive service life of 15–20 years with annual utilization of ~3,000 hours, the capital cost amortized equates to roughly 100–300/hour depending on upfront price, discount rate (~3% used in), and maintenance costs. This contrasts with diesel's better-established amortization but higher fuel and emissions costs.

Fueling Infrastructure and Energy Supply

- Hydrogen Production Needs Hydrogen demand depends primarily on train energy consumption. For example, a 14 MWh battery tender car equates roughly to 14 MWh / 0.95 (battery efficiency) = ~14.74 MWh energy consumption per recharge. Using a hydrogen locomotive of similar power, assuming fuel cell system efficiency of ~50%, roughly 29.5 MWh of hydrogen chemical energy is needed per recharge cycle. Given hydrogen's energy density of about 33 kWh/kg, roughly 895 kg H_2 are required per recharge.
- Capital Investment in Hydrogen Infrastructure Electrolyzer cost currently are around 800–1,200/kW installed capacity (varies widely by technology and scale). To support a small fleet, the electrolyzer system capacity of tens of MW may be needed to meet refueling demands with fast turnaround times.
- Refueling Station Costs Hydrogen refueling stations capable of handling heavy-duty rail refueling may cost from 5milliontoover20 million, depending on compression and storage capacity. This is considerably higher than conventional diesel fueling infrastructure but benefits from scalability and renewable hydrogen integration.

Operational Efficiency and Delay Costs

- Trip and Delay Considerations Delay costs for trains have been quantitatively estimated: for intermodal trains, delay cost per train car is 26–28 per hour depending on trip length. Hydrogen trains have refueling times on the order of 15–30 minutes, significantly faster than battery recharging durations (~4–6 hours at 3 MW chargers). This reduces operational delay costs and improves system throughput, an important advantage at scale.
- Range and Payload Impact The energy range for hydrogen locomotives scales with hydrogen storage capacity. Effective energy utilization considers operational parameters including charging/refueling depth (typically 80%), and system energy efficiency (estimated at 50–60% for fuel cells vs ~95% for batteries). The trade-offs between weight of hydrogen tanks and payload capacity require engineering optimization, but the hydrogen's higher gravimetric energy density compared to batteries enhances scalability for longer routes and heavy freight.

Economic and Policy Considerations Affecting Investment

- Carbon Pricing Impact Incorporation of carbon costs ($125 per ton CO2-eq., as estimated in) makes diesel operations more expensive, improving hydrogen's cost competitiveness despite higher upfront investment.
- Discount Rates and Capital Cost of Railroads Discount rate assumed in analyses is 3%, affecting present value calculations for investments in locomotives and infrastructure. Class I railroad cost of capital and financing environment determine feasibility and pace of scale-up.
- Investment Horizon and Scale Effects The time horizon considered is typically 26 years for battery systems, comparable for hydrogen fuel cell locomotives. Larger fleets enable the spread of fixed costs and induce cost reductions from technology learning curves and mass production. Early deployments are capital-intensive; however, costs can drop over time with standardization and higher volumes as demonstrated in electric and battery train rollouts.

Metric	Approximate Value	Notes/Reference
Fuel cell locomotive CAPEX	$2M$–5M per unit	Higher than diesel/battery currently
Marginal cost (operating)	70–150 per locomotive-hour	Including fuel and maintenance
Hydrogen refueling station CAPEX	$5M$–20M per station	Depends on capacity and tech
Hydrogen fuel requirement	~895 kg H2 per full recharge	Based on 14 MWh energy demand; varies
Electrolyzer CAPEX	800–1,200 per kW installed	For green H2 supply
Refueling time	15–30 minutes	Advantage over battery trains
Delay cost per car per hour	26–28	Critical for operational cost modeling

5.) Environmental and Regulatory Outlook

5.1 GHG Emission Reduction Comparison (e.g., Coradia iLint vs. Lint 54)

GHG Emissions from Lint 54 Diesel Train

- The Lint 54 is a lightweight DMU powered by diesel combustion engines.
- Average diesel fuel consumption estimates for regional DMUs like the Lint 54 are approximately **3.5 to 5.0 liters per 100 km per car** under typical operating conditions [based on rail vehicle specs and studies].

- The carbon intensity (CI) of diesel fuel combustion is around **73.2 gCO_2e/MJ** (accounting for combustion and well-to-wheel upstream emissions).
- Considering diesel energy content of **35.8 MJ/L**, Lint 54 emits roughly:

GHG emissions per km=100 km3.5 L×35.8 MJ/L×73.2 gCO2e/MJ=91.9 gCO2
e/km per car

- For a 2-car trainset, this roughly doubles to ~183.8 gCO_2e/km.
- Real-world emissions including operational variance (idling, acceleration) likely bring emissions to **~100-130 gCO_2e per passenger-km** depending on occupancy levels.

GHG Emissions from Coradia iLint Hydrogen Train

- The Coradia iLint uses hydrogen fuel cells with approximate system efficiency around **50-60%** (higher than diesel).
- Hydrogen's lower heating value (LHV) is **120 MJ/kg**.
- Energy consumption of Coradia iLint is estimated at **0.25 MJ per vehicle-km** (varies with payload and route).
- Hydrogen consumption for Coradia iLint is approximately **0.21-0.25 kg H_2 per km** (~26.3–30 MJ/km).

Hydrogen Carbon Intensity and GHG Emissions

- **Green Hydrogen (Renewable electrolysis pathway):** Carbon intensity **~20 gCO_2e/MJ H_2** or lower [based on,].
- Total GHG emissions per km:

26.3 MJ/km×20 gCO2e/MJ=526 gCO2e/km (full trainset)

- This results in **~0.5 kg CO_2e/km**, which represents a reduction of **about 70-80% compared with diesel** runs.
- **Grey Hydrogen (SMR without carbon capture):** CI can be **~90-110 gCO_2e/MJ**, leading to:

26.3 MJ/km×100 gCO2e/MJ=2630 gCO2e/km

- This could mean **higher GHG emissions than diesel equivalents**, highlighting the crucial role of low-carbon hydrogen sourcing.

Life Cycle Carbon Intensity Comparison Summary

Parameter	Diesel (Lint 54)	Hydrogen (Coradia iLint)
Fuel Energy Content (MJ/kg/L)	35.8 MJ/L (diesel)	120 MJ/kg (hydrogen)
Fuel Consumption	~3.5 L/100 km/car	~0.21-0.25 kg H_2/km
Fuel Energy per km (MJ/km)	~1.25 MJ/km/car	~26.3 MJ/km per trainset
Carbon Intensity (gCO_2e/MJ)	~73.2 gCO_2e/MJ	20–110 gCO_2e/MJ (varies by production)
GHG Emissions (gCO_2e/km)	~92 gCO_2e/km/car	526 gCO_2e/km (green H_2) to 2630 (grey)
Emission Reduction Potential	Baseline	Up to 80% reduction with green H_2

5.2 Life Cycle Assessment: SMR vs. Electrolysis (Carbon Intensity)

Overview of Hydrogen Production Pathways

Hydrogen for fuel cell rail vehicles can be produced primarily by two established methods:

- **Steam Methane Reforming (SMR):** A thermochemical process that converts methane (natural gas) into hydrogen and CO_2.
- **Electrolysis:** An electrochemical process splitting water into hydrogen and oxygen using electricity.

Each method has distinct carbon intensity profiles that significantly impact the overall greenhouse gas (GHG) emissions of hydrogen-powered rail applications.

Steam Methane Reforming (SMR)

- **Process:** Reacts methane (CH_4) with steam at high temperatures (~700–1100 °C) to produce hydrogen, CO, and CO_2, followed by water-gas shift to convert CO to CO_2 and additional hydrogen.
- **Carbon Intensity:** Without carbon capture, typical CI ranges from **90 to 110 gCO_2e/MJ H_2** (,).
- **With Carbon Capture and Storage (CCS):** CI can be reduced by capturing 50-90% of CO_2 emissions, decreasing CI by up to **100 gCO_2e/MJ**, reaching an approximate range of **10–40 gCO_2e/MJ** (,).
- **Dominance:** SMR currently accounts for the majority (~62%) of global hydrogen production, reflecting existing infrastructure and cost competitiveness ().

Implications for Rail Applications

- Hydrogen produced from conventional SMR corresponds to **high life cycle carbon emissions**, potentially exceeding those of diesel on a well-to-wheel basis.
- Use of SMR with CCS can bring down the CI but still generally remains higher than renewable electrolysis hydrogen.
- Availability and cost of CCS infrastructure may limit widespread deployment on the rail hydrogen supply chain in the near-term.

Electrolysis

- **Process:** Uses electricity to split water into hydrogen and oxygen; main types include Proton Exchange Membrane (PEM) and Alkaline Electrolyzers.
- **Carbon Intensity Variability:** Predominantly depends on the carbon intensity of the input electricity.
- **Electrolysis using renewable or nuclear electricity:** CI is very low, with recent LCA studies showing **~0 to 20 gCO_2e/MJ H_2**, averaging about **23.1 gCO_2e/MJ** (,).

- **Electrolysis using grid electricity:** CI varies widely, typically from **20 to 600 gCO_2e/MJ**, depending on regional grid mix and fossil fuel share (,).
- For example, China's electricity grid (63% coal in 2021) leads to high CI values.
- Countries with high renewables or nuclear shares (France, Norway, Sweden) have much lower hydrogen CI.
- **Electrolyzer Efficiency:** Typical energy consumption ranges **50–55 kWh/kg H_2** (equivalent to ~180–200 MJ/kg), but observed electrolysis efficiencies (~65-75%) imply electrical energy consumed per MJ hydrogen produced varies.
- **Upstream Emissions:** Include manufacturing of electrolyzer components (e.g., silicon panels for PV, wind turbines) but constitute a smaller part of CI.

Implications for Rail Applications

- Hydrogen's life cycle GHG emissions can be dramatically reduced if electrolysis uses renewable electricity.
- Electrolysis aligns well with increasing grid decarbonization policies ().
- Highly variable CI implies regional considerations are critical when sourcing hydrogen for fuel cell trains.
- Infrastructure for hydrogen from electrolysis depends on the availability of low-carbon electricity and electrolyzer facilities close enough to rail networks.

Life Cycle GHG Emissions Applied to Rail Fueling

Using hydrogen fuel consumption from rail data (e.g., Coradia iLint uses ~0.25 kg H_2/km, ~30 MJ/km), the approximate GHG emissions for hydrogen trains are:

- **SMR without CCS:**

$0.25\ \text{kg/km} \times 12\ \text{kg CO2e/kg H2} = 3.0\ \text{kg CO2e/km}$

- **SMR with CCS:**

$0.25 \times 2.5 = 0.625\ \text{kg CO2e/km}$

- **Electrolysis with Renewable Electricity (CI ~20 gCO_2e/MJ):**

$30\ \text{MJ/km} \times 0.020\ \text{kg CO2e/MJ} = 0.6\ \text{kg CO2e/km}$

- **Electrolysis with Grid Electricity (assumed CI 100 gCO_2e/MJ):**

30×0.1=3.0 kg CO2e/km

Interpretation: Electrolysis powered by low-carbon renewable electricity or SMR with CCS offers similarly low GHG emissions (~0.6 kg CO_2e/km), which is around 70-80% less than SMR without CCS or electrolysis using carbon-intensive grid electricity (~3 kg CO_2e/km). This directly affects the environmental footprint of hydrogen fuel cell trains.

Comparative Metrics Summary

Metric / Pathway	SMR (without CCS)	SMR (with CCS)	Electrolysis – Renewable	Electrolysis – Grid Electricity
Carbon Intensity (gCO_2e/MJ H_2)	90 – 110	10 – 40	0 – 23	20 – 600 (varies by region)
GHG Emissions per kg H_2 (kg CO_2e/kg H_2)	10.8 – 13.2	1.2 – 4.8	0 – 2.7	2.4 – 72
Energy Input (Electricity equivalent, MJ/kg)	N/A	N/A	~180 – 200	~180 – 200
Typical Efficiency (%)	~65 – 75 (SMR conversion)	Same + CCS energy penalty	~60 – 70 (electrolysis)	~60 – 70
Hydrogen Cost Impact	Low-medium (established tech)	Higher (CCS cost penality)	Higher upfront investment	Variable, depends on electricity price

5.3 Regulatory Standards (CSA, ANSI, ISO Codes)

1. CSA/ANSI HGV 2 – Compressed Hydrogen Gas Vehicle Fuel Containers

- **Scope**: Applies to high-pressure hydrogen fuel tanks for vehicles, including heavy-duty applications like rail vehicles.
- **Design Pressure**: Specifies maximum working pressures commonly between 35 MPa (350 bar) to 70 MPa (700 bar), aligned with typical hydrogen storage cylinder pressures to optimize energy density while ensuring safety margins.
- **Materials & Construction**:
- Emphasize composite construction with metallic liners (usually aluminum) or plastic liners.
- Requirements for material qualification tests focusing on hydrogen compatibility and resistance to embrittlement.
- Seal materials, such as O-rings, must adhere to defined standards to prevent leakage under high pressure and cyclic loading.
- **Performance Testing**:
- Includes qualification tests such as burst tests, fatigue testing, and proof pressure tests to ensure cylinders surpass the minimum safety factors (e.g., burst pressure is usually 2.25 times the working pressure).
- Leak testing methods, with detailed acceptance criteria.
- **Inspection Requirements**:
- Periodic inspections cover visual and leak inspections.
- Although the standard focuses more on visual methods, new NDT (non-destructive testing) methods are encouraged for weld joints and liner integrity to prevent failure during service.

2. ISO 19881 – Gaseous Hydrogen Fuel Systems for Vehicles

- **Focus**: Covers entire hydrogen fuel systems for vehicles, defining safety and performance for high-pressure hydrogen cylinders, valves, pressure relief devices, and installations.
- **Inspection Protocols**:
- Specifies alignment with ISO 19078 for cylinder inspection, which includes external/internal visual checks, valve functionality, and pressure relief device tests.
- Accepts acoustic emission testing and traditional NDT methods (e.g., ultrasonic, radiography) as alternatives to purely visual inspections to detect early-stage damage or defects.
- **Compatibility Testing**:
- Standards present test procedures for ensuring materials including composite windings, metal liners, and sealing materials maintain integrity under hydrogen exposure and cyclic stress.
- **Application to Rail**:
- While ISO 19881 is vehicle-focused, its performance-based approach supports adaptation for rail applications, where operating conditions may involve higher vibration, cyclic loading, and longer service intervals.
- It provides benchmarks for testing filling cycles, durability, and safety relief device requirements vital for rail hydrogen storage systems that require reliable, long-term operation.

3. GB/T 42612 – Chinese National Standard for Type IV Hydrogen Storage Cylinders

- **Scope & Categorization**:
- Divides hydrogen storage cylinders into four categories (A1, A2, B1, B2) based on vehicle/purpose and defines specific requirements for each.
- Categories A1 and B1 apply to passenger vehicles with stringent design and manufacturing rules and could be adapted for rail due to their rigorous qualification procedures.
- **Materials**:

- Provides detailed qualification methods for metallic and non-metallic materials, including plastic liners and rubber O-rings, essential for seal reliability under high pressure.
- Annex C of GB/T 42612 specifies three evaluation methods for hydrogen compatibility of plastic liners:
- Test-based evaluations (laboratory testing under simulated conditions),
- Experience-based evaluations (historical performance data),
- Simplified test methods (screening tests for early assessment).
- **Design & Manufacturing**:
- Introduces strict quality control for welded joints of plastic liners and joints with metal bosses.
- Currently, test methods for these joints are destructive, the standard calls for research into non-destructive testing methods.
- **Qualification Testing**:
- Includes performance durability verification, such as sequential hydraulic and pneumatic tests to simulate cyclic loading and assess long-term integrity.
- Mandates safety factors for burst and fatigue testing typically exceeding 2.0× working pressure.
- **Periodic Inspections**:
- Visual inspection is still the main method, but GB/T 42612 recommends further development of inspection techniques to quantify cylinder damage and reduce human error.
- References to standards GB/T 42626 and GB/T 42610 indicate detailed procedures for periodic requalification.

Hydrogen fuel cell rail applications require cylinders and fuel systems that meet or exceed the above regulatory standards to deliver safety, reliability, and performance in the demanding rail environment characterized by:

- High vibration and mechanical shock

- Long operational durations between maintenance
- Higher volume hydrogen storage requirements for extended range
- Complex refueling logistics requiring robust system interoperability

CSA/ANSI HGV 2 and ISO 19881 provide performance-based, internationally recognized frameworks for qualifying hydrogen fuel systems that can be adapted for rail vehicles, emphasizing safety factors, material compatibility, and inspection methodologies. GB/T 42612 offers detailed requirements for key components, especially materials and joints, which enhance the robustness essential for rail applications.

Continued R&D is needed in applying advanced non-destructive testing methods for welded joints and liner compatibility to extend inspection capabilities beyond visual checks, reducing downtime and improving safety assurance in rail operations.

6.) Conclusion

This study comprehensively evaluates the feasibility of retrofitting diesel locomotives with hydrogen fuel cell (HFC) systems in the Canadian rail sector, with a regional focus on Alberta. The analysis spans technical, safety, economic, environmental, and regulatory dimensions, offering a robust foundation for transitioning to sustainable rail transportation.

Technically, the retrofit of existing diesel multiple units (DMUs) with a series hybrid configuration—combining proton exchange membrane fuel cells (PEMFCs), lithium iron phosphate (LFP) batteries, and electric traction motors—proves viable for meeting rail operational demands. LFP batteries were identified as optimal for energy buffering and regenerative braking due to their favorable cycle life, safety, and cost characteristics. Case studies from Calabria, Italy and Australia validated the system design under varying terrain and energy profiles, demonstrating significant energy recovery, improved efficiency, and reduced emissions. The importance of fuel cell stack sizing, battery hybridization, and thermal management was highlighted to ensure system durability and performance.

Hydrogen storage and safety considerations were rigorously addressed. Pressurized Type IV tanks and underground salt caverns were assessed for onboard and bulk storage, respectively. The study also presented detailed risk assessments of hydrogen leaks, jet fires, and explosion scenarios, incorporating computational fluid dynamics (CFD) and failure mode analysis. Battery safety, particularly thermal runaway hazards, was also evaluated, emphasizing the need for integrated safety protocols and engineering controls such as gas monitoring, fire suppression, and system redundancy.

The economic analysis revealed that while current capital (CAPEX) and operational expenditures (OPEX) for HFC retrofits remain higher than diesel, ongoing technology advancements, hydrogen cost reductions, and carbon pricing policies could make HFC locomotives cost-competitive soon. Canadian suppliers such as Ballard Power Systems and Accelera have the technical capabilities to deliver scalable PEM solutions tailored for rail. Investment in green hydrogen infrastructure, including electrolyzers, high-pressure refueling stations, and renewable electricity—will be critical to achieving economic feasibility and deployment at scale.

Environmentally, HFC retrofits offer substantial greenhouse gas (GHG) reduction potential. Life cycle assessments show that using hydrogen produced via renewable electrolysis can reduce emissions by over 70% compared to diesel. However, hydrogen sourced from steam methane reforming (SMR) without carbon capture can negate these benefits, underscoring the importance of clean hydrogen sourcing. The transition also brings secondary benefits, such as lower noise, NOx, and particulate emissions.

From a regulatory perspective, alignment with CSA, ANSI, and ISO standards ensures safe implementation. However, policy gaps remain around hydrogen infrastructure codes, fuel cell safety certifications, and incentive mechanisms. Addressing these will require coordinated government support, stakeholder engagement, and continued research and demonstration projects.

In conclusion, hydrogen fuel cell retrofits for locomotives present a technically feasible and environmentally compelling pathway for decarbonizing Canada's rail sector. While economic and regulatory challenges remain, targeted investments in infrastructure, supplier capability, and clean hydrogen production—alongside strong policy support—can drive this transition forward. The report recommends prioritizing pilot projects, leveraging Alberta's renewable energy potential, and fostering industry-academic-government collaboration to scale sustainable rail innovation.

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