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Technical Report

Risk Assessment of Hydrogen and Battery Power in Locomotives – Part 1 – Literature Review

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Abstract

A literature review was conducted to assess the risks and hazards associated with the operation of hydrogen fuel cell and battery powered (hydrail) locomotives. Two complementary reports were produced: a risks and hazards analysis (Part 2), and a codes and standards review (Part 3). A hydrail locomotive reference design was developed to identify major systems and components, and permit a comparison with current diesel-electric locomotives. Several real-world hydrail demonstrations were examined, and a summary of considerations for the adoption of hydrail technology were presented. Recommendations included a risk and hazard analysis of freight hydrail locomotives in revenue service, and a literature review for a battery-electric locomotive. This follow-on work is currently planned for Phase 2 of this project.

Executive Summary

The purpose of this study was to perform an assessment of the risks and hazards associated with the operation of hydrogen fuel cell and battery powered (hydrail) locomotives. This report presents the findings of a literature review on the subject. Two complementary reports were produced: an analysis of the risks and hazards associated with the operation of a hydrail locomotive (M. Hernandez, I. Jimenez, C. Rabbitt and E. Toma, "Risk assessment of hydrogen and battery power in locomotives - Part 2 - Risks and hazards assessment," National Research Council of Canada, Ottawa, 2022.), and a review of applicable codes and standards (M. Hernandez, C. Rabbitt, I. Jimenez and E. Toma, "Risk assessment of hydrogen and battery power in locomotives - Part 3 - Codes and standards," National Research Council of Canada, Ottawa, 2022.). The literature review found that most hydrail locomotive projects to date have been of a prototype nature and developed for passenger trains. There are currently no in service hydrail locomotives in Canada. Recommendations included performing a risk and hazard analysis of freight hydrail locomotives in revenue service, and conducting a literature review for a battery-electric locomotive.

The design and function of a typical diesel-electric locomotive was presented, to permit identification and discussion of key differences between a diesel-electric locomotive and a hydrail locomotive. Reference designs for a hydrail switcher locomotive (for use in rail yards assembling and disassembling trains) and a locomotive with a fuel tender (for moving trains over long distances) were presented, including a functional block diagram detailing the systems and sub-systems, and a conceptual baseline configuration detailing the physical layout of components. The purpose and function of each of the sub-systems was described. The advantages and disadvantages of the all-in-one hydrail locomotive versus the tender-style of hydrail locomotive were discussed. A battery-only (i.e., fully electric) locomotive design was also briefly discussed.

The design and function of a typical diesel-electric locomotive was presented, to permit identification and discussion of key differences between a diesel-electric locomotive and a hydrail locomotive. Reference designs for a hydrail switcher locomotive and a locomotive with a fuel tender were presented, including a functional block diagram detailing the systems and sub-systems, and a conceptual baseline configuration detailing the physical layout of components. The purpose and function of each of the sub-systems was described. The advantages and disadvantages of the all-in-one hydrail locomotive versus the tender-style of hydrail locomotive were discussed. A battery-only (i.e., fully electric) locomotive design was also briefly discussed.

A thorough summary of hydrail locomotive examples around the world was presented, including those that have been implemented and those that will be implemented in the near future. Five annotated examples were examined in detail: Vehicle Projects LLC mining locomotive; Vehicle Projects LLC Green Goat (heavy rail switcher); Alstom Coradia iLint (multiple unit train); Telligence Group (proposed hydrail locomotive and motorized tender car); and East Japan Railway Company (two-car train).

Lessons learned from other applications of fuel cell technology were also presented, including three hydrogen fuel cell powered bus trials, a maritime fuel cell generator project, a mine locomotive project, and a forklifts study. Issues related to refuelling, temperature management, reliability, systems design,

audible signature, training, storage, start-up, gaps in standards, fuel availability, and other issues were noted.

Finally, considerations for the adoption of hydrail technology were summarized, addressing design, operation, maintenance and fueling. It is expected that diesel and hydrail locomotives will coexist for a considerable length of time, so they will need to be compatible and interchangeable. The hydrail locomotive introduces new equipment, procedures and hazards, such that personnel must be trained. There are tractive effort limitations that must be considered or addressed, since a hydrail locomotive will weigh less than a diesel locomotive. There are fuel storage limitations which would likely affect the operating range of a hydrail locomotive. There are also refuelling challenges. Failure rates, modes, causes, consequences, and severity for hydrail locomotives were briefly discussed. The potential to reuse or retrofit existing diesel-electric locomotive components was also explored.

Table of contents

- 1 Introduction 11
 - 1.1 Purpose 11
 - 1.2 Background..... 11
 - 1.3 Objectives 11
 - 1.4 Scope..... 12
- 2 Literature review..... 13
 - 2.1 Literature scan methodology 13
 - 2.2 Reference summary 13
- 3 Review of diesel-electric locomotives 15
- 4 Hydrail locomotive: reference design 17
 - 4.1.1 Hydrogen fuel cell and battery powered locomotive 17
 - 4.1.2 Baseline configuration for hydrail 20
 - 4.1.3 Battery-only locomotive..... 21
- 5 Real-world hydrail demonstrations..... 23
 - 5.1 Lessons learned 26
 - 5.2 Annotated hydrail examples 28
 - 5.2.1 Vehicle Projects LLC – Mining locomotive 28
 - 5.2.2 Vehicle Projects LLC – Green Goat..... 29
 - 5.2.3 Alstom Coradia iLint..... 30
 - 5.2.4 Telligence Group..... 30
 - 5.2.5 East Japan Railway Company 31
- 6 Adoption of hydrail technology considerations 32
 - 6.1 Design..... 32
 - 6.2 Tractive effort limitations..... 33
 - 6.3 Fueling and fuel capacity 35
 - 6.4 Failure rates and severity 36
 - 6.5 Legacy component and system reuse..... 37
- 7 Summary and recommendations 38
 - 7.1 Summary 38

7.2 Recommendations..... 38

Acronyms and abbreviations..... 39

References..... 40

Appendix A: Relevance of selected references A-1

Appendix B: Reference summary – key findings B-1

List of tables

Table 1: Summary of relevance of selected references 14

Table 2: Summary list of hydrail locomotive examples 24

List of figures

Figure 1: Schematic of diesel electric locomotive 15

Figure 2: Functional block diagram of a diesel-electric locomotive 16

Figure 3: Functional block diagram of a hydrogen fuel cell and battery powered locomotive 17

Figure 4: Conceptual fuel cell locomotive 20

Figure 5: Conceptual fuel cell locomotive with hydrogen fuel tender 21

Figure 6: Schematic of a battery-only powered locomotive 22

Figure 7: Countries that have or will be implementing hydrail 23

Figure 8: Mining fuel cell locomotive 28

Figure 9: Vehicle Projects LLC annotated example..... 29

Figure 10: Alstom Coradia iLint annotated example 30

Figure 11: Hydrail configuration (locomotive and motorized tender car) suggested by the Telligence Group..... 31

Figure 12: East Japan Railway Company FV-E991 31

Figure 13: Energy density volume vs. weight including storage container weight..... 35

1 Introduction

1.1 Purpose

The National Research Council of Canada (NRC) Automotive and Surface Transportation (AST) Research Centre was tasked by Transport Canada (TC) to perform an assessment of the risks and hazards associated with the operation of hydrogen fuel cell and battery powered locomotives. This report presents the findings of a literature review on the subject. Separate (complementary) reports were produced to present a risks and hazards analysis (Part 2) [1], and a codes and standards review (Part 3) [2].

1.2 Background

TC is creating an ongoing dialogue between government, railway companies, and the broader rail industry about the risks and hazards associated with the operation of hydrogen fuel cell and battery powered locomotives. Understanding the risks and hazards, and how to mitigate them, will assist in developing a clear and efficient process for undertaking testing and deployment of these technologies in a manner that is safe, secure and sustainable.

Canadian railway companies are expanding their collaboration with hydrogen/battery technology developers, standards development organizations, academia, and equipment manufacturers to advance the technological readiness of hydrogen fuel cell and battery powered locomotives. For example, Canadian Pacific Railway (CP) has announced a plan to carry out real-world testing of at least one hydrogen fuel cell and battery powered freight locomotive. Canadian National Railway (CN) has also announced the purchase of electric freight locomotives to diversify their fleet from the currently-used diesel electric locomotives.

The term *hydrail* is frequently used in the literature, and it is defined as “a rail vehicle that uses a hybrid configuration of hydrogen fuel cells, batteries and electric traction motors”.¹ Where used in this report, the term *hydrail* is synonymous with “*hydrogen fuel cell and battery powered (locomotive or train)*”. For convenience it is sometimes used as an adjective, as in “hydrail locomotive”.

1.3 Objectives

The technical goals of Phase 1 of the project were to:

- build a foundation of knowledge about the risks and hazards of operating hydrogen fuel cell and battery powered (i.e., hydrail) locomotives;
- use an appropriate comparative risk analysis methodology to quantify the severity (e.g., probability, impact) of each type of hazard;
- identify appropriate means and best practices (e.g., training, engineering design, procedural modifications, etc.) for mitigating the identified risks and hazards;

¹ https://www.btb.termiplus.gc.ca/tpv2alpha/alpha-eng.html?lang=eng&i=1&srchtxt=hydrail&codom2nd_wet=1#resultrecs

- assess how current industry codes and standards could be leveraged to support the deployment of pilot demonstrations of hydrogen fuel cell and battery powered locomotives in the near term, and used to mitigate risk; and
- identify gaps in the current industry codes and standards landscape and specific modifications that may be needed in order to improve the management of risks.

1.4 Scope

The current diesel-electric locomotive was used as a basis of comparison and to identify new risks and hazards associated with hydrail. A hydrail locomotive reference design was then developed and used to identify systems and components, which were further examined using the available literature. The study focused on the hydrail locomotive, and therefore did not examine related topics such as:

- fueling and de-fueling the locomotive;
- hydrogen storage off the locomotive;
- locomotive maintenance, inspection and testing;
- personnel training and safety; and
- emergency planning and procedures.

These and other topics would be the subject of further study. The literature review presented below also examined several real-world hydrail demonstrations, and gives a summary of considerations for the adoption of hydrail technology.

2 Literature review

2.1 Literature scan methodology

A literature scan was completed by the NRC's National Science Library using various publication databases and sources. This report presents the results of searching in the following scientific databases: Scopus and ProQuest (Advanced Technologies & Aerospace Collection, and Materials Science & Engineering Collection), Cordis Europa, and the UIC Publications database. The report also contains the information on various Hydrogen Rail applications found in press releases, news and web sites including, Science.gov, WorldWideScience.org, OSTI.gov, the Society of Automotive Engineers (SAE) website, and the American Society for Testing and Materials (ASTM) website. In order to identify as many relevant papers as possible, the search was conducted at a very broad and high-level on the concept of hydrogen fuel cell powered locomotives. The document searches were further refined based on their relevance in relation to:

- technical design for hydrogen powered locomotives, trains or switcher locomotives (used in rail yards assembling and disassembling trains);
- failure rates, modes, causes, consequences and severity for hydrogen powered locomotives, trains or switchers;
- compatibility of lithium ion batteries and hydrogen fuel cells;
- fuel cell and battery application to power a locomotive traction motor;
- locomotive operation, maintenance and fuelling;
- codes and standards applicable to a hydrogen powered locomotive, train or switcher; and
- existing hydrail applications around the world.

2.2 Reference summary

The findings from the literature scan are summarized as follows:

- 33 references mentioned different concepts and designs of hydrogen fuel cell powered locomotive systems;
- 7 references were related to failure of hydrogen fuel cell powered locomotive systems;
- 7 references mentioned traction motors with fuel cells and batteries;
- 36 references were related to the operations, maintenance and fuelling of hydrogen fuel cell powered locomotive systems; and
- 23 documents were related to the standardization of hydrogen fuel cell powered locomotive systems.

References that mentioned fuel tenders and the keyword "compatibility" in the databases were limited. The search was expanded to include articles that were related to power management systems in hydrogen fuel cell and battery powered locomotives. Furthermore, 32 commercial or experimental hydrail projects around the world were identified, including some at the proposal stage, in testing phases, in

service, and some of which were cancelled prior to completion. The bibliographies from each paper were reviewed to identify additional references.

After a second refinement, 28 references were identified as being relevant to the subject. The selected references were analyzed and given a grading from 1 to 5 to identify the most relevant references (where a rating of 1 is not relevant, and a rating of 5 is very relevant.). The grading helped identify the current trends and challenges associated with hydrogen fuel cell and battery powered locomotives research and understanding around the world. Table 1 summarizes the quantity of references for the corresponding relevance grade. Appendix A lists the references with their corresponding relevance grade and a brief summary.

Relevance grade	Quantity of references
5	6
4	2
3	6
2	10
1	10

Table 1: Summary of relevance of selected references

3 Review of diesel-electric locomotives

The purpose of this section is to review the design and function of a typical diesel-electric locomotive currently in service in North America, to permit identification and discussion of key differences between a diesel-electric locomotive and a hydrogen fuel cell and battery powered locomotive. A schematic of a diesel-electric locomotive, illustrating the mechanical and electrical sub-systems, is shown in Figure 1 [3].

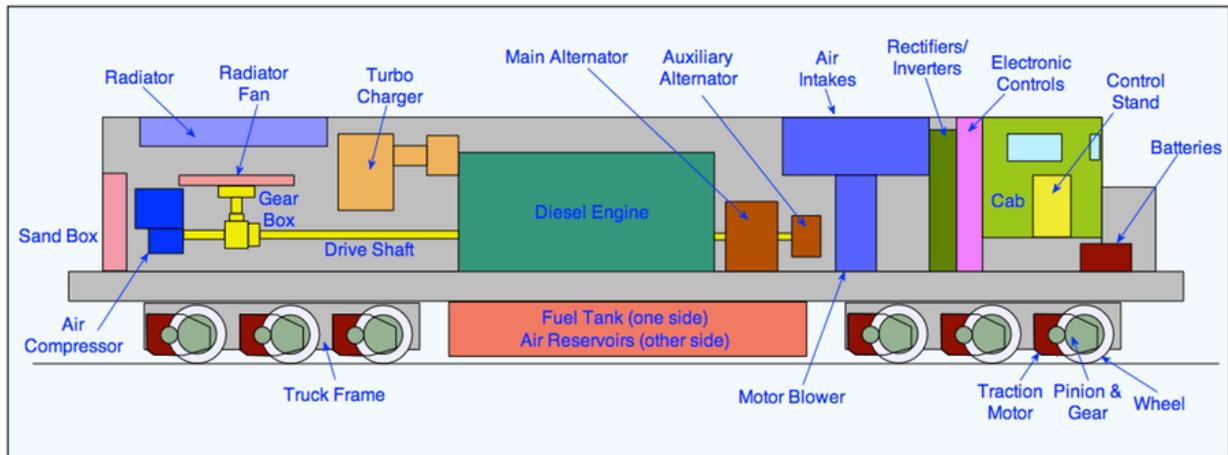


Figure 1: Schematic of diesel electric locomotive

The diesel engine drives the main and auxiliary alternator², generating electrical energy which is used to power the traction motors and other electrical systems. Diesel engines are inherently energy efficient due to their combustion cycle, and modern diesel engines meeting Tier 4 standards have low emissions. The technology is mature, and the mechanical systems in the locomotives have long lifespans and generally require low maintenance.

This diesel-electric system was developed to address the requirement for locomotives to generate high levels of tractive effort at zero speed in order to start moving a long freight train. It permits the diesel engine to turn at a speed which produces maximum power, even while the train is not yet in motion. The system can produce maximum tractive effort (i.e., high pulling power) at low speeds, and the use of electric traction motors allows for a smooth application of power to the wheels, minimizing wheel slip and maintaining maximum traction.

Locomotive braking is accomplished in part using tread brakes (brake shoes which apply braking force to the wheel tread surfaces). In addition, the traction motors can be driven as generators with the resulting current directed through high power resistor banks, resulting in what is called dynamic braking. The heat generated during dynamic braking is forced out of the top of the locomotive by large cooling fans. The use

² In the literature the terms alternator and generator are often used interchangeably, despite their technical differences. For the purpose of this review they will not be distinguished, as they perform essentially the same function – generating either alternating current (AC) or direct current (DC) power, which is used to drive the traction motors and other electrical systems.

of dynamic braking does not save fuel, but does reduce wear of the friction brakes on the locomotive and the freight cars, and allows braking of the train to be better controlled.

Batteries (typically lead-acid composition) are used to start the diesel engine, and they provide electric power for lights and controls when the engine is shut down. The diesel fuel tank is normally located under the locomotive frame. Depending on the type of locomotive, the fuel tank will typically have a capacity of 5,000 to 6,000 L. Air reservoirs containing compressed air, located adjacent to the fuel tank, supply compressed air for the locomotive and the train brakes. The electronic control cabinet contains the controls for all electrically powered subsystems. A functional block diagram of the main components of a diesel locomotive is shown in Figure 2 [3].

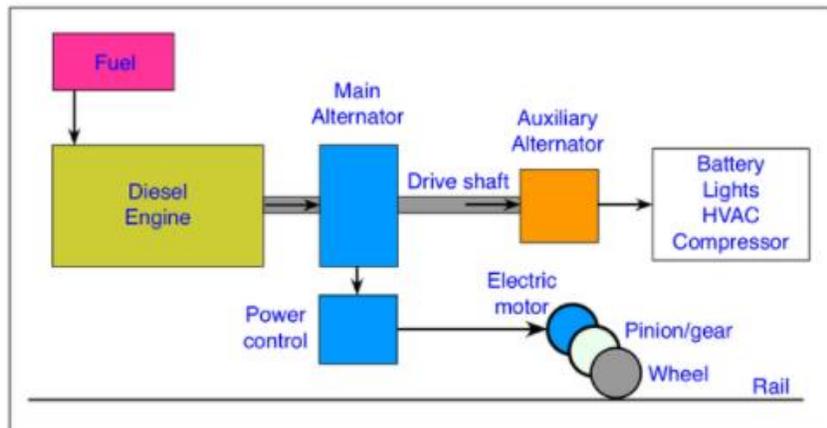


Figure 2: Functional block diagram of a diesel-electric locomotive

4 Hydrail locomotive: reference design

The following section presents a proposed power architecture in the form of a functional block diagram and a reference design of a hydrogen fuel cell and battery powered locomotive and a standalone battery powered locomotive. The reference design put forward in this project is used to identify and locate the potential power systems that could be required for a hydrogen fuel cell power architecture in locomotives. It is not meant to impose on the design freedom that is required when designing complex mechanical power systems for the railways and is not a guideline with detailed requirements as seen in prescriptive engineering approaches. The reference design is intended to act as a proxy design in the absence of an actual locomotive as part of the risks & hazards, and codes and standards work in the overall risk assessment approach.

4.1.1 Hydrogen fuel cell and battery powered locomotive

From the literature review, various designs for hydrogen fuel cell and battery powered locomotives were found. These examples were used to create reference designs for a switcher locomotive and a locomotive with a fuel tender (typically used to move trains over long distances). A functional block diagram of the systems and subsystems of a hydrogen fuel cell and battery powered locomotive is shown in Figure 3 [4].

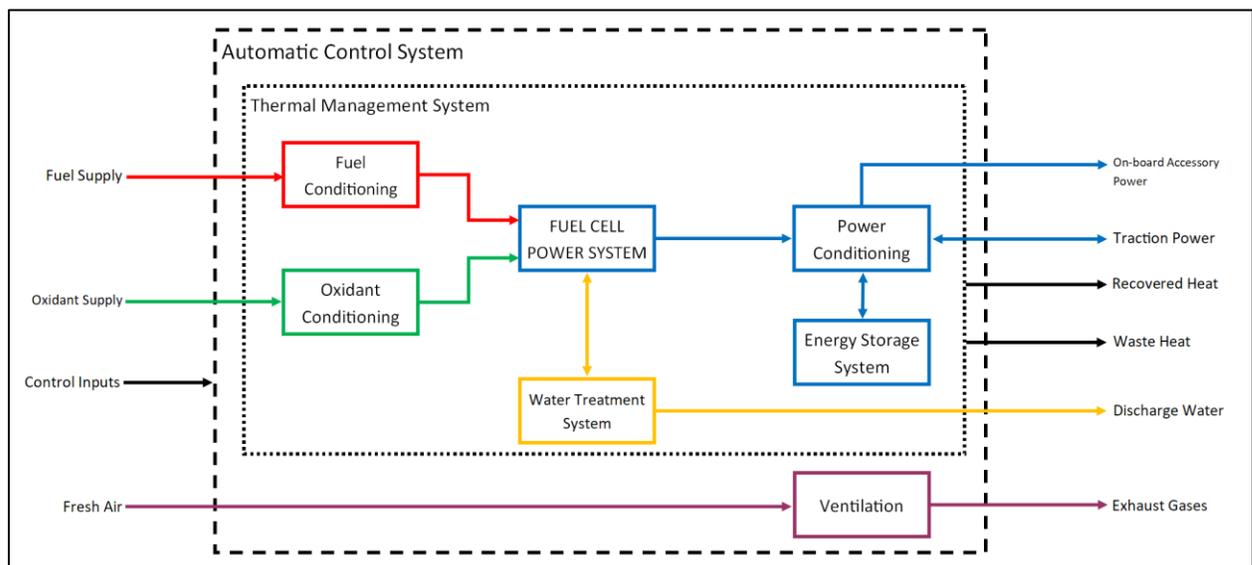


Figure 3: Functional block diagram of a hydrogen fuel cell and battery powered locomotive

4.1.1.1 Automatic control system

The automatic control system is responsible for the safe, efficient operation of the entire fuel cell power system. It monitors parameters such as temperature, current, cell voltage (or group of cells voltage), etc. These parameters are important for both performance and safety. For example, if the voltage on a cell or group of cells drops or changes polarity, a fuel cell reversal may occur, resulting in damage to the electrode membrane assembly and very high localized temperatures. As shown in Figure 3, the automatic control system encompasses the various functional blocks; however, a practical implementation may see

multiple smaller control systems for one or more separate blocks, each operating as an independent stand-alone system, or as part of a larger network connected control system.

4.1.1.2 Thermal management system

A thermal management system controls the temperature of various components and sub-systems, ensuring safe, reliable function in all conditions. As shown in Figure 3, the thermal management system encompasses the various functional blocks; however, a practical implementation may see multiple smaller thermal management systems for one or more separate blocks, each operating as an independent stand-alone system, or as part of a larger integrated thermal management system. A sophisticated thermal management system would seek to recover waste heat from one system for use as energy in another where possible.

4.1.1.3 Fuel supply & fuel conditioning

The fuel supply in this case is hydrogen, and can be high-pressure gaseous hydrogen supplied at storage pressure; or cryogenic hydrogen, supplied as a liquid. The fuel conditioning block prepares the supplied fuel to be fed into the fuel cell. This preparation can include regulating the pressure of the fuel cell feed to a safe level, and controlling the fuel temperature for optimum reaction conditions. If the fuel supply is liquid, the fuel conditioning block will also have facilities to vaporize the liquid fuel into a gas before feeding it into the fuel cell.

4.1.1.4 Oxidant conditioning & oxidant supply

For hydrogen fuel cells, the reactant is oxygen, and this oxygen is typically supplied as ambient air drawn into the fuel cell with blower fans. The oxidant conditioning block prepares the ambient air for use in the fuel cell and can include filtration of contaminants, temperature & pressure regulation, humidification, and other process control.

4.1.1.5 Control inputs

These represent any number of parameters that control the complete power generation process. Parameters such as ambient temperature, ambient pressure, operator commands, etc. are all fed into the automatic control system, which then applies the necessary process controls to achieve the desired result.

4.1.1.6 Fresh air, ventilation, & exhaust gases

As a method to reduce and/or control the build-up of fugitive hydrogen gas in the machinery sections, a ventilation system is fitted and part of the automatic control system. The ventilation system draws in fresh air with fans, and distributes it around the machinery sections, pushing out any stray hydrogen as exhaust before it can accumulate to dangerous levels. The ventilation system also helps regulate the temperature of the machinery compartments for optimum equipment operation.

4.1.1.7 Fuel cell power system

This is the core of the hydrail locomotive. The fuel cell combines hydrogen and oxygen, which produces usable electrical power, as well as heat and water as a by-product of the reaction. The fuel cell consists of different semi-permeable membranes through which gases flow. These membranes are then arranged in stacks which create alternating channels for the gases. The fuel cell power system contains one or more fuel cell modules, as well as other supporting equipment & systems to create a complete power system.

4.1.1.8 Water treatment & discharge water

Hydrogen fuel cells create water as a by-product of the fuel cell reaction. This water can be used to maintain the proper humidification of the reaction membrane for optimal function. The on-board water treatment facility maintains the proper water chemistry for use in the fuel cell. The treatment system also provides proper freeze protection as well as treating any excess water to allow for safe discharge.

4.1.1.9 Power conditioning

The power conditioning block manages the interaction and distribution of the fuel cell's electrical output. The power conditioning block has many functions: management of the energy storage system (ESS) charge/discharge, providing regulated low-voltage power for on-board use, regulating the fuel cell output for use by the traction motors, regulating the flow of energy between the heater grid and the ESS during regenerative (dynamic) braking, and regulating the output of the fuel cell itself.

4.1.1.10 On-board Accessory Power & traction power

Low-voltage power is needed for on-board equipment. A high-voltage and high-power supply is needed for traction motors. Historically, the operator selected from several discrete (usually eight) "notches" for speed control (in addition to forward and reverse). This is mostly a holdover from when diesel electric locomotives were first introduced as power electronics were unable to handle the power demands for switching. These notches represented contactors physically switching the DC motor winding configurations within the traction motor to provide variable speed control.

Today, with the advent of advanced power electronics, it is possible to replace the discrete notches with infinite control using AC induction motors or brushless DC permanent magnet motors. These motors require sophisticated solid-state controllers to operate them, but are much more efficient as they continuously monitor and adjust the magnetic field within the motor to maximize efficiency. Many modern diesel-electric locomotives have some form of AC traction motors using proprietary control systems to optimize power generation and use and overall locomotive traction.

4.1.1.11 Energy storage system

Fuel cells generally have relatively poor transient response to sudden electrical load demands, therefore an ESS provides an energy buffer for the fuel cell. When a sudden demand in power is required (such as acceleration), the ESS "fills in" the energy deficit while the fuel cells ramp up to meet the demand. During braking, the ESS can recover braking energy and store it for future use, as well as absorbing the output of the fuel cell while it ramps down. Depending on how the ESS is sized and managed, it can be used to provide only transient suppression for short periods; or a significant amount of additional energy for extended periods, allowing for limited movement on stored power alone.

4.1.1.12 Recovered heat & waste heat

Recovered heat energy will typically be from cooling of the power electronics such as inverters, batteries, and motors. Depending on the heat recovery system architecture, this recovered heat can be routed to provide some freeze protection for the water wetted fuel cell components, fuel conditioning, and other systems. The typical source of waste heat is predominantly from two sources; excess electrical energy from regenerative (dynamic) braking of the locomotive and from the fuel cell as a by-product of electricity generation.

Energy recovered from dynamic braking is electrical and is typically routed to the ESS. When the ESS is at capacity and no longer able to accept charge, or cannot accept electrical energy at the rate it is being produced, this excess energy must be dissipated through the traditional resistive heater grid and rejected to the atmosphere.

During operation, the electricity producing reaction within the fuel cell creates heat. There are two types of fuel cells: low temperature proton-exchange membrane (PEM) fuel cells and high temperature PEM fuel cells. High temperature fuel cells have the advantage the fuel does not have to be as clean and can tolerate small quantities of CO, however they have the disadvantage of having to be stored in extreme dry environments. In this report we are assuming that the locomotive will be powered by a low temperature fuel cell which works at 80°C and thus produces low quality heat and are up to 65% efficient where the remaining waste energy is produced as heat [5]. This heat must be removed from the fuel cell in order to ensure proper, safe, and efficient functioning, and as this energy is thermal it must be rejected to the atmosphere through a radiator. A small portion of this waste energy may be recovered for use in crew compartment space heating and for other heating needs (e.g., vaporizing liquid hydrogen), but the vast majority is radiated out as heat.

4.1.2 Baseline configuration for hydrail

The all-in-one switcher style hydrail locomotive (Figure 4) outwardly has the same look, feel, and footprint as a traditional diesel-electric locomotive as all the relevant hydrogen systems are packaged into the same form-factor. The main drawback of this design is the relatively small amount of hydrogen that is able to be carried, owing to hydrogen's significantly lower volumetric energy density compared to diesel. Multiple fueling cycles during a single 24-hour period may be required, and could become an operational reality as a result of fueling capacity.

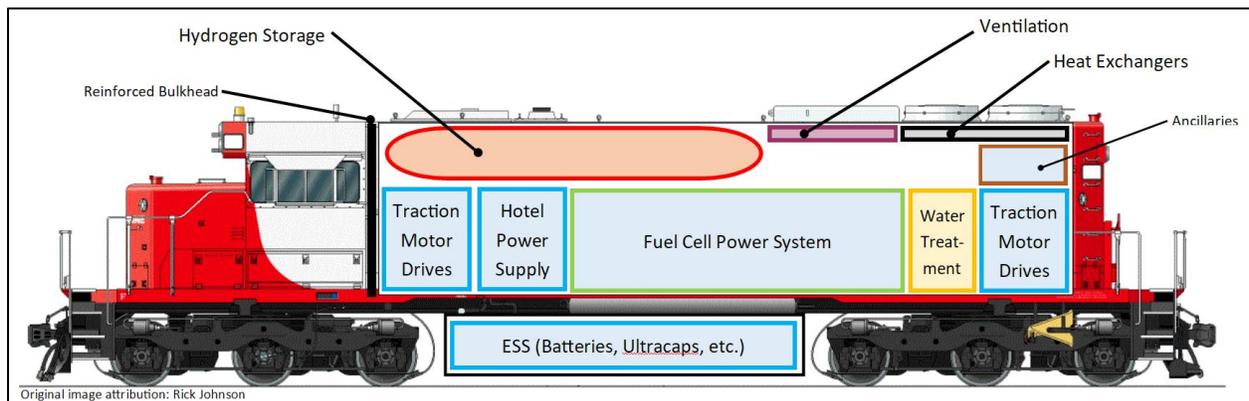


Figure 4: Conceptual fuel cell locomotive

One method to address the lost productivity due to requiring multiple fuel stops is to refuel the hydrogen as quickly as possible. However, refuelling gaseous hydrogen rapidly creates other problems, specifically compression heating of the fuel gas, which is exacerbated by faster fueling rates. Active cooling is typically needed to mitigate compression heating effects of rapid fuel transfer. However, it may be possible to make the hydrogen storage a removable cassette which can be removed and fueled slowly offline.

The tender style of hydrail locomotive (Figure 5) typically has the hydrogen storage as a separate railcar that is coupled to the locomotive where a service umbilical connects the hydrogen tender to the locomotive. This umbilical carries fuel from the tender mounted storage containers to the locomotive mounted fuel cell modules. This umbilical carries fuel from the tender mounted storage cells to the locomotive mounted fuel cell modules. This umbilical can also carry electrical power from the locomotive to the traction motors located on the tender. The locomotive in the tender style can be battery powered if it needs to be moved on its own. Additionally it could have a small hydrogen tank storage to power the fuel cell and use it as a stand-alone locomotive for short durations. Different combinations of Figure 4 and Figure 5 could be generated.

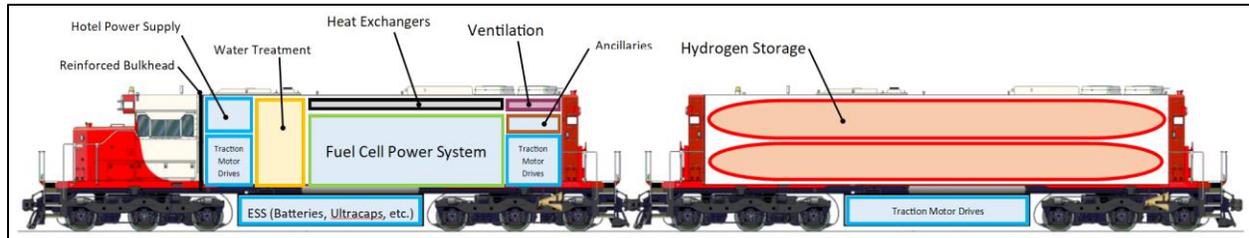


Figure 5: Conceptual fuel cell locomotive with hydrogen fuel tender

The conceptual design shown in Figure 5 uses a multi-element gas cylinder arrangement for storing high-pressure gaseous hydrogen. This is the typical method for gaseous hydrogen storage. An alternative storage method is to store the hydrogen as a cryogenic liquid. When stored as a liquid, the hydrogen tank is simpler to construct as it only must withstand a relatively low pressure, but the vessel must be very well insulated, and is typically a double-walled vessel with the void space between the two vessels evacuated into vacuum. Additional layers of insulation on the outside of the vessel may also be present to increase thermal resistance, and these insulation layers may be in the form of rigid foam, mineral wool batts, foil blankets, ceramic blanket etc.

The tender style of hydrail has the potential to offer one compelling advantage over a more traditional hydrail locomotive, and that is in regards to fueling. It is possible to disconnect the tender from the locomotive to have the tender fueled offline. In this instance, another fully fueled tender would then be connected to the locomotive, making refueling a matter of swapping tender cars instead of taking the locomotive portion out of service for the duration of fueling. However this would introduce physical complications such as dedicating sections on the track for storing hydrogen tenders, reorganization and moving them to the locomotive and cost implications to buy multiple tender cars.

Regardless of the style of hydrail locomotive, offline fueling partially solves the issue with compression heating when refuelling quickly with gaseous hydrogen. By refuelling offline, the fuel transfer process can happen much more slowly, dramatically reducing the compression heating effects and the mitigation efforts required to manage it. Offline fueling also can reduce the on-site hydrogen storage and other requirements that would be needed to accommodate rapid fueling.

4.1.3 Battery-only locomotive

In recent years, rail companies have announced the use of a battery standalone locomotive for freight and passenger rail [6]. A limited amount of information concerning battery-only locomotives was found in

the literature. However, BNSF shared a high level design of Wabtec's standalone battery powered locomotive purchased in 2019 (Figure 6) [7].

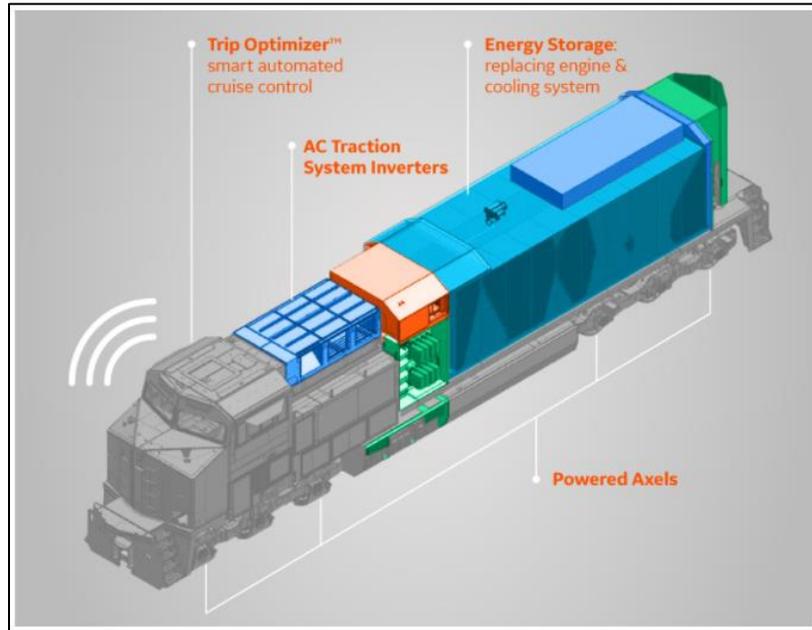


Figure 6: Schematic of a battery-only powered locomotive

Functionally, the batteries take the place of the diesel-electric generator portion of a traditional diesel locomotive. The rest of the locomotive and related systems remains relatively unchanged.

Compared to a hydrail locomotive, the battery only locomotive dispenses with the fuel cell and related components on the hydrail locomotive and fits as many batteries as possible into the available space. As a result, a battery-only locomotive has no on-board energy generation, and must be recharged separately.

If the batteries are integrated into the locomotive, then the battery-only locomotive is out of service during charging, leading to a relatively poor uptime or availability, even with high-power charging. High power charging infrastructure also leads to additional challenges with utilities and battery life (e.g. unpredictable, sudden and extreme demand when charging).

Alternatively, it may be possible to make the battery pack removable (e.g., containerized) so that a discharged battery can be swapped with a charged battery. The discharged battery can then be charged offline, which can help alleviate infrastructure requirements and improve uptime.

One advantage of a battery-only locomotive is the reduced requirements of the supporting systems, particularly cooling. Comparatively speaking, a typical diesel or fuel cell locomotive with 3,500 kW of installed power would require approximately 3,500 kW of cooling capacity, an equivalent 3,500 kW battery-only locomotive may require 800 kW or less cooling capacity.

5 Real-world hydrail demonstrations

Most of the hydrail technology currently ongoing is found in Europe, Asia and North America. Figure 7 depicts countries that have implemented or will be implementing hydrail, based on the findings of the literature review. Table 2 lists the hydrogen powered locomotives, passenger trains, shunters and tramways that have been or will be in use between 2002 and 2024, also based on the findings of the literature review. The power, application, railway company, rail vehicle company and the ownership are presented. Most of the active hydrogen fuel cell powered locomotives in service around the world are multiple-unit configuration passenger trains (including switchers).

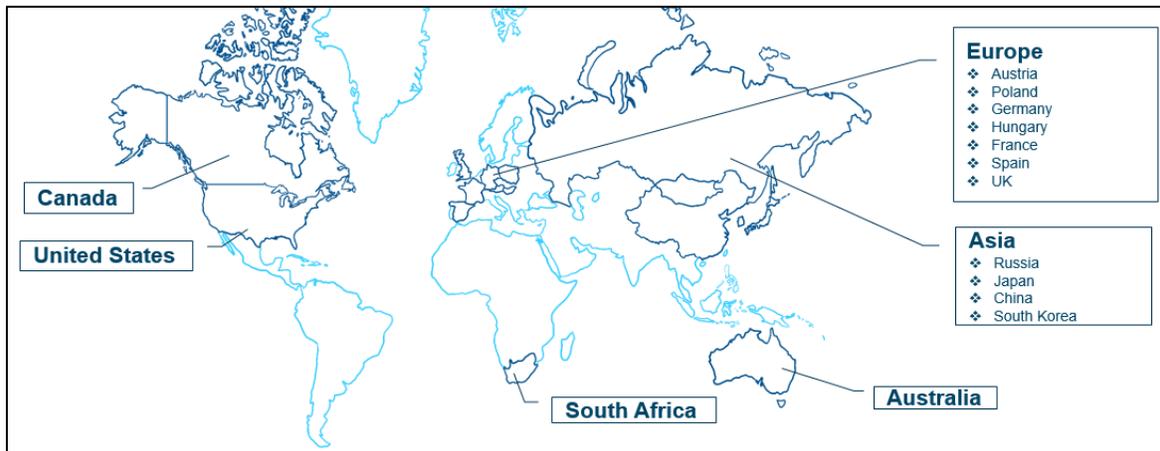


Figure 7: Countries that have or will be implementing hydrail

Country	Year	Use	Power (kW)	Application	Railway Company	Rail Vehicle Company / Research Group	Ownership
Aruba	2013	Tramway	120	Revenue	Arubus	TIG/m LLC	State
Austria	2017	Shunter	1,520	Demo	Austrian Federal Railways	HET Verkehrstechnik	State
Austria	2020	Passenger	400	Revenue	Austrian Federal Railways	Alstom Coradia iLint	State
Austria	2022	Passenger	1,400	Revenue	Zillertaler Verkehrsbetriebe AG	Hytrain Consortium	Private
Canada	2022	Freight	1,200	Demo	Canadian Pacific Railway		Private
Canada	2023	Shunter	N/A	Demo		University of British Columbia	Private
China	2016	Passenger	N/A	Demo	Qingdao Metro	CRRC Qingdao Sifang Company	State
China	2017	Passenger	200	Revenue	Chinese Railway Headstream Tour tram line	CRRC Tangshan Railway Vehicle Company	State
China	2019	Passenger	200	Revenue	Foshan Gaoming tram line	CRRC Qingdao Sifang Company	State
China	2021	Freight	700	Revenue	Jinzhou-Baiyinhua Railway	CRRC Datong Co., Ltd.	State

Country	Year	Use	Power (kW)	Application	Railway Company	Rail Vehicle Company / Research Group	Ownership
France	2021	Passenger	400	Demo		Alstom Coradia iLint	Private
Germany	2018	Passenger	400	Revenue	German Railway Office	Alstom Coradia iLint	Private
Germany	2024	Passenger	1,700	Revenue	H2goesRail	Siemens Mireo Plus H	Private
Japan	2007	Passenger	130	Demo	East Japan Railway Company		Private
Japan	2007	Passenger	100	Demo	Railway Technical Research Institute		Private
Japan	2009	Passenger	120	Demo	Railway Technical Research Institute		Private
Japan	2022	Passenger	240	Demo	East Japan Railway Company	Hitachi and Toyota	Private
Netherlands	2020	Passenger	400	Demo		Alstom Coradia iLint	Private
Poland	2021	Shunter	720	Demo		Pojazdy Szynowe Pesa Bydgoszcz	Private
Poland	2021	Passenger	400	Demo		Alstom Coradia iLint	Private
Russia	2019	Tramway	N/A	Demo	Gorelektrotrans	Central Research Institute of Electrical & Marine Technology	Private
South Africa	2012	Mining	N/A	Demo	Vehicle Projects LLC	Anglo American Platinum	Private
South Korea	2023	Passenger	380	Demo	Hyundai Rotem		Private
Spain	2022	Passenger	N/A	Demo		Talgo	Private
Sweden	2021	Passenger	400	Demo		Alstom Coradia iLint	Private
United Kingdom	2019	Passenger	100	Revenue	University of Birmingham	Porterbrook	Private
United States	2002	Mining	17	Demo	Sandia National Laboratories	Vehicle Projects LLC	Private
United States	2009	Shunter	300	Demo	BNSF - "Green Goat"	Vehicle Projects LLC	Private
United States	2024	Passenger	300	Revenue	San Bernardino County Transportation Authority	Stadler	State

Table 2: Summary list of hydrail locomotive examples

In Europe, Alstom Coradia iLint has been deployed in Austria and Germany [8]. The first pilot project for the Coradia iLint passenger train was conducted in Salzgitter, Germany in 2018 on the Buxtehude-Bremervörde-Bremerhaven-Cuxhaven route and Alstom one route. After both tests were successful, the first hydrogen powered locomotive was launched into service on the Eisenbahnen und Verkehrsbetriebe

Elbe-Weser network. In March 2020, the Netherlands joined Alstom in a successful trial run to test the performance of the Coradia iLint on the Dutch network [9]. During the same year, Austria launched the Coradia iLint on the Austrian Federal Railways for passenger service. In 2021, Alstom demonstrated the Coradia iLint in France, Sweden, and Poland [8].

Austria obtained prior experience with hydrogen fuel cell trains from the Austrian Federal Railways' and HET Verkehrstechnik³ shunter locomotive demonstration in 2017. Austria is expecting the delivery of their very own HyTrain that will have a capacity of 1,400 kW [10]. Furthermore, Polish company Pojazdy Szybowe Pesa Bydgoszcz has demonstrated its own shunter locomotive in 2021 [11].

Germany and Siemens Mobility collaborated on the Mireo Plus H commuter train, a hydrogen passenger train for the H2goesRail R&D project expected to launch in 2024 [10]. In the United Kingdom (UK), HydroFLEX, the first hydrogen-powered train in the UK developed by the University of Birmingham and Porterbrook, started operational trials in 2019. The train is expected to go in service in 2023 [12]. In addition to HydroFLEX, the UK signed an agreement with Alstom and Eversholt Rail to build a new hydrogen power train [13]. Lastly, the Spanish manufacturer Talgo announced that its Vittal-One hydrogen trains will be ready for testing in 2022, and will eventually displace diesels in its catalog. Commercial production is expected in 2023 [14].

In Asia, a consortium of Hitachi, Toyota and East Japan Railway Company will be testing a Toyota-built hydrogen fuel cell to battery-drive trains by Hitachi in 2022. The railway will design and build a two-car train, which will have a refueling range of 140 km and a top speed of 100 km/h [15]. This comes after three demonstrations of passenger trains by East Japan Railway in 2007 and Railway Technical Research Institute in 2007 and 2009 [10]. Moreover, in 2019 a hydrogen-powered tram developed by China's CRRC Sifang Co., Ltd using Ballard Power Systems' FCveloCity®-HD was launched in Gaoming District, Foshan City, Guangdong Province [16]. In November 2021, the first China-developed hydrogen fuel cell hybrid locomotive from core power to main components started trial runs on a 627 km railway line for coal transport in north China's Inner Mongolia Autonomous Region [17]. Although no hydrail locomotive or train has been developed, South Korea state-run railway research body has embarked on the development of locomotives based on liquefied hydrogen [18]. In Russia, an agreement was signed to cooperate on the development of mainline locomotives using a power plant based on hydrogen fuel cells together with lithium-ion batteries [19]. Russia has previous experience with hydrogen locomotives due to their testing of a hydrogen powered tramway in 2019 [20].

In Australia, Anglo American, the mining company has announced that they will collaborate with Aurizon to do a feasibility study that could lead to the development of a hydrogen fuelled heavy haul locomotive prototype [21].

In Canada, Hydrogen-In-Motion (H2M) will be collaborating with Loop Energy, the University of British Columbia (UBC) School of Engineering, and Southern Railway of British Columbia (SRY), to convert a SRY diesel electric switcher locomotive to hydrogen electric. The two British Columbia (BC) based companies will be using Loop energy's 50 kW eFlow fuel cell system and a low pressure solid-state hydrogen storage tank developed by H2M. The fuel cell powered switcher locomotive will initially be 250

³ Research and development engineering-company.

hp (186 kW), however if the trial is successful the fuel cell locomotive will be scaled up to 700 hp (522 kW) [22]. The UBC team will compare the hydrogen electric powertrain performance characteristics and operational functionality with those of the previous diesel electric. This will be done by conducting a computational modelling of the low pressure hydrogen tank [23].

As well, Calgary-based Canadian Pacific Railway (CP) and Ballard Power Systems are developing the first long-distance hydrogen locomotive in North America. The Ballard fuel cells will provide 1.2 MW of electricity to power the locomotive, from six 200 kW fuel cell modules. CP has planned to convert three diesel electric powertrain locomotives to hydrogen electric powertrains: two line-haul locomotives and a yard switcher locomotive. CP does not intend to use a tender car. Additionally, CP will add hydrogen production and fueling facilities [24].

In the United States (US), Vehicle Project LLC trialed a mining locomotive and a shunter in 2002 and 2009, respectively. Sierra Northern Railway, San Bernardino County Transportation Authority (SBCTA) and Burlington Northern and Santa Fe (BNSF) Railway have plans to introduce hydrogen powered trains. Sierra Northern Railway obtained a \$4,000,000 award to fund the design, integration, and demonstration of a hydrogen fuel cell switching locomotive at the Port of West Sacramento [25]. BNSF announced in December 2021 that they will work with Caterpillar together to “confirm the feasibility and performance of hydrogen fuel for use as a viable alternative to traditional fuels” in long-haul rail [26]. SBCTA partnered with Stadler who will manufacture a hydrogen fuel cell powered train, the Fast Light Intercity and Regional Train (FLIRT H2) which is expected to operate in 2024. The train will consist of two cars with a power pack in the middle that will contain the fuel cells and the hydrogen tanks [27].

Other transportation technology that uses hydrogen fuel cell includes streetcars, buses, trucks and forklifts. For example, Aruba and Russia have had hydrogen powered tramways since 2013 and 2019, respectively [20]. Hydrogen powered buses have served in Canada, the US, China and the UK. Walmart and Amazon have slowly transitioned into hydrogen powered forklifts, and various car manufacturers like Toyota have launched hydrogen powered vehicles.

5.1 Lessons learned

Lessons learned from other technologies using hydrogen have been taken into consideration. This section will cover the lessons learned from three hydrogen fuel cell powered bus trials, a maritime fuel cell generator project, a mine locomotive project and a forklifts study.

During the bus trial by Orange County Transportation Authority (OCTA) and the maritime fuel cell generator project by Sandia National Laboratories found range issues due to a tank not being fully filled [28] [29]. Both parties attributed this problem to high temperature heating up the hydrogen, causing an increase in pressure in the tanks and reduction of mass flow rate (in comparison to a cooler hydrogen situation). The National Renewable Energy Laboratory (NREL) suggest that more research and development of hydrogen station compressors need to occur to increase their reliability and performance [30].

During the same project, Sandia National Laboratories found that balance of plant components such as the battery and the inverter should be carefully assessed to prevent technical issues. Long idle-periods

may lead to start-up issues and coolant evaporation. Additionally, high temperatures can lead to higher than expected hydrogen evaporation through the vent in the tanks. To prevent high temperatures in the generator room that may cause overheating, the fuel cell containers should be painted in a light color [29]. The balance of plants components were an issue found by SunLine with the fuel cell Transit Agency. The majority of fuel cell system issues involved components such as a sensor, commutator, regulator, blower motor, and pump. NREL suggested that research and development of fuel cell balance of plant components should be explored to increase reliability and durability [30].

Moreover, Vehicle Projects LLC, during the mine locomotive project, noted that through every step of the development of a hydrogen powered locomotive, the power and operational requirements and limitations need to be known. A discrepancy between the flow resistance in the air and direct water injection of the fuel cell stacks caused unbalanced feeding. An evenly distributed feeding system, is needed for the air and water circuits to prevent an unbalanced feeding. Similarly to the Maritime Fuel Cell Generator project, Vehicle Projects LLC found that high temperatures (40°C to 60°C) create an evaporation effect. However, Vehicle Projects LLC found that adding no more than 50 L of demineralized water from time to time and a condenser will keep a constant positive water balance in the system [31].

Change Energy Services learned during the Assessment of the Design, Deployment Characteristics and Requirements of a Hydrogen Fuel Cell Powered Switcher Locomotive project that the locomotive will operate at a lower decibel rating than a diesel locomotive which may require personnel to rely on audible signals for safety [20]. Additionally, it is important to allocate time for operators to become familiar with the characteristics of the locomotive and the specific procedures that may be needed with the associated training. As an example, hydrogen fuel cell power module can be stored at -40°C, and start up below -30°C, but if the converted locomotive is off for an extended period of time some special procedures for storage and start-up may be needed. Meanwhile, in warm temperatures the fuel cell power modules may shut down for self-protection against damage if there is no proper cooling system for thermal management [20]. NREL noted that communication with the original equipment manufacturers (OEMs) at the beginning of the demonstration or service is important [32]. This allows the transfer of technical knowledge from the OEM to the operation and maintenance staff [30].

Nuvera Fuel Cell, a manufacturer of heavy-duty, zero-emission engines for mobility applications noted that there is a lack of harmony in the current standards. Additionally, they found that during commissioning of the vehicles there is an opportunity to establish a safety culture among the operators. They also suggest that all hydrogen vehicle OEMs consider the implications of aftermarket referring to how components might be modified or replaced later in the vehicle's service life use of components. OEMs should develop reasonable guidelines to prevent misuse or abuse during a study on hydrogen forklifts [33].

Finally, during the Orange County Transportation Authority (OCTA) bus trial, the agency learned that agencies considering fuel cell electric buses need to plan ahead to avoid high fuel cost. This can be done by planning on adding a source of hydrogen to the infrastructure of the agency [34].

5.2 Annotated hydrail examples

This section will examine five annotated examples of hydrail found in the literature. These examples were selected due to their detail on the location of each component. In addition, the Vehicle Projects LLC mining locomotive project will be discussed due to the knowledge acquired throughout this experiment that was implemented during the Green Goat project.

5.2.1 Vehicle Projects LLC – Mining locomotive



Figure 8: Mining fuel cell locomotive

In 2002, this project started and was divided into two phases. The first phase was taken on by Fuelcell Propulsion Institute (FPI) and Sandia National Laboratories, they developed a 14.4 kW fuel cell power plant with metal-hydride energy storage system. An existing battery-electric locomotive with similar power requirements was used as a base vehicle. The battery was removed from this commercial 4 ton battery locomotive that was manufactured by project partner RA Warren Equipment.

During the development of the locomotive, it was noted that the hydride-fuel cell locomotive was 30% lighter than the battery version. In order to add weight to reach 4 ton, a 1,100 kg ballast was added. The fuel cell contains two stacks that provide a continuous rated power of 17 kW gross. The hydride storage system stores sufficient hydrogen for 8 hours of locomotive operation at the predicted 6 kW average power of its duty cycle.

Once the fuel cell was created, Atlas Copco Wagner of Portland was tasked to install the fuel cell into the base vehicle and initiated the integration of the system into the vehicle (Figure 8). Sandia National Laboratories finished the development and integration, with the initial system power-up in December 2001. The second phase included surface test, risk and safety analysis and underground locomotive test of the integrated locomotive. The prime contractor of this phase was Vehicle Projects LLC. The surface test resulted in the fuel cell stacks having reduced power output. This was corrected by replacing them with new technology that increased gross power output from 14.4 kW to 17 kW.

Canada Centre for Mineral and Energy Technology (CANMET) and Hatch Associates under subcontract to Vehicle Projects LLC undertook the risk and safety analysis. They established minimum requirements for underground testing. CANMET upgraded the programmable logic controller software used to monitor and control the fuel cell power plant. During the underground testing, the locomotive performed with no failures or downtime. The tests occurred during a two week period involving the movement of both gold ore and waste rock over a 1,000 m track [31].

5.2.2 Vehicle Projects LLC – Green Goat

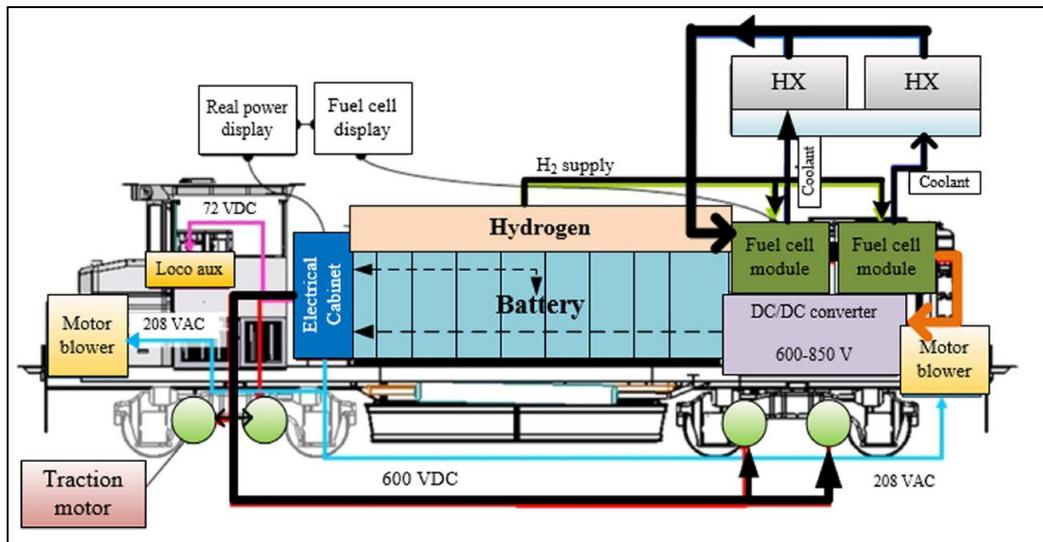


Figure 9: Vehicle Projects LLC annotated example

In 2007, BNSF converted a Railpower Green Goat diesel and battery powered heavy-rail switcher locomotive to a hydrogen fuel cell-based prime mover for Vehicle Projects LLC (in a manner similar to the conceptual fuel cell locomotive and tender in Figure 9) [35]. At the start Nuvera Fuel Cells Inc. designed the fuel cell based on their PEM Forza™ Cathodic Water Injecting fuel cell stack (18.7 kW). In total, 8 PEM fuel cell stacks that contain 116 cells each for a total of 150 kW gross power. Each fuel cell was 1,650 mm x 1,250 mm x 15,000 mm with a weight of 1,650 kg. This fitted into a GP9 locomotive platform.

Railway Technical Research Institute (RTRI) tested the fuel cell module in 2006 by installing it into a new train car test bed and using compressed gaseous hydrogen. During the test, various fuel cell stacks modules failed due to excessive water on the anode side flooding the cells. It was concluded that the flooding was caused by the purging scheme and the inability of the design to handle long idling times. Another flaw of the fuel cell was that the Forza stacks were based on a Nuvera stationery design and were not meant to be used in transportation.

After the testing the fuel cell was replaced with a power module from Ballard Power Systems and the metal hydride storage replaced with gaseous hydrogen storage systems [36]. Each of the 116 fuel cell hydrogen storage systems was designed to store 70 kg of hydrogen at a pressure of 5,100 psi, or 8,120 kg in total. The new fuel cell stacks produced a gross power of 300 kW [35]. While the locomotive was being tested, a minor mechanical failure occurred unrelated to the fuel cell. The sensors of the fuel cell detected an increase in temperature and shut down the system. From there, the project closed due to a lack of funding.

Similar to the conceptual fuel cell locomotive and tender in Figure 9, the fuel cell power plant, power converter, and cooling module are housed in the rear compartment of the locomotive. The power plant is located above the power converter to allow for the fuel cells to be oriented symmetrically opposite on the same plane. This also allows for a symmetric piping of air and coolant allowing for a balanced flow of air and coolant system. The rear compartment of the locomotive also has an air compressor and a blower motor. The access points to de-ionized water fill and filter, electrical panels, DC/DC converter panel, batteries, and resin filter can be accessed from the outer platform of the locomotive. Their location allows full service access without having to remove the module. Furthermore, each fuel cell module is isolated from the impact loads of the coupling of other cars through the use of springs and damping elements, specifically rubber or synthetic mounts or isolators. The isolation system also provides proper shock protection in the horizontal, lateral, and vertical directions.

5.2.3 Alstom Coradia iLint

The Coradia iLint by Alstom is an electric multiple unit train that uses hydrogen fuel cell generators supplied by Cummins that can reach 540 kW at peak propulsion power (Figure 10) [20]. Various countries have or plan to purchase the Coradia iLint such as: Germany, Austria, France, Poland and the Netherlands. During the Alstom Netherlands trial, they noted that over time, average consumption is fairly constant but losses throughout the system occur when there are high levels of braking and subsequent acceleration [9].

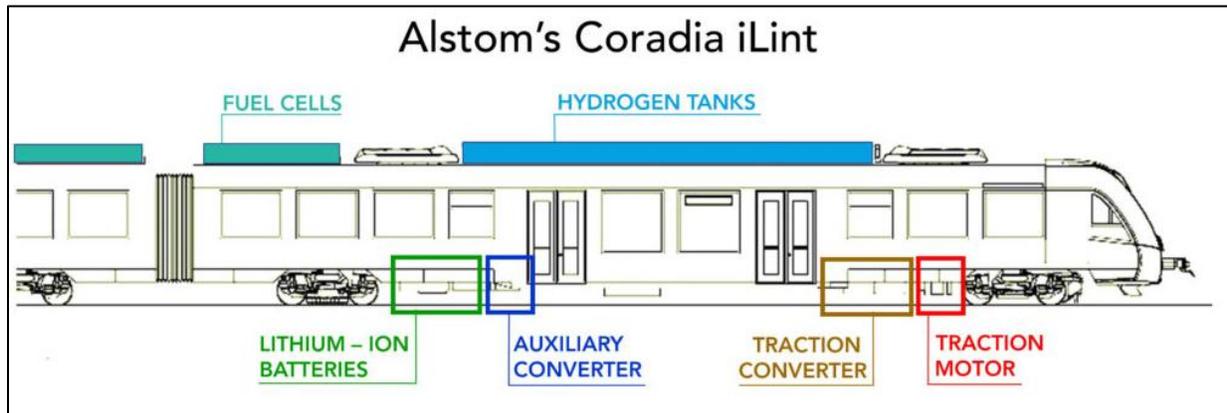


Figure 10: Alstom Coradia iLint annotated example

5.2.4 Telligence Group

In 2020, the Telligence Group⁴ interviewed organizations deemed to be within portions of the hydrail ecosystem including: technology, regulatory, societal, financial, operational, infrastructure and innovation. A concern about range related to the quantity of hydrogen gas that can be stored within the train and the safety aspects of the latter were raised by various interviewees. The Telligence Group suggested a configuration that would address these concerns (Figure 11) [10]. The solution proposed to overcome the challenges consists of a locomotive and motorized tender car. The design combines the structures of two

⁴ Consultants in Transportation Technology based in Saint-Lambert, Quebec.

diesel-electric locomotives; a Motive Power Industries MP40 commuter locomotive serving as the lead unit, and an EMD F59PH commuter locomotive serving as the trailing tender car.

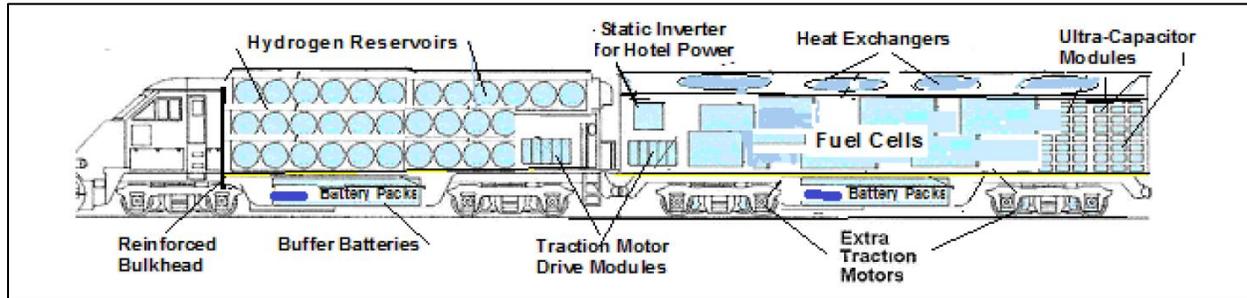


Figure 11: Hydrail configuration (locomotive and motorized tender car) suggested by the Telligence Group

The hydrogen gas reservoirs will be in the lead unit, while the fuel cells, buffer batteries, and ultra-capacitors for braking energy recouptment, storage, and regeneration will be in the motorized trailing unit (tender vehicle). The justification for all hydrogen gas reservoirs being placed in the lead unit is that the trailing unit could separate, either intentionally or in an accident, and shield the commuter passenger-carrying coaches from the lead unit containing the hydrogen gas reservoirs. Reinforced structural bulkheads would be constructed behind the driver's compartment and electrical cabinet, as well as at the rear of the locomotive, to divert any combustion upwards for the safety of the crew. Similarly, for safety reasons, the hydrogen gas reservoirs are placed higher up in the locomotive to guarantee any hydrogen gas leakage escapes rapidly to atmosphere [10].

5.2.5 East Japan Railway Company

The East Japan Railway Company, in collaboration with Hitachi Ltd. and Toyota Motor Corporation, will be testing their FV-E991 series hybrid systems that use high-pressure hydrogen-powered fuel cells and storage batteries as their source of electricity. The hydrogen will be used at 70 MPa (10,000 psi) allowing longer distance travel. Test runs for the new train will be performed in March 2022, with plans to start commercial operation in 2030. An annotated side view of the train components was shared by the company and is shown in Figure 12 [37]. Toyota will develop the fuel cell module and Hitachi will develop the hybrid drive system that will supply electric power to the traction motors from the fuel cell and battery.

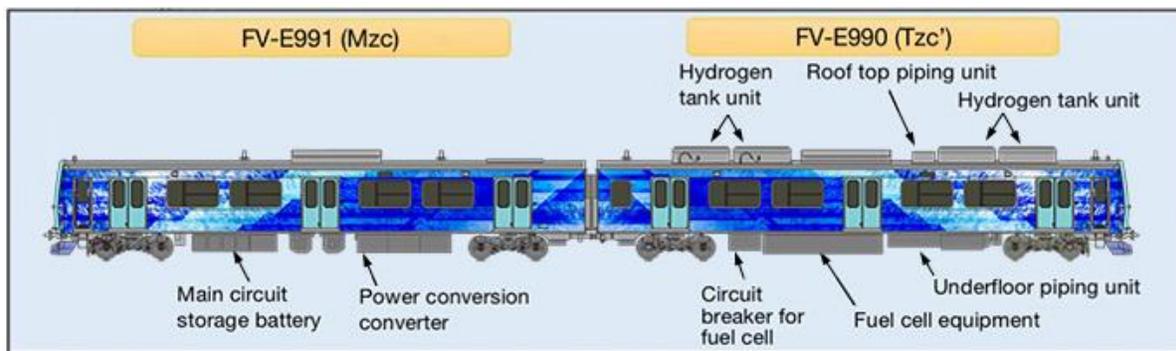


Figure 12: East Japan Railway Company FV-E991

6 Adoption of hydrail technology considerations

In this section, some considerations for adopting hydrail technologies for the design, operation, maintenance and fueling will be presented.

In 2021 Metrolinx reported the completion of a feasibility study for the use of a hydrogen powered locomotive for the GO transit which expanded on the design, operation and fueling of hydrail [38]. According to Metrolinx, the hydrogen fuel cell system for the locomotive or the electric multiple units will consist of a combination of fuel cell, battery, ultra-capacitor, and regenerative braking. Some of the key design characteristics include but are not limited to:

- The battery should be charged by the fuel cell as the train is moving, and should also be charged with the regenerative braking as the train brakes;
- The power management system should be designed so that the amount of energy recovered by braking is maximized to reduce the size of the fuel cell needed;
- The ultra-capacitors and the battery should be sized to provide the power needed by the train to accelerate to the required speed;
- The fuel cells should be arranged in parallel so that in case of failure of one unit there will only be a reduction in output power. Even if all of the fuel cell systems are unavailable, the battery system should have sufficient power to allow the train to reach a place of safety;
- The battery system should be designed so that if one unit fails there will only be a reduction in peak power; and
- The refueling system should simultaneously fill multiple tanks on the rail vehicle using a manifold system.

Given the above points highlighted by the Metrolinx feasibility study, the following topics are expected to be different in hydrail compared to diesel-electric locomotives.

6.1 Design

Locomotives are expensive pieces of equipment with long service lives. Even if hydrogen fuel cell locomotives with acceptable performance were available today, it would be prohibitively expensive for operators to replace their entire diesel locomotive fleet with hydrogen (or its various alternatives) immediately. As a result, it is entirely expected that diesel and hydrogen locomotives will have to coexist for a considerable length of time before hydrogen (and its alternatives) have sufficient numbers to significantly displace diesel locomotives in service.

Existing diesel locomotives have the ability to operate with two or more together as a unit; either as multiple power units at the head of a consist or multiple power units distributed within a consist. As far as the operator interface is concerned, multiple makes & models of locomotives can operate in the same consist as the control interface in the lead locomotive is standardized for all locomotive positions in the train and locomotive types.

Outwardly, a hydrogen fuel cell locomotive should be functionally interchangeable with a diesel locomotive, so far as operational touch points are concerned (e.g., coupler, air brake, other interfaces, etc.). Similarly, industry should and would expect from hydrail locomotives the ability to be backwards compatible with diesel locomotives in the same consist. However, with the additional unique requirements of a hydrogen fuel cell locomotive, it may be that during early phases of the introduction of the hydrail locomotive that it must be the lead (master) locomotive, which would allow the operator to monitor the operation of the hydrogen specific systems. As experience and confidence in hydrail systems increase, the use of remote hydrail locomotives could then be implemented.

Furthermore, the hydrogen storage within the locomotive will be time, space and demand driven. Hydrogen can be stored in two forms; liquid or gaseous phase. Liquid hydrogen can be stored for a shorter amount of time but will have a smaller volume of storage than gaseous hydrogen. If the locomotive needs to store hydrogen for a long period of time and does not require a small storage tank, gaseous hydrogen would be ideal to use. On the contrary, if there is a restriction on space, liquid hydrogen is to be considered. Additionally, the demand of hydrogen will influence delivery characteristics like the transfer rates and losses. The vehicle's propulsion storage tanks will be different for a gaseous hydrogen (70 MPa, -20°C to +30°C) and liquid hydrogen (atmospheric pressure, -253°C to +30°C).

Although there is less experience with liquid hydrogen than with compressed gas hydrogen for transportation applications and operation, both require safe handling measures. Liquid hydrogen requires additional measures like the selection of proper storage material (stainless steel or aluminium) and rapid measures for loss of vacuum in the containing vessel. It also requires more elaborate equipment to handle and to convert to gas, though it is faster to fuel the train than compressed gas hydrogen.

For compressed gas hydrogen, a precooling of the tank will be required to offset the heat from the adiabatic expansion of the hydrogen. The current commercial tank option available for vehicles is the Type IV tanks at 70 MPa (10,000 psi). Moreover, the temperature of the hydrogen changes depending on the pressure change during transfers. The refuelling tanks are designed to store hydrogen compressed gas at a pressure of 85 MPa (12,300 psi) to provide enough pressure to fill on board tanks designed to be at 70 MPa. The dispensing system will have a nozzle, a temperature-controlled hose, a refrigeration unit to prevent the expansion of hydrogen as it warms up from the change in pressure of the tanks, and a control system that distributes and manages electrical power.

Staff will require retraining that is specific to the hydrogen and lithium battery systems. Training during hiring as well as on-going awareness training, hazard prevention programs, and safe working procedures are expected to be required. The exposure to high voltage systems is similar, but new systems such as high pressure gas piping and storage will be new and unfamiliar.

6.2 Tractive effort limitations

There is an expectation that hydrogen fuel cell and battery powered locomotives will be physically lighter than a comparable diesel electric locomotive. As an example, heavy haul locomotives that weighs around 432,000 lb, can generate a tractive effort of around 166,000 lbf, resulting in a 38.4% equivalent adhesion factor [39]. Hypothetically, removing the diesel engine alone from the locomotive could account for up to 43,000 lb in weight. It is not expected that the weight reduction will be fully realized as the weight of the

fuel cell power system will negate a portion of the overall reduction. It is difficult to quantify the exact weight loss that would be experienced after removing the diesel engine, but estimates suggest that the hydrogen fuel cell locomotives could be approximately 7-10% lighter than diesel-electric versions. This potential weight loss will result in a reduction to the peak amount of tractive effort that the hydrogen fuel cell locomotives will be able to exert against the track and is seen as a potential limitation that must be addressed through product engineering optimizations prior to full scale adoption by the railway industry.

To fully understand the proportional loss in tractive effort, it is useful to understand the factors involved with transmission of power from the locomotive. In a locomotives the tractive effort is a function of the operating weight and it has been desirable to balance the maximum adhesion allowable by the rails to effectively increase the ratio of weight to horsepower for line-haul locomotives up to 100 lbf/hp [40]. Modern day diesel-electric locomotives use AC-powered traction motors that enable maximum hauling conditions with adhesion factors of more than 35% that can be achieved under optimal track conditions without inducing wheel slip [41].

$$F_{max} = \mu N$$

Since the relationship between the maximum tractive effort (F_{max}) is directly proportional to the weight on the wheels (N) multiplied by the coefficient of friction (μ), the lighter hydrogen fuel cell and battery powered locomotives could result in a proportionally 7-10% lower tractive effort capacity. An initial solution to this reduction in capacity would be to employ additional weight by means of ballast. While the addition of ballast seems like a simple solution, there may not be adequate room to add the required offsetting weight depending on the volume of space required for all the hydrogen fuel cell and battery equipment; this is particularly relevant for the conversion of an existing diesel-electric platform to hydrogen fuel cell power with the operational expectation of having comparable tractive effort. The intention is that the additional deadweight ballast for the fuel cell powered locomotives would increase the weight available to operate at equivalent maximum tractive effort; maintaining comparable operational standards of diesel-electric versions.

However, no definitive evidence is available as to what the tractive effort of a newly built, purpose designed hydrogen fuel cell and battery locomotive could be. This is an important factor to consider, since a new hydrogen fuel cell and battery specific design may provide opportunities to make up the potential difference in mass, resulting in comparable tractive efforts for line-haul locomotive versions without resorting to deadweight ballast. Designers would have the freedom to "disguise" additional weight by increasing the thicknesses of structural components, repackaging equipment, or other similar design techniques. Traction motor systems will remain common with diesel-electric locomotives, the main changes to maintenance are in the new fuel cell, fuel storage and battery systems.

One of the benefits of hydrail locomotive is that energy that is wasted during braking may be recovered. For example, current diesel-electric locomotives expel dynamic braking energy as heat, but both hydrail and battery-only locomotives would be able to capture the waste energy and store it in the batteries. This has implications for increased range of hydrail locomotives for the fuel carried on board compared to diesel-electric locomotives.

6.3 Fueling and fuel capacity

When compared to diesel, the amount of hydrogen stored relative to the storage container's weight and/or volume is poor. When storing hydrogen as a high-pressure gas, the storage vessel is heavy and bulky relative to the amount of energy stored. For any given mass of a filled high-pressure hydrogen tank, the same mass can be fashioned into a diesel fuel tank capable of storing diesel fuel with approximately three to four times the amount of energy, as seen in Figure 13 [42], where it is seen that the energy density by volume and weight of diesel is higher than all other comparable fuels.

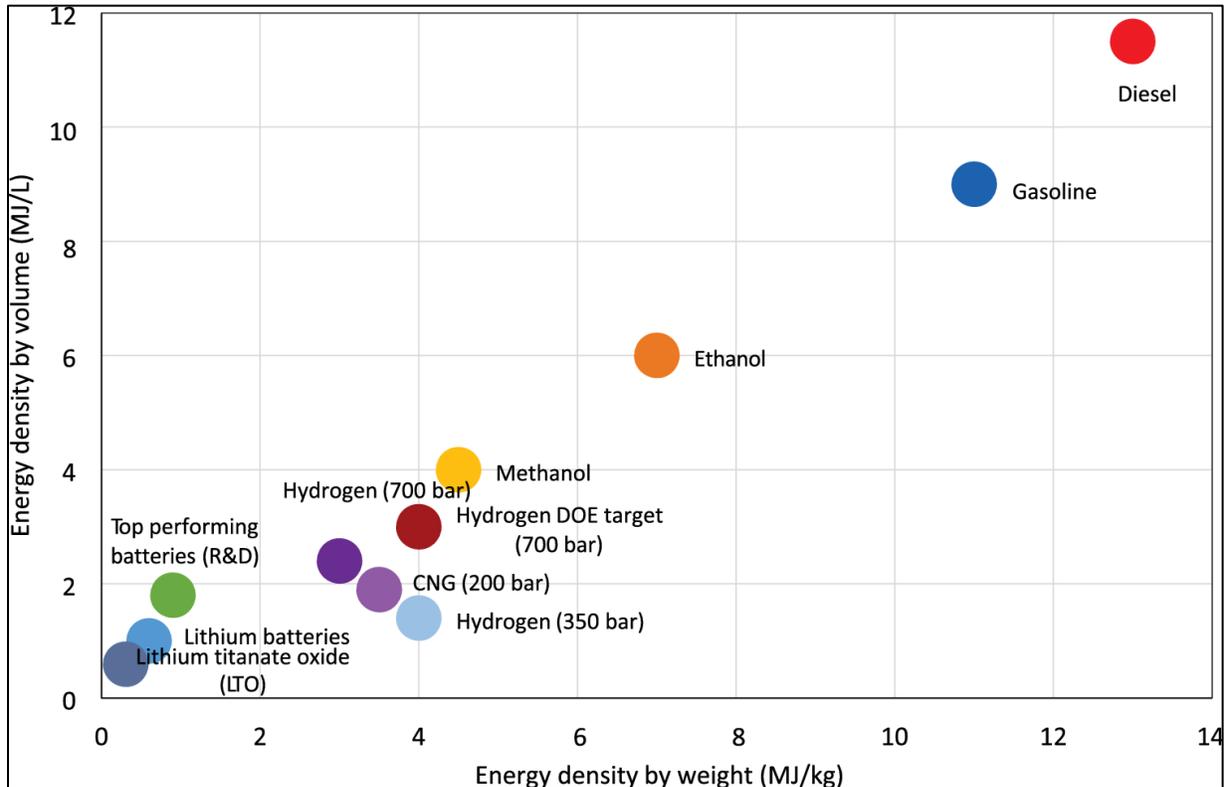


Figure 13: Energy density volume vs. weight including storage container weight

The fuel storage limitations of hydrogen vs. diesel comparison is improved somewhat when hydrogen is stored as a cryogenic liquid. In the case of liquid storage, the pressure vessel strength requirements are modest, which allows more volume to be dedicated to fuel storage. However the gain in volume is offset by volume lost to insulation. Liquid storage offers the best storage efficiency for hydrogen, however, diesel is still superior as an energy storage medium and can store significantly more energy in any given tank mass.

Diesel fuel tanks do not need to be fabricated as pressure vessels, and can be exposed to ambient temperature and pressure without creating dangerous conditions for the fuel inside. Diesel tanks do not require thermal insulation, do not need to be made from high-performance materials such as carbon fibre, and can be fabricated simply with commodity engineering materials (steel) and methods (welding). Additionally, diesel fuel is stable across a wide range of temperatures, is compatible with many engineering materials, does not promote corrosion or degradation of wetted components, and is easily stored, transported, and handled with minimal special precautions.

The process to fuel a diesel-electric locomotive is well understood and relatively quick. The process is considered safe when simple precautions are taken. In contrast, hydrogen fueling may be complex, and procedures will depend on the density and state (liquid or gas) of the fuel, as well fill times will vary depending on if gaseous or liquid hydrogen is used.

In the literature reviewed it was noted that hydrogen re-fueling procedures appeared to be non-standardized. It is expected that for North American freight industry use hydrogen refuelling will need to be formalized, and should follow an industry standard. As well, standardized shutdown procedures, use of protective coverings, use of safety devices such as electrical grounding or bonding, forced ventilation methods, re-fueling line connection methods, and fuel metering systems are all issues that will need to be addressed and standardized.

It is expected that there will be a need for multiple fuel tank redundancy of onboard fuel storage for maintenance switching. This would prevent full shutdown of the systems if a leakage is detected. Similar requirements may be needed for the battery packs.

6.4 Failure rates and severity

In this section the failure rates, modes, causes, consequences, and severity for hydrail powered locomotives, train or switchers from previous trials will be presented. San Bernardino County Transportation Authority shared a summary of hydrogen safety incidents relevant to transportation applications; eighteen incidents reported by the Center for Hydrogen Safety that occurred from 1969 to 2019 [43]. The type and quantity of incidents are: one pressure relief device incident, one hydrogen cylinder incident, five piping incidents, three industrial truck incidents, and eight fueling station incident. Six out of eighteen incidents resulted in an explosion or fire. More details about the incidents are presented below.

- Pressure relief device incident (one)
 - Relief valve was set incorrectly to open at line pressure. Poor design of venting system caused inadequate venting and buildup of static electricity. This led to an explosion.
- Hydrogen cylinder incident (one)
 - A high-pressure hydrogen cylinder failed in service causing hydrogen to leak from a screw fitting. The hydrogen gas sensors detected the leakage and triggered an alarm. No ignition occurred.
- Piping incidents (five)
 - The compression style fitting was missing the front ferrule;
 - Check valve shaft blow-out. The valve had a shaft or stem piece which penetrated the pressure boundary and ended inside the pressurized portion of the valve;
 - Constant vibration caused a bolt to create a hole in the high-pressure suction piping;
 - Valves could not be reopened without securing all charging pumps. Spring of the disc guide assembly in two solenoid-operated globe valves underwent complete catastrophic failure creating hydrogen embrittlement; and
 - Ball valve failed to open due to valve stem failure.
- Industrial truck incidents (three)
 - An O-ring failed during a pressure test at approximately 4,500 psi (31 MPa). This released all of the hydrogen in the tank in about 10 minutes. The situation was caused by an internal thread on the tank that did not allow full engagement and hence full compression of the O-ring;

- A broken drill bit on top of the fuel cell stack plates caused a spark and fire; and
- The evaporator pad in a fuel cell power unit installed in a hydrogen powered forklift caught fire during operation.
- Fueling station incidents (eight)
 - Fueling hose failed;
 - Two fitting failures occurred in the filling systems of the fueling equipment;
 - A valve packing started to leak during cold ambient temperatures;
 - A crankshaft bearing started failing after a compressor turned on for about 2 hours to refill the storage. This created great movement of a shaft which led to a shaft seal leak;
 - A hydrogen leak occurred when a vendor's hydrogen fill truck trailer pulled away at a hydrogen fill station after filling and caught an improperly stored hydrogen fill line;
 - Pressure relief valve failed;
 - Fueling station high pressure storage leak from a tank; and
 - Hydrogen tanker truck was being fueled and a leak occurred. An explosion occurred when the tanker truck that was being fueled shut down.

6.5 Legacy component and system reuse

If the desire is to convert or retrofit any existing diesel-electric locomotive to hydrail operation, it may be possible to reuse existing legacy internal combustion engine (ICE) locomotive components and systems in a hydrail locomotive as a means to manage risk and/or cost.

The traditional radiator for ICE cooling has approximately the same heat rejection capacity and operating temperatures as the cooling system that would be required in a hydrail implementation on a kW for kW basis. Additionally, the dynamic braking heater grid in an ICE locomotive would also be a good candidate for re-use within a hydrail implementation.

Another area of re-use that is possible is the air compressor that provides compressed air for the mechanical braking system on the locomotive and throughout the entire train. Traditionally, this compressor is constantly driven by the ICE, with unloader valves that vent excess compressed air to atmosphere. This can represent a significant waste of energy both in wasted compressed air, and as a parasitic load on the engine. In a hydrail implementation, the air compressor could be electrically driven, which would allow the compressor to be shut off, rather than running continuously and venting excess compressed air. More sophisticated controls would vary the speed of the compressor motor, continuously matching compressor output to the actual demand for compressed air.

As mentioned previously, modern traction motors using variable frequency AC or brushless permanent magnet DC motors offer significantly better efficiency and performance over traditional brushed DC motors. These advanced motors and drives can operate in constant torque, constant power, or constant speed modes, seamlessly switch between modes rapidly as the situation demands to maximize efficiency, and all without operator intervention.

7 Summary and recommendations

7.1 Summary

Two reference designs for a hydrogen fuel cell powered locomotive were presented to identify and locate the potential power systems that could be required for a hydrogen fuel cell power architecture in locomotives. They are not meant to impose on the design freedom that is required when designing complex mechanical power systems for the railways and is not a guideline with detailed requirements as seen in prescriptive engineering approaches. The first design outwardly has the same look, feel, and footprint as a traditional diesel-electric locomotive and could be suited for switcher applications. The second design, the tender style of hydrail locomotive, has the hydrogen storage as a separate railcar that is married to the locomotive; a service umbilical connects the hydrogen tender to the locomotive. This could be used to move trains over long distances. From the literature review, various hydrail projects for hydrogen and battery-powered locomotives were found. From the 29 projects from 2002 to 2024, 19 are for passenger use, leaving the rest to be shared between shunter, mining locomotives, freight and tramways. In addition to the literature review, the adoption of hydrail involves taking into consideration the possible design, tractive effort, fuelling and fuel capacity limitations, the failure rates and the legacy components.

7.2 Recommendations

The literature review found that most hydrogen fuel cell powered locomotives have been of a prototype nature and for passenger use. There are currently no in service hydrail locomotives in Canada. The NRC authors recommend that the following activities be undertaken:

- conduct a risk and hazard analysis of freight hydrail locomotives in revenue service (this will be done in Phase 2);
- conduct a literature review for a battery-electric standalone locomotive to better understand the state of technical readiness of these locomotives in the industry (this will be done in Phase 2); and
- update Table 2 of this report so that it includes battery-electric standalone systems, and keep it up to date with hydrail systems as they enter service (this will be done in Phase 2).

Acronyms and abbreviations

AAR	Association of American Railroads
AC	alternating current
AST	Automotive and Surface Transportation
ASTM	American Society for Testing and Materials
BNSF	Burlington Northern and Santa Fe Railway
CANMET	Canada Centre for Mineral and Energy Technology
CN	Canadian National Railway
CP	Canadian Pacific Railway
DC	direct current
ESS	energy storage system
FLIRT H2	Fast Light Intercity and Regional Train hydrogen train
FPI	Fuel Cell Propulsion Institute
H2M	Hydrogen-In-Motion
ICE	internal combustion engine
NRC	National Research Council of Canada
NREL	National Renewable Energy Laboratory
OCTA	Orange County Transportation Authority
OEM	original equipment manufacturer
PEM	proton-exchange membrane
RTRI	Railway Technical Research Institute
SAE	Society of Automotive Engineers
SBCTA	San Bernardino County Transportation Authority
SRY	Southern Railway of British Columbia
TC	Transport Canada
UBC	University of British Columbia
UK	United Kingdom
US	United States

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Appendix A: Relevance of selected references

Relevance (1 to 5)	Report title	Organization	Publication date	Brief summary	Ref.
5	Study of hydrogen fuel cell technology for rail propulsion and review of relevant industry standards	Sandia National Laboratories / Federal Railroad Administration	June 2021	Standards from the Association of American Railroads (AAR) and other industry best practices were reviewed for applicability with hydrogen fuel cell technology. Technical gaps related to the physical properties of hydrogen, such as embrittlement of metals, invisible flames, and low liquid temperatures are discussed	[44]
5	Regional Express Rail program hydrail feasibility study report	CH2M HILL Canada Limited; Ernst & Young Orenda Corporate Finance Inc.; Canadian Nuclear Laboratories / Metrolinx	February 2018	Feasibility study of hydrogen fuel cells powered passenger rail vehicles operation on the GO network as an alternative to overhead wire electrification.	[38]
5	Assessment of the design, deployment characteristics and requirements of a hydrogen fuel cell powered switcher locomotive	Change Energy Services Inc. / Environment and Climate Change Canada	June 2020	An assessment of the potential to replace the diesel engine onboard an EMD GP38-2 locomotive with hydrogen fuel cells and hydrogen as the fuel.	[20]
5	Lithium-ion battery safety issues for electric and plug-in hybrid vehicles	Battelle / National Highway Traffic Safety Administration	October 2017	An assessment of lithium-ion battery to identify vehicle's operational safety issues.	[45]
5	Fuelcell prototype locomotive	Vehicle Projects LLC / U.S. Department of Energy	June 2007	Final technical report of the conversion of the Green Goat from diesel to a fuel cell hybrid switcher locomotive for commercial railway applications and power-to-grid generation applications.	[46]
5	Advanced underground vehicle power and control; the locomotive research platform	Vehicle Projects LLC	October 2002	Final technical report of the development of a fuel cell mining locomotive with metal-hydride.	[31]
4	Refueling infrastructure scoping and feasibility assessment for hydrogen rail applications	Sandia National Laboratories	October 2021	The feasibility and component cost of hydrogen rail refueling infrastructure is examined	[47]

Relevance (1 to 5)	Report title	Organization	Publication date	Brief summary	Ref.
4	Lithium battery transport study: Canadian risk perspective	National Research Council Canada	March 2014	Review of scientific and technical documentation on potential risks attributed to battery chemistry, materials, design, fabrication, handling, and environmental factors related to the battery air transportation cycle.	[48]
3	Maritime fuel cell generator project	Sandia National Laboratories	May 2017	A study on the use of a hydrogen fuel cell generator in the maritime environment. The report identified areas requiring additional research and development, analyzed the business case, regulatory and other market barriers.	[29]
3	Characteristics of cryogenic hydrogen releases under unignited and ignited conditions	Sandia National Laboratories	August 2019	Assessment of the risks at hydrogen fueling stations with cryogenic hydrogen on-site by experimenting with controlled release of cryogenic hydrogen in a laboratory.	[49]
3	Hydrail deployment in Canada – defining the prerequisites	TELLIGENCE Group	May 2020	This reports touches upon the definition and implications of introducing Hydrail in a number of organizations that play key roles in the provision of railway services. This includes the safety and regulatory norms, training for first responders, and the familiarity of the public with hydrogen powered rail vehicles.	[10]
3	Review and assessment of hydrogen propelled railway vehicles	University of Birmingham	May 2010	A review of hydrogen powered locomotive implementations between 2006 and 2008.	[50]
3	BC Transit fuel cell bus project evaluation results: second report	National Renewable Energy Laboratory	September 2014	Evaluation of 20 fuel cell electric buses in Whistler, BC, Canada for a 5 year demonstration.	[32]
3	Hydrogen fuel applications report: San Bernardino County Transportation Authority zero-emission multiple unit project	Mott MacDonald	November 2020	Provides information about hydrogen and its transportation and industrial applications.	[43]
2	Hydrail railway transition in Canada: technological, operational, economical, and societal (TOES) barriers and opportunities	Change Energy Services Inc.	March 2021	An assessment of the technical, operational, economic and societal changes to conceptually transition Canada's railway sector from diesel to hydrogen powered energy system for primary movers.	[51]
2	A review on fuel cell-based locomotive powering options for sustainable transportation	University of Ontario Institute of Technology	October 2018	Literature review of the development of fuel cell-based locomotives and their progress.	[35]

Relevance (1 to 5)	Report title	Organization	Publication date	Brief summary	Ref.
2	H2@Rail Workshop	Sandia National Laboratories	August 2019	Proceedings of the H2@RailSM Workshop held by the US Department of Energy's Fuel Cell Technologies Office and the US Department of Transportation's Federal Railroad Administration	[52]
2	CHBC briefing: hydrogen rail project showcase	California Hydrogen Business Council	May 2021	Presentations on current technology by various companies involved with hydrogen technology.	[53]
2	Safety of hydrogen powered industrial trucks, lessons learned and existing codes and standards gaps	Nuvera Fuel Cells	September 2011	An introduction to a hydrogen powered forklift, the safety similarities with the automotive application and safety lessons learned.	[33]
2	Zero-emission bus evaluation results: Orange County Transportation Authority fuel cell electric bus	National Renewable Energy Laboratory / Federal Transit Administration	May 2018	Summary of the experience and results from the fuel cell electric bus demonstration by Orange County Transportation Authority.	[28]
2	Fuel cell buses in U.S. transit fleets: current status 2020	National Renewable Energy Laboratory	March 2021	Summary of the fuel cell electric bus development progress, achievements and challenges in the US.	[30]
2	Zero-emission bus evaluation results: Stark Area Regional Transit Authority fuel cell electric buses	National Renewable Energy Laboratory	October 2019	Summary of the experience and results from the fuel cell electric bus demonstration by Stark Area Regional Transit Authority in Ohio.	[54]
2	American fuel cell bus project evaluation: third report	National Renewable Energy Laboratory	May 2017	Results of the American Fuel Cell Bus Project.	[55]
2	Main results test with hydrogen train in Groningen	Provincie Groningen	September 2020	Results of the Alstom Coradia iLint trial in the Netherlands.	[9]
1	Fuel cell-based powertrain analysis for Tramway Systems	SAE International	October 2019	A comparison of three different hybrid powertrains in a Matlab-Simulink environment.	[56]
1	Study on the use of fuel cells & hydrogen in the railway environment	Roland Berger	April 2019	An analysis of overcoming technological and non-technological barriers to widespread use of hydrogen fuel cell in rail applications.	[57]
1	Side impact test and analyses of a DOT-111 (CPC-1232) tank car	Federal Railroad Administration	October 2018	Results from a side impact test on a DOT-111 railway tank car at the Transportation Technology Center, Inc. (TTCI) to evaluate its performance under dynamic impact conditions.	[58]
1	Low- or zero-emission multiple-unit feasibility study	Michigan State University and University of Birmingham	December 2019	This reports aims to compare low and zero-emission technology to replace diesel power for railway applications.	[59]

Relevance (1 to 5)	Report title	Organization	Publication date	Brief summary	Ref.
1	Pipeline and hazardous materials safety administration	Pipeline and Hazardous Materials Safety Administration (PHMSA), Department of Transportation (DOT).	July 2020	Hazardous materials regulations for the transport of methane and refrigerated liquids in rail tank cars.	[60]
1	Fuel cells based on natural polysaccharides for rail vehicle application	Łukasiewicz Research Network–Rail Vehicles Institute with Poznan University of Technology	February 2021	This report covers the use of natural polysaccharides as a carbon source for fuel cells.	[61]
1	Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric	Nature Energy	November 2021	This paper shows that battery-electric trains can achieve parity with diesel-electric trains if environmental costs are included.	[62]
1	Best practices and strategies for improving rail energy efficiency	Research and Innovative Technology Administration / U.S. Department of Transportation	January 2014	A study on technology development opportunities, equipment upgrades, and best practices of international and U.S. passenger and freight rail industry.	[63]
1	Technology assessment: freight locomotives	Air Resources Board and Transportation and Toxics Division	November 2016	Freight rail technology assessment of potential advanced locomotive technologies on the existing rail network that could lower emissions below Tier 4 emission levels.	[64]
1	Fueling the future of mobility hydrogen and fuel cell solutions for transportation	Deloitte and Ballard	January 2020	Covers the economic viability of fuel cell vehicles and the impact on the environment.	[65]

Appendix B: Reference summary – key findings

Key findings from 5 references in Appendix A that were assigned an Applicability Grade of 5.

[44] **Study of Hydrogen Fuel Cell Technology for Rail Propulsion and Review of Relevant Industry Standards**

Sandia National Laboratories identified that current rail standards will need to be modified to accommodate hydrogen fuel cell use in locomotives. The following codes and standards were reviewed for applicability and assessed for gaps:

- Manuals of Standards and Recommended Practices (MSRP) Section T (M-1004) (Association of American Railroads Section T, 2019)
- Section C Part III (M-1002) (Association of American Railroads Section C-III, 2014)
- Section M (Association of American Railroads Section M, 2008)
- National Fire Protection Association (NFPA) 2 Hydrogen Technologies Code (National Fire Protection Association 2, 2020)
- American National Standards Institute (ANSI)/American Institute of Aeronautics (AIAA) G-095A Guide to Safety of Hydrogen and Hydrogen Systems (ANSI/AIAA G-095A, 2017)

The identified gaps were grouped in the following categories:

- Ventilation: Avoidance of forced ventilation needs to be revised for rail electronic components, fuel cell assemblies and for enclosed spaces fuel cell technology in a rail environment.
- Fuel tank location;
- Vibration testing: There seemed to be no AAR document specifying the shock/vibration testing of a locomotive diesel engine but hydrogen systems and fuel cell electronics need to undergo shock and vibration testing;
- Fueling: Breakaway devices do exist for gaseous hydrogen refueling lines, but it is not clear that breakaway lines are commercially available for liquid hydrogen. Breakaway devices from other cryogenic fluids such as liquid nitrogen and liquefied natural gas (LNG) could be adapted or modified for liquid hydrogen;
- Materials: The AAR documentation needs to be modified to include the design rules around the optimal materials necessary to make hydrogen technology (e.g., tanks, tubing, valves, and fuel cells) work and work safely; and
- Physical phenomena: The differing physical properties of hydrogen require some revision of the AAR documentation.

[38] **Regional Express Rail Program Hydrail Feasibility Study Report**

The feasibility study done by Metrolinx on using hydrogen fuel cells to power the rail vehicles started at the beginning of June 2017 and ended in December 2017. The relevant topics to this literature review covered by the study are:

- The subsystems and components of a Hydrail system and the types of applications.
 - Hydrogen production
 - Fuel storage: gaseous hydrogen and liquid hydrogen
 - Refuelling and dispensing
- Overview of existing regulations, standards and codes, and the existing gaps
- Case studies of other jurisdictions
- Risks that could affect design, implementation and operation

[45] **Lithium-Ion Battery Safety Issues for Electric and Plug-in Hybrid Vehicles**

The report covers the electrochemistry, the cell design architecture and system analysis and the battery management of lithium-ion batteries in vehicles. The following standards were mentioned to be relevant; SAND2005-3123, SAE J2464, SAE J2929, ISO 6469-1, ISO 6469-2, UL 1642, UL 2580, IEC 62133, IEC 62281, 38.3 (E.09.VIII.3), IEEE 1625, IEEE 1725. Potential gaps in the following battery related topics were discussed:

- Component and System Safety Standards
- Performance-Based Design Qualification Requirements
- Safety Systems Integration and Testing
- Systematic Crashworthiness Requirements for Each System Level
- Quality Control Requirements.

[31] **Advanced Underground Vehicle Power and Control; the Locomotive Research Platform**

The final technical report includes various report from the various partners that were part of the project. It includes the design, surface tests, risk and safety analysis and the locomotive underground testing. The applicable government regulations and applicable industry standards reviewed are:

- Ontario Occupational Health and Safety Act;
- Ontario Occupational Health and Safety Act; Regulation 854 – Mines and Mining Plants;
- CSA B51-97; Boiler, Pressure Vessel, and Pressure Piping Code;
- CSA C22.1-02; 2002 Canadian Electrical Code; and
- CSA M421-93; “Use of Electricity in Mines”.

[20] **Assessment of the Design, Deployment Characteristics and Requirements of a Hydrogen Fuel Cell Powered Switcher Locomotive**

This research evaluates the viability of using hydrogen fuel cells as the prime mover in place of a combustion engine to produce motive and auxiliary power, as well as replacing the diesel onboard a typical switcher locomotive with hydrogen as the fuel. The reference locomotive was chosen to be the GP38-2 road switcher produced by General Motors, Electro-Motive Division. Using commercially available fuel cell power modules, hydrogen storage containers, and battery packs with the capacity to meet the power and energy needs of daily use, a conceptual design was created. A review of the regulatory environment was done in order to understand how a railway firm subject to federal regulation would implement hydrogen technology. This included applicable laws, rules, and regulations that were issued by

the federal government as well as any codes and standards that were referred to by other governing bodies.

[36] **Fuelcell Prototype Locomotive**

This report follows the thought process and execution of the Green Goat fuel cell hybrid switcher locomotive for commercial railway applications and power-to-grid generation applications. The following topics are presented:

- Fuel cell Power Module;
- Metal-Hydride Evaluation;
- Fuel cell-Battery Hybrid Evaluation; and
- Hazard Analysis Report.

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