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Pollution Probe

Towards Net Zero: Developing a Rail Decarbonization Roadmap for Canada

December 2022

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EXECUTIVE SUMMARY

Rail has always been a highly efficient mode of transportation for both freight and passengers. It has become increasingly efficient over the last 26 years, in part due to efforts from the rail sector and a long-standing MOU between the Railway Association of Canada (RAC) and Transport Canada. Deeper decarbonization of the rail sector can contribute meaningfully to meeting Canada's GHG reduction target, but the nature of railway equipment and operations make this challenging. There are several technologies that may contribute to the deep decarbonization of the sector, but most are nascent and all face significant challenges. As such there is no clear, singular pathway to deep decarbonization. The Canadian railway industry is rising to the challenge of charting a path forward; both mainline freight railways and one shortline recently announced pilot projects to test alternative propulsion technologies, and Canada's primary passenger railway announced plans to electrify much of its operations.

The objective of the Rail Pathways Initiative was to create a roadmap to rail decarbonization based on emerging low-carbon technologies. This entailed developing a framework for assessing GHG reduction opportunities in Canada's rail sector and creating a strategy to apply it to inform decision-making on decarbonization in the years and decades ahead.

This work is based on the understanding that the trajectory to net zero for rail will unroll in three overlapping "waves": efficiency improvements, low-carbon fuels, and alternative propulsion. Efficiency has been and should remain an ongoing focus of railway decarbonization efforts. While efficiency improvements should continue to be prioritized, they are not the focus of this report, which examines options with deeper decarbonization potential. Alternative (low-carbon) fuels, while unlikely to achieve full decarbonization on their own, present an attractive short to medium term solution, particularly when paired with developing alternative propulsion technologies. The latter are widely expected to represent the ultimate solution to decarbonization but remain years or even decades away from full commercial viability.

The Analytical Assessment Framework presented in Section 2.6 was developed to track the evolving potential of alternative fuels and propulsion technologies. As noted above, these are now being tested both in Canada and internationally, generating data on performance, emissions, costs and associated challenges. The Framework can be used to analyse this data, rating the technologies relative to one another based on an assessment of their current costs, emissions reduction potential and challenges. In terms of costs, the three areas assessed by the Framework are related to development, implementation, and operation. Emissions reduction potential is broken down into potential on a per-train basis (relative to diesel-powered trains) and applicability to mainline usage, as mainlines are responsible for a large majority of rail emissions in Canada. Challenges are assessed through three categories in the Framework: operational, refueling, and safety and regulatory compliance. These categories, along with the Framework architecture in general, were thoroughly vetted by leading rail experts prior to the initial assessments.

The Framework provides a combined rating out of 100 for each technology assessed. This is not a projection of future potential, but instead a snapshot of the current status of each decarbonization option. The value of the ratings that the Framework provides is expected to be realized as it is reapplied at regular intervals, based on updated data, to map the trajectory of each option. In other words, each application of the Framework provides a "snapshot" rating of the current status of each decarbonization option and repeating those snapshots at regular intervals will reveal the trajectory of each option, relative to the others, in terms of its viability to decarbonize Canada's rail sector. This can give stakeholders a head start on preparing for the technologies that show the most promise. Due to the time required to deploy new infrastructure and upgrade rail equipment, the technology platform that will ultimately replace diesel locomotives must be determined by 2035 at the latest. This will allow the rail sector to align with Canada's net zero 2050 target. In the interim, accelerated rail RD&D and the re-application of the Framework can help to inform the most promising options for Canadian railways.

The Framework was applied to generate 2021 ratings of the two alternative fuels and three alternative propulsion technologies that were found to be the most viable candidates for the deep decarbonization of the sector. The fuels are biodiesel and hydrogenation-derived renewable diesel (HDRD), while the alternative propulsion technologies are battery electric, catenary electric, and hydrogen fuel cell. Results from this initial assessment can serve as a baseline to which future assessments can be compared.

Assessment Category	Alternative Fuel		Alternative Propulsion		
	B20	HDRD30	Battery Electric	Catenary Electric	Hydrogen Fuel Cell
Cost	76	72	56	76	32
Carbon Reduction Potential	70	70	80	100	80
Challenges	80	67	67	40	40
OVERALL	**75**	**70**	**68**	**72**	**51**

The 2021 ratings reflect the current commercial availability of each option. As an example, the ratings for catenary electric are high relative to battery electric and hydrogen fuel cell, reflecting the fact that it is a commercially available technology, already in wide application globally. For this same reason, the ratings for catenary are expected to stay reasonably static as the Framework is reapplied in future years. The ratings for battery electric and hydrogen fuel cell, conversely, are expected to have more room for growth as these are both rapidly developing technologies. The Canadian pilot projects mentioned above, along with others in the United States and overseas, will contribute meaningfully to advancing these technologies and will provide useful data for future Framework evaluations. Regular application of the Framework in future years, overseen by a multi-stakeholder committee, is a core recommendation of this report.

Summaries of the 2021 assessments for the five leading decarbonization options are provided in Sections 3.2 through 4.2, while details from each assessment are provided in Appendices C through G.

The roadmap also accounts for key non-technology related considerations including funding support that railways will require to continue to test emerging technologies and ultimately to incorporate them into their fleets, the requirement for interoperability across the continent, and the simultaneous decarbonization of competing modalities. The Roadmap Implementation Plan, included here as Section 4.3, compiles both technical and non-technical considerations in a process to expedite decarbonization of the rail sector. It further captures roles and responsibilities for key stakeholders, in recognition of the understanding that the pursuit of these pathways will require collaboration between all key stakeholder groups on technology, regulation, and policy and program development. It includes the following five recommendations:

1. Complete assessments of technology options every 2-5 years using the Assessment Framework included in Section 2.6. Report on the relative trajectories of each option to 2030 and 2050. The results of each assessment should be published and shared broadly with rail stakeholders throughout North America if it is possible to do so while respecting confidentiality of railways and other private sector stakeholders.

2. Renew the longstanding Memorandum of Understanding between TC and RAC in 2022. Reference the findings of both Phases 1 and 2 of the Rail Pathways work, including the Assessment Framework, the recommendations, and the stakeholder roles and responsibilities.

3. Establish a national Rail Decarbonization Committee. The Committee can lead on setting decarbonization targets, tracking progress towards them, overseeing future applications of the assessment framework, identifying optimal areas for government support, proposing appropriate short- to mid-term actions, as well as engaging with U.S. counterparts to align high level approaches and actions.

4. Create a Project Manager function to support the Rail Decarbonization Committee.

5. Establish a joint government-industry program to support and realize the decarbonization opportunities identified in this Roadmap. This program should have an exclusive focus on rail in recognition of its inherent efficiency benefits over other modes and the vital role it plays in Canada’s economy. It should include both a funding component and a convening component intended to support collaboration.

There are a multitude of variables that must be considered when plotting out the most efficient pathway to rail sector decarbonization. When these variables interact with each other, the number of potential pathways is compounded greatly. This makes the development of conventional decarbonization scenarios challenging in the case of rail and reduces the likelihood that any scenario or projection developed today will come to fruition.

As such, the information and the Framework presented in this report are provided with the intention that they will continue to produce useful outputs and inform decision-making as the rail sector, associated technologies and practices, and the over-arching context of decarbonization continue to evolve.

1. INTRODUCTION

1.1 THE RAIL PATHWAYS INITIATIVE

With over 49,000 route kilometres of track running from coast-to-coast, three national railway companies and numerous regional and short line railways that carry freight and passengers, Canada's extensive rail network supports both the Canadian economy and the quality of life enjoyed by Canadians. Class 1 and short line freight rail moves more than $320 billion worth of goods, and passenger rail moves more than 100 million people per year.[1]

Roughly one quarter of Canada's greenhouse gas (GHG) emissions come from the transportation sector.[2] Once dominated by passenger transportation, emissions from this sector increasingly result from the movement of freight. Emissions from freight are projected to exceed those from passenger transportation by 2030.[3] On a tonne-km basis, rail is the most prevalent method of transporting freight domestically (44%, versus 33% by truck). Yet the rail sector accounts for only 4% of Canada's total transportation-related GHG emissions,[4] and 93% of total rail emissions result from the transportation of freight.[5] This is a testament to the fuel efficiency of this mode.

By consistently investing in efficiency and sustainability, Canada's freight railways have reduced their GHG emissions intensity by over 40% since 1990, and intercity passenger railways have reduced their GHG emissions intensity by about 55%.[6] These efficiency gains have largely been realized through locomotive engine upgrades, and operational efficiencies including precision scheduled railroading. As Canada and the world moves towards deep carbon reductions and eventually net zero, however, all sectors will need to look beyond efficiency to decarbonize the sources of energy they consume.

Since 1995, Transport Canada and the Railway Association of Canada (RAC) have signed four Memoranda of Understanding (MOU) to establish voluntary reduction targets for emissions produced by locomotives in Canada. The most recent of these, the 2018 – 2022 MOU, includes a commitment to collaborate on a "comprehensive pathway document for aligning government and industry efforts to reduce emissions produced by the railway sector." The two-phase Rail Pathways Initiative is intended to build off the successes achieved to date by the MOU via collaborative public-private efforts to explicitly target GHG reductions from Canada's rail sector.

1 RAC, 2022 (https://www.railcan.ca/who-we-are/)
2 ECCC, 2020 (https://www.canada.ca/en/environment-climate-change/services/environmentalindicators/greenhouse-gas-emissions.html)
3 ECCC, 2016 (https://www.canada.ca/content/dam/eccc/migration/main/ges-ghg/02d095cb-bab0-40d6-b7f0-828145249af5/3001-20unfccc-202nd-20biennial-20report_e_v7_lowres.pdf)
4 Transport Canada
5 ECCC, 2020 (https://publications.gc.ca/collections/collection_2020/eccc/En81-4-2018-3-eng.pdf)
6 RAC, 2020 (https://www.railcan.ca/wp-content/uploads/2020/05/RailCan_EnvironmentalBrief_Final.pdf)

Phase 1, completed in 2020, catalogued ongoing and potential activities related to rail sector decarbonization that are led by industry and government, or collaborations between the private and public sectors. The common understanding of the current state of rail sector decarbonization in Canada developed by Phase 1 was intended both to support the Pathway development, and as a tool for collaboration. Due to high cost, long-lasting equipment with high energy requirements, as well as Canada's vast geographic expanse, decarbonizing this sector presents unique challenges. It will require alignment and strategic cooperation from all sectors noted above, including academia/ research organizations, OEMs, fuel producers/ energy suppliers, rail operators and government bodies.

1.1.1 OUTCOMES OF PHASE 1: LANDSCAPE DOCUMENT

Phase 1 explored the current state of play on rail-related decarbonization activities and policies in Canada.[7] It created an inventory of legislative instruments and activities that impact rail carbon intensity in Canada, including:

- Federal instruments: regulations, policies and programs being led at the federal level;
- Provincial instruments: regulations, policies and programs being led at the provincial/territorial level;
- Federal and provincial research, development and demonstration (RD&D) initiatives: specifically, in areas such as technologies, fuels and feasibility assessments; and
- Canadian rail industry activities: industry-led activities aimed at reducing the GHG emissions intensity of rail operations.

The Landscape Document identified that Canada's rail industry is engaged in decarbonization activities related to fuel efficiency, alternative fuels, alternative propulsion, infrastructure, and modal shift. It found that the category most intensively addressed to date is fuel efficiency, largely driven by fleet renewal and the implementation of software and data analytics related to energy and route optimization. The utilization of alternative fuels continues to advance as well, as does infrastructure expansion to enhance network capacity and fluidity. Since Phase 1 was completed in August 2020, Canada's three largest railways, Canadian National Railway (CN), Canadian Pacific Railway (CP) and Via Rail have all announced that they will be introducing electric or hydrogen fuel cell trains to their fleets. Smaller shortlines are also actively pursuing zero-emission options, including BC's Southern Railway who has announced plans to convert a diesel-powered switcher to hydrogen fuel cell.

7 The Landscape Document also recorded best practices in the international rail decarbonization landscape.

1.1.2 OBJECTIVES OF PHASE 2: DECARBONIZATION ROADMAP

Phase 2 of the Pathways Initiative leveraged the Landscape Document along with extensive stakeholder engagement and analysis of existing recent studies to develop a methodology to map the trajectory towards deep decarbonization of the rail sector. This entailed establishing a common vision, developing a framework for assessing GHG reduction opportunities in Canada's rail sector, and creating a comprehensive strategy to inform decision making on pathways to decarbonization in the years and decades ahead.

Early on in the process it was noted that findings from roadmapping exercises similar to this one can quickly become obsolete if they do not include frameworks that allow them to be regularly updated to account for emerging developments. All stakeholders involved wanted to avoid this outcome. Therefore, in order for the assessment framework to be optimally useful, it needs to be revisited and reapplied regularly in the coming years. Reapplying the framework based on real-world data from near-term Canadian pilots and other testing will shed light on the commercial readiness trajectories and GHG reduction potential of leading decarbonization options as RD&D focused on them accelerates. It will further serve to highlight concrete recommendations that are fuel and/or technology specific.

As noted earlier, the 2018 – 2022 MOU includes a commitment to collaborate on a "comprehensive pathway document for aligning government and industry efforts to reduce emissions produced by the railway sector." This document identifies a method to assess potential GHG reduction measures, and outlines stakeholder roles in leveraging these measures for meaningful emissions reduction for the rail sector. In so doing, it is intended to inform both government policy and industry direction, to help educate legislators from all levels of government and to support the rail industry in its efforts to support Canadian climate commitments.

2. TECHNOLOGY ASSESSMENT FRAMEWORK

2.1 ANALYTICAL ASSESSMENT FRAMEWORK DESIGN

The Analytical Assessment Framework was created as a tool to assess decarbonization measures relative to one another. The framework generates a "snapshot" of the current state of each of the key alternative fuel and alternative propulsion technologies that are expected to contribute to deep decarbonization of the sector. Applied regularly in the lead-up to determining the most viable decarbonization options as these technologies continue to develop, it will reveal the relative trajectories of each and assist in decision-making around the most promising options. As indicated in Section 4.1 of this report, an approximate window to continue to test and assess different options is between 2022 and 2035, after which a wholesale shift away from petroleum diesel should accelerate to ensure 2050 net zero target can be met. The Assessment Framework is underpinned by the following assumptions, each of which was validated through stakeholder interviews.

The trajectory to net zero for rail will unroll in overlapping "waves"

Efficiency improvements: Efficiency improvements to existing and new equipment and infrastructure have been the focus of railway decarbonization efforts to date and must continue to be prioritized. All efficiency improvements will serve to reduce the decarbonization burden placed on fuels and propulsion technologies.

Low-carbon fuels: Through low-carbon/renewable fuel regulations, federal and provincial governments have already mandated minimum blending requirements of up to 5% renewable content in diesel, and these will continue to increase. As some railway companies have begun to face increasing pressure from investors and other stakeholder groups to decarbonize, efficiency improvements may be supplemented by the blending of renewable and low-carbon fuels beyond what is regulated.

Alternative propulsion: As railways seek to move past the limits of what low-carbon fuels and combustion engines can offer, electrification via battery or catenary systems, or hydrogen fuel cells are likely to prevail in the long-term.

This will look different for different railways, and some waves may be skipped

Locomotive duty cycles and power ranges, utilization profiles and operational areas vary based on the services they provide: commuter passenger, intercity passenger, rail yard switchers and work trains, regional and short lines, and Class 1 freight. As a result, not all railways will be expected to follow the same trajectory to deep decarbonization. Further, it must also be noted that rail companies do not have comparable resources to contribute towards decarbonization, as margins also vary greatly. This is also expected to impact adoption rates and timelines.

The purpose of the Framework is to identify the near-, medium- and long-term measures most likely to achieve deep decarbonization in the sector; and to provoke further consideration of how partnerships may be leveraged to address associated challenges, including new cost-sharing models that could support timely uptake.

2.1.1 FRAMEWORK STRUCTURE

CORNERSTONE

The assessment framework is built on three cornerstones: cost, decarbonization potential and challenges. The selection of cornerstones and their relative weighting were validated and refined through stakeholder consultations. Each of the three cornerstones must be addressed in order for a decarbonization option to become commercially viable, and the failure of a given option to address any one of the three will prohibit the widespread implementation of that option.

FACTORS

The primary objective of the framework development stage was to identify and weigh all contributing factors that are relevant to the cost, decarbonization potential, and challenges cornerstones, identifying and accounting for interplay between them. These are discussed at greater length in sections 2.3, 2.4 and 2.5 of this report.

For each contributing factor, the framework provides a scale from 1 to 5. Bespoke criteria were developed for each factor based on expert interviews and existing literature to ensure consistency in how measures are ranked. These are intended to be applicable across the broad range of decarbonization measures that will be assessed using the framework.

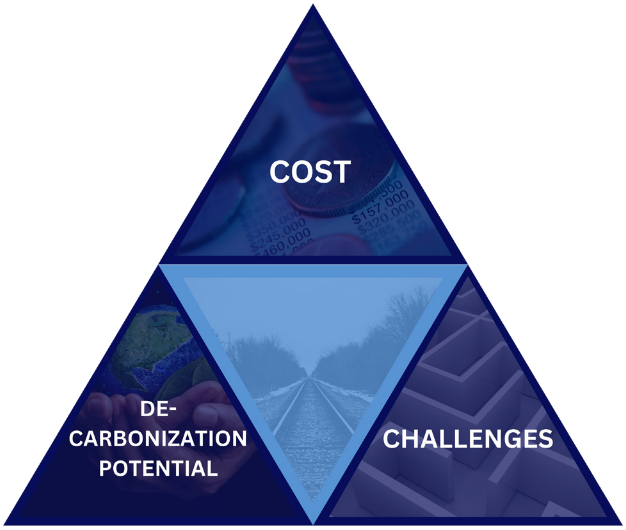


Figure 1: Cornerstones of the Assessment Framework

WEIGHTING

Decarbonization measures within each wave are compared against each other based on the three cornerstones of cost, decarbonization potential and challenges. These three scores are weighted equally.

2.2 WAVE (COMMERCIAL READINESS)

The concept of waves informs the understanding of, and expectations for, the commercial availability of the full suite of rail decarbonization measures over time. That a particular technology is not yet widely commercially available does not reduce its overall value in a decarbonization pathway. To the contrary, the technologies that are only now beginning to be developed may indeed hold the greatest promise.

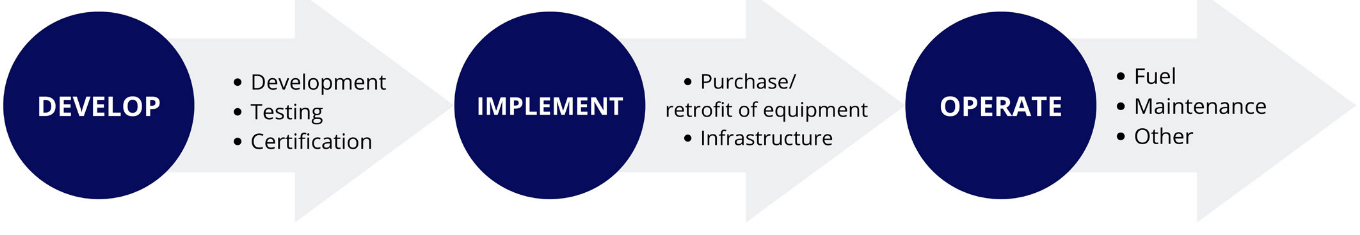
Commercial readiness, then, or rather, the timeline within which a particular decarbonization option is expected to become commercially available, should be used to ensure that a particular measure is being assessed against others that will be available within a similar timeframe. As such, commercial readiness was used to "sort" measures into three timeframes, which were subsequently found to overlap closely with the "waves" described above – efficiency, alternative fuels and alternative propulsion – resulting in a change in the terminology from commercial readiness to decarbonization wave.

Three timeframes align with the timing of Canada's milestones of 40-45% reduction of GHGs by 2030 and Net Zero by 2050.

- Wave 1: Efficiency aligns with near-term: Many measures in this category are in use in the rail sector now, and new efficiency measures will continue to be developed.
- Wave 2: Alternative fuels align with the medium-term: These are in use in low blend rates now, and the technology to allow for the use of higher blend rates is in development and expected to be commercially available in the context of rail application by 2030.
- Wave 3: Alternative propulsion aligns with the long-term: While some alternative propulsion options are in use now, wide-spread commercial availability across all Canadian rail applications is not expected until after 2030.

2.3 COST

The costs associated with introducing any new decarbonization measure can be split into three buckets: costs to develop, implement and operate.



2.3.1 DEVELOP

Development costs are inexorably linked with commercial readiness levels. Decarbonization measures that are already commercially available will have low to no development costs. Solutions such as increased blending of renewable fuels are closer to commercialization and costs will likely be borne by OEMs and railways who are expected to partner to test higher blends. This analysis, then, is applicable primarily to longer term solutions, and as such, it is limited to those that will yield significant decarbonization potential.[8]

The costs to develop a new decarbonization measure (technology and/or fuel) from inception to commercialization includes the initial development, testing through pilot and demonstration projects, and final certifications. These have been estimated at up to one hundred million dollars in some cases.[9] The assessment framework accounts for development costs based on current commercial readiness and on the complexity of adapting the technology for rail-based applications. It does not account for who will bear these costs, whereas other cost categories account solely for costs borne by railway companies.

2.3.2 IMPLEMENT

The assessment framework accounts for incremental capital costs of equipment and infrastructure costs of a particular decarbonization measure over the base case scenario of diesel technology. The framework handles these two cost areas separately as equipment costs are estimated on a per-vehicle basis and infrastructure is a fleet-wide cost.

CAPITAL COSTS

Where adoption of a measure will entail replacement of existing fleet equipment or infrastructure, estimates of incremental capital costs should account for differences in expected lifespan as compared to the base case scenario.

Where existing locomotives can be modified or refurbished rather than replaced, incremental capital costs are assumed to be lower. As such, where implementation of a new technology can be accomplished by retrofitting lower efficiency equipment to operate with fewer GHG emissions, this will have a favourable impact on its rating.

Assessment criteria are based on current incremental capital costs per locomotive, ranging from $0 to over $5 million. The framework will need to be updated regularly (e.g., every 2-5 years out to at least 2035) to ensure that it continues to reflect current costs.

8 Based on the assumption that railways will seek more significant GHG reductions as we move towards and past 2050.
9 Based on hydrail long distance freight as outlined by CUTRIC, 2020

INFRASTRUCTURE REQUIREMENTS

Infrastructure requirements may include blending facilities, fuel distribution infrastructure, refueling infrastructure, scale up of electricity distribution and/or charging infrastructure.

2.3.3 OPERATE

To date in Canada, decarbonization measures have largely been limited to options that increase fuel efficiency and so have resulted in cost savings realized by the railways. Measures to achieve deeper decarbonization may incur incremental operating costs, however. An overall increase in operating costs would be expected if fuel costs were incrementally higher than the base case scenario of diesel technology (factoring in expected cost increases to the cost of diesel based on federal and provincial clean fuel regulations and carbon pricing). Increased maintenance costs or increases in expenses in other areas, for example insurance, could also contribute to varying degrees to an overall operating cost increase.

Assessment criteria are based on current incremental operational savings/costs. These are expected to evolve as technology matures and fuel prices change as a result of policies including the Clean Fuel Regulation and carbon pricing. The framework will need to be updated regularly to ensure that it continues to reflect current costs.

2.3.4 WEIGHTING THE COST-RELATED FACTORS

The assessment framework provides four rating scales to cover the three factors: Develop; Implement – Equipment; Implement – Infrastructure; and Operate. The weighting of these four scores will depend on the relative size of each “bucket” and how the costs associated with each are expected to be shared amongst stakeholders.

The framework assigns a double share to the “Operate” category as it represents an ongoing cost whereas the others are either one-time or intermittent costs. This is especially notable given the long-lived nature of most rail assets.

2.4 CARBON REDUCTION POTENTIAL

The potential of a new technology or fuel to reduce overall GHG emissions from the rail sector will depend on the savings that can be garnered on a locomotive by locomotive basis; and on the degree to which railways might be expected to implement the measure in question.

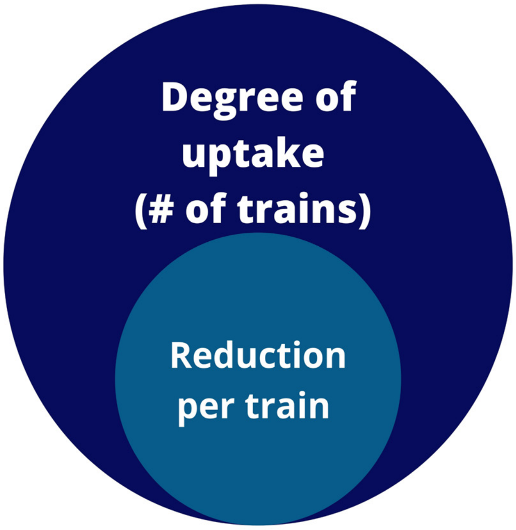
2.4.1 DEGREE OF REDUCTIONS ACHIEVABLE

The framework considers, on a per-equipment basis, the degree of reductions achievable based on implementation of a new technology or fuel type over the base case scenario of diesel technology.

In applying the framework to compare technology or fuel options, lifecycle emissions must be accounted for. This includes, where applicable: raw materials, production, distribution, use and end-of-life. A detailed lifecycle assessment of carbon emissions is not within the scope of the framework, but the analyses will nevertheless consider the overall scale of each of these key elements as they apply to each option and will highlight any areas of concern that may warrant further investigation.

2.4.2 DEGREE OF EXPECTED UPTAKE

The degree of expected uptake represents the degree to which railways might be expected to implement the technology or fuel in question. Forecasts of uptake must be exclusive of cost-related factors or challenges to avoid double-counting. Degree of uptake, then, will be in large part influenced by the proportion of the fleet for which the technology or fuel presents a viable option.



APPLICABILITY TO KEY SERVICES

The Canadian rail landscape encompasses a diverse fleet spread across several rail services. These include mainline and short line freight trains, yard and work trains and intercity and commuter trains. While some decarbonization measures will be applicable across the entire Canadian fleet, others will be limited based on factors including power output requirements, duty cycles and operating areas.

Based on the 2018 Locomotive Emissions Monitoring report, GHG emissions from freight operations represent 95% of the total GHG emissions from the rail sector in Canada: 87% of these are based on mainline freight operations.[10] Mainline freight operates more locomotives than any other services, and they travel significantly longer distances on an annual basis, as illustrated in Tables 2 and 3.

10 Railway Association of Canada. 2021. Locomotive Emissions Monitoring Report: 2018. (https://www.railcan.ca/wp-content/uploads/2021/06/2018_LEM_Layout_ENGLISH-rev3.pdf)

Table 1: Locomotive Fleet Breakdown by Service, 2018 [11]

Locomotive Fleet Breakdown by Service	Number	Percent of Total
Freight Operations		
Locomotives for Line Haul Freight		
Mainline	*2,531*	*67%*
Regional	*130*	*3%*
Short Line	*166*	*4%*
Locomotives for Freight Switching Operations		
Yard Switching and Work Train Locomotives	*499*	*13%*
Road Switcher Locomotives	*195*	*5%*
Total Freight Operations	*3,521*	*93%*
Passenger Operations		
Passenger Train Locomotives	*234*	*6%*
DMUs	*24*	*1%*
Yard Switching Locomotives	*3*	*0%*
Total Passenger Operations	*261*	*7%*
Total- Passenger & Freight Operations	*3,782*	*100%*

11 Ibid.

Table 2: Fuel Consumption by Service, 2018 [12]

Canadian Rail Operations Fuel Consumption	Litres (Million)	Percent of Total
Class 1	1,949.92	87%
Regional & Short Line	111.88	5%
Total Freight Train	2,061.80	92%
Yard Switching	51.56	2%
Work Train	7.10	0%
Total Yard Switching and Work Train	58.66	3%
Total Freight Operations	2,120.46	95%
Intercity - Total	52.77	2%
Commuter	65.74	3%
Tourist Train & Excursion	3.22	0%
Total Passenger Operations	121.72	5%
Total Rail Operations	2,242.19	100%

The analysis framework accounts for this by assigning additional weight to decarbonization options that are directly applicable to mainline freight operations. It further accounts for indirect applicability to mainline freight by considering that yard switchers and other work trains are expected to provide opportunities to test and refine alternative propulsion technologies for future application to mainline freight.

2.4.3 WEIGHTING THE DECARBONIZATION POTENTIAL-RELATED FACTORS

The decarbonization potential of any measure will be a product of the emissions reductions that are possible on a per-equipment basis and the uptake of the measure, in terms of number of units. As such, these two factors should be equally rated.

2.5 CHALLENGES

As new/ disruptive technologies, all decarbonization measures have inherent challenges associated with rolling them out at scale. These challenges fall into one of two categories, both of which must be accounted for in the assessment framework:

- Problems, which can be overcome; or
- Barriers, which can not be overcome and so represent risks that must be managed.

12 Ibid.

In assessing challenges, the framework avoids"double counting", by omitting any factors relating to cost. While high costs undisputedly represent significant challenges, this is factored into the assessment framework in the cost section.

Based on expert interviews conducted, all challenges identified for both new and existing decarbonization measures were relevant to the implementation and operations phase, which puts them strictly in the purview of rail companies. Challenges were identified in the following areas: operation/ performance, refueling, and safety/ regulatory compliance. These may be interconnected, but typically are not.

Despite the disparate nature of these challenges, it was necessary that the assessment framework assign criteria that can be used to compare decarbonization measures against one another and rate them based on the challenges that each measure presents. To achieve this, it normalized these challenges by considering the scale of the impacts rather than the challenges themselves.

2.5.1 OPERATION

The Assessment Framework accounts for a wide range of operational challenges including increased complexity, performance issues and mechanical and maintenance issues. Given the broad range of issues, and on differences in the impacts of those issues across different types of rail operations, it becomes challenging to define objective ranking criteria. Due to the dynamic and technology/practice-specific nature of operational challenges, this was scaled based on high, moderate, and low levels of expected complexity, as determined by the judgement of the assessment team, accounting for all available information.

COMPLEXITY

This sub-category includes the widest range of issues. These include considerations such as cross-border and cross-company interoperability; geographical/ terrain based challenges; limitations to factors such as range, rail car height and loading configurations; and impact on local criteria air contaminant (CAC) emissions.

PERFORMANCE

Decarbonization measures may impact the performance of locomotives, either in general or specifically in cold climates. In assessing these, the framework considers primarily the impact on reliability. Other impacts, such as complexity of operations and increased mechanical or maintenance issues will be considered under the other two subsections.

MECHANICAL/MAINTENANCE

This includes potential mechanical impacts of decarbonization measures, including those requiring changes to maintenance practices or schedules and/or threats to warrantees. In assessing this, the framework considers the potential burden to rail companies, including a worst case scenario of the loss of an asset.

2.5.2 REFUELING

Refueling challenges related to cost, including the scope of new refueling infrastructure required, are addressed in the relevant section under cost (Implement –Infrastructure Requirements). This assessment, then, focuses strictly on availability (including supply chain complexity) and time to refuel or recharge. This includes competition for technology and/or fuel; quality of fuel/ electricity; interdependencies (for example, with utilities, hydrogen producers or bio fuel suppliers); energy storage; and flexibility of operations.

2.5.3 SAFETY AND REGULATORY COMPLIANCE

Safety concerns of potential decarbonization solutions are expected to be partially addressed by increased training–this may include training both on rail operations and refueling.

Regulatory compliance is broad and covers are as such as CAC emissions and noise and vibration, which may improve with some technology operations. Some solutions will require additional regulation, however, and it is the burden of meeting those regulations that is considered by the Assessment Framework.

2.6 ANALYTICAL ASSESSMENT FRAMEWORK

The analytical assessment framework is based on a rating scale from 1 to 5 points for each of the factors identified under the three cornerstones, where 5 represents the best possible score. Criteria within each column are used to assign a score for the factor in question to the decarbonization measure being assessed.

The resulting scores are then weighted within each category by multiplying them by the weighting factor and summed for a total score out of 100 for the measure.

RATING	COST				CARBON REDUCTION POTENTIAL		CHALLENGES		
	Develop	**Implement Capital Cost**	**Implement-Infrastructure Requirements**	**Operate**	**Reduction Potential**	**Uptake/Applicability**	**Operation**	**Refueling**	**Safety & Regulatory Compliance**
BASED ON	Total cost to develop, test and dertify	Incremental capital cost per locomotive	Additional refueling/ charging infrastructure required	Incremental cost to operate	GHG reduction potential	Proportion of fleet	Complexity, performance, mechanical	Availability (inc. supply chain complexity)	Safety concerns, regulatory compliance
5	Commercially available: no development cost	No incremental cost	No additional infrastructure required	>20% savings	>80%	Well-suited to mainline freight rail	Equal to or better than diesel	Equal to or better than diesel	Equal to or better than diesel
4	Nearing commercial availability: development costs <$10M	Up to $1 million	Existing infrastructure can be used, with modifications	Up to 20% savings	50-80%	Partially suited to mainline freight rail	Low level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	Moderate complexity to supply chain and/or refueling requirements	Some additional training and/ or regulatory development required
3	$10-50M	$1-3 million	Significant new infrastructure required in yards only.	Par with diesel	30-50%	Suited to yard equipment	Moderate level of complexity in maintaining system reliability and existing infrastructure and/ or maintaining equipment.	Complex supply chain, >2x refuel/recharge time/ frequency	Additional training & certification and/or regulatory development required
2	$50-75M	$3-5 million	Significant new infrastructure required in yards and other locations	Up to twice the cost of diesel	10-30%	Well suited to passenger rail	High level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment	Intermittent availability issues, up to 2x refuel/ recharge time/frequency	Safety concerns and/or significant regulatory development required
1	Significant development required including complex challenges: >$75M	>$5 million	Significant new infrastructure required over entire network	>2x	<10%	Not suited to mainline freight rail, only partially suited to passenger rail	Significant risk to reliability. Significant risk of loss of an asset.	Frequent availability issues, >2x refuel/recharge time/frequency	Significant safety concerns, including to public and/or complete regulatory development required
WEIGHT	6.7%	6.7%	6.7%	13.3%	16.7%	16.7%	11.1%	11.1%	11.1%
	33.3%				33.3%		33.3%		

3. 2021 TECHNOLOGY ASSESSMENT RESULTS

3.1 SELECTION OF TECHNOLOGIES

The long list of decarbonization options identified via desktop research and consultations is included in Appendix B. Preliminary assessments of the GHG reduction potential of all options were conducted, with the intent to short-list the most viable options. The selections reflected in the technology assessments were chosen based on the assessed viability of each option as determined by stakeholder interviews and literature review findings, and on the following criteria.

3.1.1 EFFICIENCY MEASURES

There are numerous ways to continue to enhance rail efficiency including further enhancing aerodynamics of locomotives and rail cars, automation and data-driven solutions, among others. Collectively, these will continue to play a critical role in lowering rail carbon intensity, but they are not expected to get the rail sector to deep decarbonization. An aggressive suite of efficiency measures can lead to significant reductions in emissions, however the preliminary assessments of efficiency measures indicated that none could achieve decarbonization at a level commensurate with meeting national decarbonization targets or keeping pace with decarbonization measures being implemented by other land-based freight modes.

This does not diminish the importance and value of this wave, as any improvements to rail efficiency will reduce the effort required to decarbonize using renewable fuels and alternative propulsion technologies. Efficiency measures must continue to be prioritized, as reducing the energy requirements of trains reduces the challenges associated with moving beyond petroleum based fuels in all cases. As they have always done, railways are expected to continue to invest in efficiency measures that are advantageous in their specific contexts: those that have a reasonable payback time and will be expected save money over the long run. Specific measures selected will vary by railway based on these factors.

Due to the above-mentioned reasons, detailed technical assessments were not conducted for individual efficiency measures as part of this study. Of the 25 rail experts consulted and the dozens of resources reviewed as part of this project, none indicated that efficiency measures alone were capable of achieving deep decarbonization. Rather, a wide variety of existing and emerging efficiency measures will play complementary roles to the alternative fuels and propulsion technologies that will be required to do the heavy lifting in the decarbonized rail networks of the future.

3.1.2 ALTERNATIVE FUELS

Shortlisted: biodiesel and hydrogenation-derived renewable diesel (HDRD)

Under Canada's Renewable Fuels Regulations, "both ester-based biodiesel and hydrogenation-derived renewable diesel (HDRD) are admissible as renewable content that can be used to meet the requirements of the Regulations."[13]

The other renewable diesel technologies that were long listed are covered under the broader biodiesel and HDRD assessments. Alcohol-based fuels were found to be less suitable than the renewable diesel suite of fuels for replacement of petroleum diesel in rail applications. Natural gas is not being assessed based on the fact that it is a petroleum-based fuel that would require significant modifications to locomotives and under performs with regard to GHG savings based on methane slip and other issues.[14]

To optimize the benefits of renewable fuel use within the current limitations including technical limitations, cost, availability and land use concerns, the blend rates selected for assessment were B20 (a blend of 20% bio diesel and 80% petroleum diesel) and HDRD 30 (a 30% blend with petroleum diesel).

Following the project team's expert consultations, as well as considerations related to current and anticipated biofuel production capacity, availability of arable land and feed stocks, compatibility with in-use locomotives and equipment, and performance in the Canadian climate, it was determined that it would not be feasible to supplant the roughly 2.25 billion litres of petroleum diesel used by the Canadian rail sector each year with neat biofuels. Maximum blend levels that were determined to be feasible based on the above-mentioned considerations and consultations were B20 and HDRD30. The technical assessments reflect these levels.

3.1.3 ALTERNATIVE PROPULSION

Shortlisted: battery electric, catenary electric and hydrogen fuel cell

The long list included many bi-mode options. The use of alt propulsion measures in conjunction with diesel were not assessed separately but will be discussed later in this report (they do not represent unique measures, but rather stepping-stones to full electrification). Each of the three alternative propulsion technologies assessed in detail were found to be technically capable of powering Canada's entire rail network, and further, it is possible to supply the energy required for each of the three options on a net zero basis. For these reasons, they were the focus of the detailed alt propulsion technical assessments.

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13 NRCan, 2014. (https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/study-hdrd-renewable-fuel-option-north-america/3661)
14 CARB, 2016 (https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf)

3.2 TECHNOLOGY ASSESSMENT SUMMARY

Note that the technology assessments contained within this Roadmap were conducted based on the best information as of 2021. For technologies that are not yet commercially available, particularly alternative propulsion options such as battery electric and hydrogen fuel cell, this information is evolving rapidly. In order to ensure consistency across assessments and allow for fair comparison, the framework must be applied consistently using the best information available.

Scores out of 100, both for individual cornerstones and overall are summarized in Table 3 and in Figures 2 and 3. Summaries by technology type follow, and detailed technology assessments are included in Appendix C.

Table 3: Technology Assessment Scores for Alternative Fuels and Propulsion Technologies

	B20	HDRD30	Battery Electric	Catenary Electric	Hydrogen Fuel Cell
Cost	76	72	56	76	32
Carbon Reduction Potential	70	70	80	100	80
Challenges	80	67	67	40	40
OVERALL	**75**	**70**	**68**	**72**	**51**

3.2.1 ALTERNATIVE FUELS CATEGORY SUMMARY

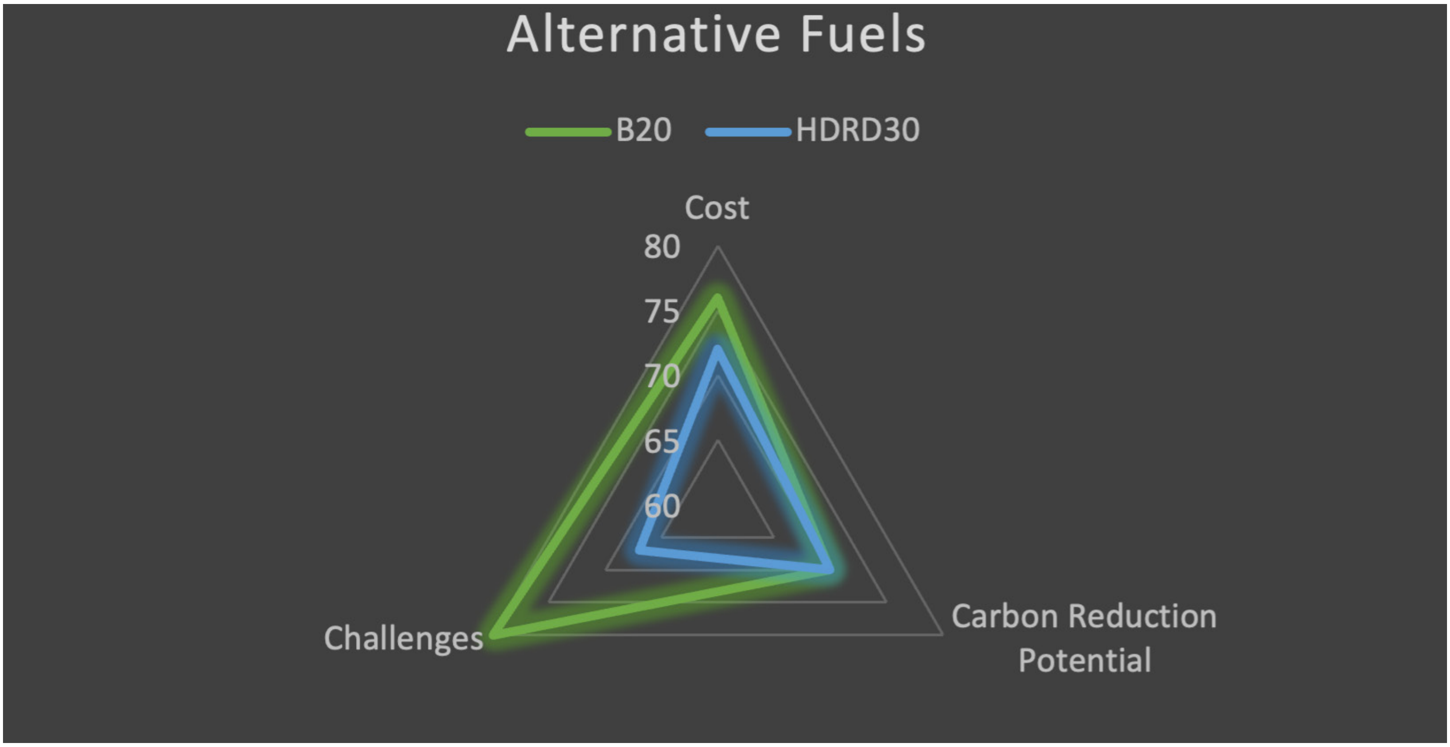


Figure 1: Alternative Fuels, Comparative Assessment

In the assessments, B20 matched HDRD30 in carbon reduction potential and outperformed it both in cost and challenges. This is largely a result of the current lack of availability of HDRD in Canada and the resulting high cost of this fuel.

A key area of strength for HDRD relative to biodiesel is that it is more chemically similar to petroleum diesel, meaning that it requires less in terms of operational practice and specialized equipment to use with existing locomotives at high blend rates. The high degree of chemical similarity with petroleum diesel also means that HDRD offers better cold weather performance than biodiesel, although more testing is needed to confirm cold weather performance in a Canadian context. Further, HDRD can be produced from a wider variety of feedstocks than biodiesel – especially a wider variety of non-food feedstocks that can be grown on marginal land, as well as waste products/residues from agriculture, forestry and municipal solid waste operations.

A major weakness of HDRD, however, and the biggest reason it received a lower overall score than biodiesel in this assessment, is related to its current lack of availability to Canadian railways.[15] Although some small-scale developments are being planned, Canada currently has no HDRD production facilities.[16] HDRD used in Canada is imported primarily from the US, but also from Finland, the Netherlands, and Singapore.[17]

15 Most HDRD produced in North America currently goes to California due to aggressive decarbonization targets and mandates for all heavy-duty diesel vehicles operating in the state, including locomotives.
16 Oil & Gas Journal, 2021. (https://www.ogj.com/refining-processing/refining/article/14205421/covenant-energy-plans-renewable-diesel-refinery-in-saskatchewan)
17 The Western Producer, 2020. (https://www.producer.com/crops/canola-growers-see-opportunity-in-biofuel-option/)

Limited HDRD availabilityis expectedtocontinue for a prolonged period, perhaps even more than a decade. This constraintresults in costs that are currentlytwo to fourtimes greater than petroleumdiesel, which in turn limits potential applications. This is salient given that the alternative fuelswave has been identified in this pathway as the primary solutionfor railways tomeet 2030 targets.That said, the alternativefuels wave is expected to remain in play at least through the early stages of alternativepropulsion use, and likely through full deployment of alt propulsion technology[18], so as the situation evolves, it is likely that there will also be a place for HDRD to be used.In the interim, biodiesel in blends up to B20 and possibly beyond presents an excellent alternative, though additional testing and development is required to ensure the safe and efficient use of these higher blends in existing locomotives.

It is also critical to note that although biofuels will be useful decarbonization stepping-stones and contributors to a lower-carbon rail sector, it is highlyunlikely that they will be able to achieve deep decarbonization on their own. In the future, both of these fuels may be used at higher blend rates (up to 100% at certain times of the year, in applications for which alt propulsion technologies are not well-suited as a stand-alone solution) –but this will be limited by availability. Some jurisdictions have already introduced caps on the quantityof biofuels that can be used to power transport, in order to stem conflicts with food production and limit further land use change. For example, in the EU the production and use of biofuels are governed under the Renewable Energy Directive (RED) and Fuel Quality Directive(FQD). The RED places stringent limitations on the types of land that biofuel feedstocks can be extracted from, with key considerations aroundbiodiversity, land-use change and agricultural crop impacts. While biofuels that do not comply with these limitations can continue to be used in the near-term(until 2030), their use cannot be counted towards renewable fuel blending requirements or GHG reduction targets.[19] These rules effectively restrict the use of a large majority of the conventional biofuelscurrentlyproduced in Europe. The UK's Renewable Transport Fuel Obligation (RTFO) requires that biofuels comprise 9.75% of combustible transport fuels (on-and off-road), however the total amount of biofuels derived from agricultural crops cannot exceed 4%(declining to 3% in 2026 and 2% in 2032). This measure is intended to avoid conflicts with food production and incentivize the production of waste-derived biofuels.[20]

It is also important to note that while biofuels result in low net GHG emissions, they canresult in increased CAC emissions which can have adverse impacts on human health.[21] In the case of biodiesel, NOx emissions can be greater than those from petroleum diesel. The use of biofuels in densely populated areas is therefore likely to be limited in the long-term, an important factor to consider when selecting optimal applications for alternative fuels.

18 There are expected to be contexts in which alternative propulsion technology is less suitable, which may lead to a continuing demand for alternative fuels up to and beyond 2050. This is addressed in Section 4.2.

19 European Commission, 2020. (https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en)

20 Biofuels International, 2017. (https://biofuels-news.com/news/uk-government-introduces-proposals-for-cap-on-crop-based-bio-fuels/)

21 DieselNet, 2021. (https://dieselnet.com/tech/fuel_biodiesel_emissions.php)

3.2.2 ALTERNATIVE PROPULSION CATEGORY SUMMARY

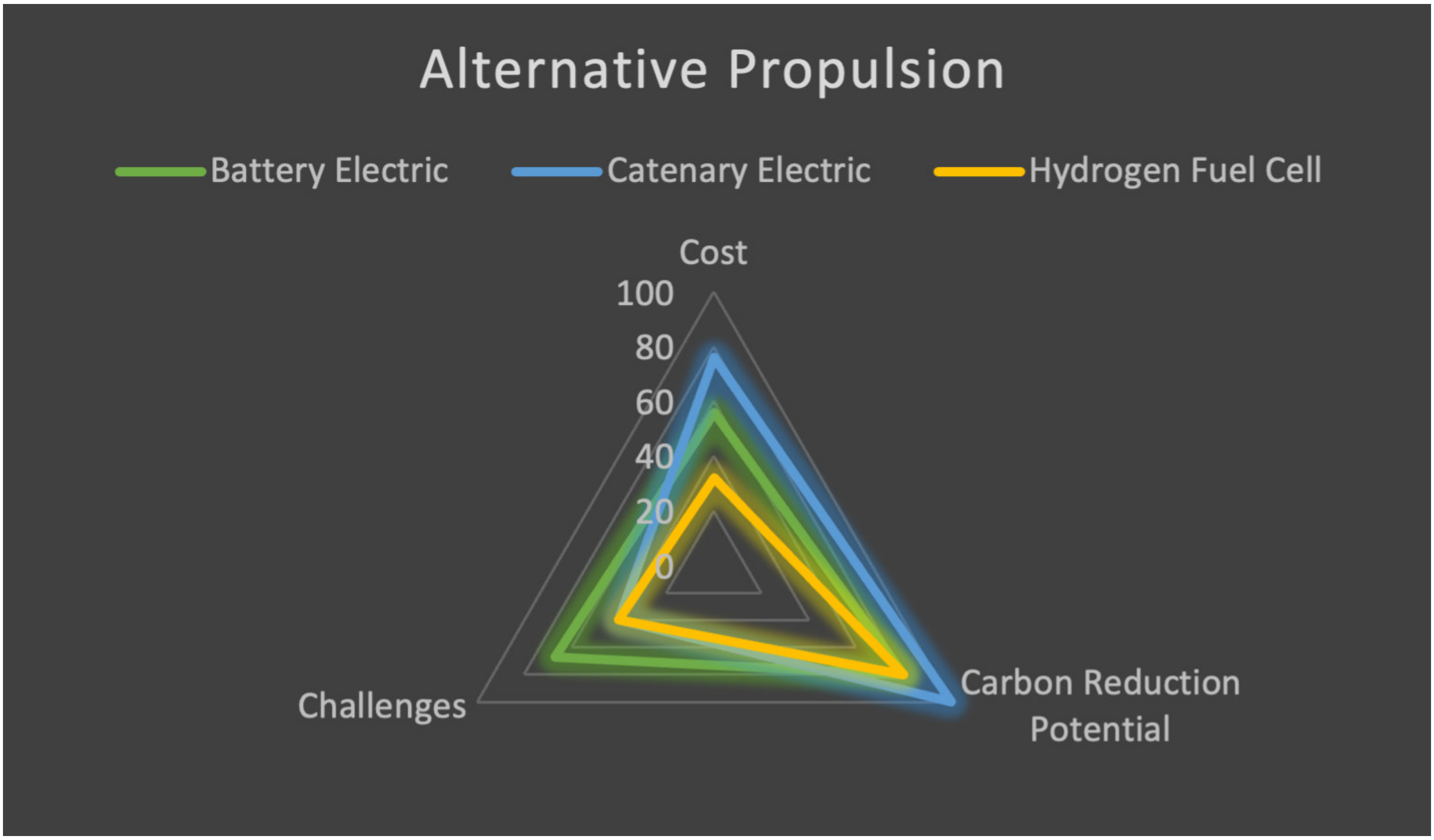


Figure 2: Alternative Propulsion Technologies, Comparative Assessment

Alternative propulsion technologies are evolving, and the relative scores of the technologies assessed strongly reflect the relative levels of maturity. The immediate priority in this area must be on continued development and testing, with regular re-evaluation over time to monitor how the respective trajectories of these technologies are comparing. Hydrogen fuel cells, battery electric, and catenary electric are all technically feasible to move all types of trains, and in theory each could power the North American rail network of the future. The ultimate "winner(s)", however, may depend on decisions made by the rail sector in the near term, based on the propulsion technology that offers the greatest overall benefits in the long term.

Catenary electric had the overall best score and the highest carbon reduction potential, though associated challenges outweigh those of battery electric. This is largely due to the fact that the technology is mature for some applications and has been in use in other countries for many years in some cases. Given the urgency to decarbonize however, this in itself presents a clear advantage. The North American rail sector has a long history of opposition to catenary electric propulsion, primarily due to the high capital costs of required infrastructure.

However, the sector's stance on this could change in light of the fact that society is facing an unprecedented challenge in the form of climate change, which compels all actors to carefully re-examine unprecedented and previously discredited options. It is currently being re-examined by the trucking sector in Canada and abroad.[22]

Battery electric and hydrogen fuel cell (hydrail) face similar challenges in key areas such as energy density. At least in the short term, this shared limitation would necessitate the use of fuel tenders in both cases, which are expected to each cost more than locomotives themselves.[23] Operationally, a major differentiator between the two technologies is that battery charging is currently lengthy (charge times per tender can range from 4 to 8 hours), and much of it would likely have to occur while in transit (via strategically situated catenaries). Even as battery capacity evolves there are still expected to be significant environmental issues inherent to battery use including mining-related issues in developing countries, and potential scarcity of materials.

For its part, hydrail technology is complex, costly, and novel, meaning there are more uncertainties around it than battery electric. Further, the GHG intensity of hydrogen production varies greatly. At the lower end of the scale (grey hydrogen – currently the most common method of production by a very large margin), hydrogen offers little-to-no GHG benefits relative to petroleum diesel. At the opposite end, green hydrogen production is capable of being carbon neutral if it is powered by renewable electricity; however, high production costs currently lead to high fuel costs for end-users.

22 HEC Montreal, 2021(https://energie.hec.ca/canada-ehighway/)
23 US Department of Energy, 2020 (https://www.hydrogen.energy.gov/pdfs/review20/ta034_ahluwalia_2020_o.pdf)

3.3 BIODIESEL (B20) ASSESSMENT SUMMARY

The full B20 technology assessment is included in Appendix C.

Table 4: B20 Assessment Summary

Technology	Biodiesel, 20% blend (B20)
Decarbonization Wave	Alternative fuel
Description	Biodiesel is a renewable fuel that can be manufactured from vegetable oils, animal fats, or recycled cooking oil for use in diesel vehicles or any equipment that operates on diesel fuel. Biodiesel's physical properties are similar to those of petroleum diesel, with some notable exceptions including inferior cold weather properties and reduced energy content. B20 refers to a blend of 20% biodiesel and 80% petroleum diesel.
Assessment Score	75%
Assessment Summary	The carbon intensity of biodiesel varies significantly based on feedstocks, production practices, and transportation, with reduction potential ranging from 20-80% relative to petroleum diesel when used neat. Most of the biodiesel produced in North America offers carbon reduction potential at the upper end of this range. Currently, blending of biodiesel with petroleum diesel for rail applications is limited to 5% (B5) by most locomotive OEM warranty stipulations (though some OEMs now allow blends of up to B20 in certain engines). At these low blending rates, biodiesel is straightforward to use without significant modifications to existing vehicles or infrastructure, however, offers little benefit in terms of emissions reductions. Neat biodiesel (i.e., B100) offers significant GHG reduction potential to heavy-duty modes of transport such as rail. It comes with some operational challenges, however, particularly in cold temperatures. Further, widespread use of higher blends, up to B100, would require a scale up in production to a level that may not be possible, primarily due to issues around food security and limited arable land. As such, biodiesel use in the long term may be limited to niche applications such as routes on low-volume, short-haul lines where alternative propulsion technologies would be cost prohibitive to introduce, or to supplant petroleum diesel in bi-mode consists which are complemented by a zero-emission propulsion technology. In the near and medium terms, it offers value as a transition fuel for all rail applications. For the above-stated reasons, this assessment is focused on the use of B20.

Table 5: B20 Assessment Score

	COST				CARBON REDUCTION POTENTIAL		CHALLENGES		
	Develop	**Implement-Capital Cost**	**Implement-Infrastructure Requirements**	**Operate**	**Reduction Potential**	**Uptake/ Applicability**	**Operation**	**Refueling**	**Safety & Regulatory Compliance**
RATING	5					5			
		4	4				4	4	4
				3					
					2				
Weight	6.7%	6.7%	6.7%	13.3%	16.7%	16.7%	11.1%	11.1%	11.1%
	76% (25.4/33.3)				**70% (23.3/33.4)**		**80% (26.6/33.3)**		

3.4 HYDROGENATION-DERIVED RENEWABLE DIESEL (HDRD) ASSESSMENT SUMMARY

The full HDRD30 assessment is included in Appendix D.

Table 6: HDRD30 Assessment Summary

Technology	Hydrogenation-derived renewable diesel (HDRD, 30% blend)
Decarbonization Wave	Alternative fuel
Description	HDRD is a renewable diesel produced by the hydrotreating/ hydroprocessing of fat or oil based feedstocks similar to those used in biodiesel production (e.g., soybeans, canola). Additional production processes that utilize alternative lignocellulosic feedstocks such as agricultural and forestry residues are being developed but are still in their infancy. Having very high chemical similarity to petroleum diesel, HDRD is closer to being a pure drop-in fuel than biodiesel.
Assessment Score	70%
Assessment Summary	Despite its strong GHG reduction potential and compatibility with existing rail equipment and infrastructure, HDRD availability is expected to continue to be constrained by either the limited availability of feedstocks (food and non-food crops and suitable triglyceride-rich waste materials), the immaturity of production processes utilizing alternative feedstocks (e.g., agricultural and forestry residues), and/or a lack of production capacity in Canada. These constraints, along with competition for HDRD from other heavy-duty diesel applications, is likely to limit the use of HDRD in rail applications (i.e., prevent the wholesale replacement of petroleum diesel with HDRD). The lack of HDRD availability is also creating an unacceptable price disparity with petroleum diesel. For these reasons, this assessment is focused on the use of 30% HDRD blends (HDRD30).

Table 7: HDRD30 Assessment Score

	COST				CARBON REDUCTION POTENTIAL		CHALLENGES		
	Develop	**Implement-Capital Cost**	**Implement-Infrastructure Requirements**	**Operate**	**Reduction Potential**	**Uptake/ Applicability**	**Operation**	**Refueling**	**Safety & Regulatory Compliance**
RATING		5	5			5			
	4						4		4
				2	2			2	
Weight	6.7%	6.7%	6.7%	13.3%	16.7%	16.7%	11.1%	11.1%	11.1%
	72% (24.1/33.3)				**70% (23.3/33.4)**		**67% (22.2/33.3)**		

3.5 BATTERY ELECTRIC ASSESSMENT SUMMARY

The full battery electric assessment is included in Appendix E.

Table 8: Battery Electric Assessment Summary

Technology	Battery Electric
Decarbonization Wave	Alternative propulsion
Description	Battery powered trains are electric multiple units and locomotives which carry batteries in order to provide traction power for in-service use. The traction system of a battery powered train is based on that of an electric train but with the addition of on-board battery storage and supporting power converters and temperature management for the battery if required.
Assessment Score	68%
Assessment Summary	While battery electric propulsion technology is technically mature and is already commercially available for commuter rail and yard applications, more RD&D is required to make it a feasible option for mainline railway service. Key goals of RD&D include reducing the weight and size of battery tenders, reducing charging times, developing optimal charging infrastructure for a variety of in-use and yard scenarios, testing battery degradation over extended use, improving overall train efficiency to reduce demands on batteries, and reducing battery costs. Significant progress in all of these areas is expected by 2030, and by 2035, battery electric propulsion could be feasible for mainline freight service throughout North America.

Table 9: Battery Electric Assessment Score

	COST				CARBON REDUCTION POTENTIAL		CHALLENGES		
	Develop	**Implement-Capital Cost**	**Implement-Infrastructure Requirements**	**Operate**	**Reduction Potential**	**Uptake/ Applicability**	**Operation**	**Refueling**	**Safety & Regulatory Compliance**
RATING					5				
				4			4		
	3					3		3	3
			2						
		1							
Weight	6.7%	6.7%	6.7%	13.3%	16.7%	16.7%	11.1%	11.1%	11.1%
	56% (18.7/33.3)				**80% (26.7/33.4)**		**67% (22.2/33.3)**		

3.6 CATENARY ELECTRIC ASSESSMENT SUMMARY

The full catenary electric assessment is included in Appendix F.

Table 10: Catenary Electric Assessment Summary

Technology	Catenary electric (overhead line electrification; overhead contact system)
Decarbonization Wave	Alternative propulsion
Description	Catenary electric systems for rail consist of suspended overhead power lines which feed electricity to electric locomotives or power units (EMUs) through a pantograph.
Assessment Score	72%
Assessment Summary	Catenary electric propulsion is technically feasible and mature for all types of rail. Catenary electric offers the greatest and clearest GHG benefits of all options assessed, as its use mirrors electricity grid carbon intensity, which is among the best in the world in Canada. However, significant (potentially prohibitive) challenges are associated with the deployment of catenary infrastructure. Costs per km of electrified track are likely to average up to $2 million, while modifications to existing rail infrastructure such as tunnels, bridges, sidings and yards will be extensive and costly. Significant modifications to operational practices, such as foregoing the use of double-stacked railcars and gaining high levels of aptitude in electricity management would also be required. The use of catenary systems would allow the rail sector to completely avoid competition for highly sought-after low-carbon technologies and commodities such as batteries, hydrogen fuel and equipment, and biofuels, as other transport modes and economic sectors race to decarbonize. No other propulsion measure comes with as great a list of pros and cons. Ultimately, the potential use of catenaries may be limited to highly-trafficked rail lines, complemented by alternative low-carbon propulsion technologies on other lines.

Table 11: Catenary Electric Assessment Score

	COST				CARBON REDUCTION POTENTIAL		CHALLENGES		
	Develop	**Implement-Capital Cost**	**Implement-Infrastructure Requirements**	**Operate**	**Reduction Potential**	**Uptake/ Applicability**	**Operation**	**Refueling**	**Safety & Regulatory Compliance**
RATING				5	5	5			
	4	4							
							2	2	2
			1						
Weight	6.7%	6.7%	6.7%	13.3%	16.7%	16.7%	11.1%	11.1%	11.1%
	76% (25.3/33.3)				**100% (33.4/33.4)**		**40% (13.3/33.3)**		

3.7 HYDROGEN FUEL CELL ASSESSMENT SUMMARY

The full hydrogen fuel cell assessment is included in Appendix G.

Table 12: Hydrogen Fuel Cell Assessment Summary

Technology	Hydrogen fuel cell (HFC)
Decarbonization Wave	Alternative propulsion
Description	Hydrogen-powered trains are electric multiple units which carry hydrogen, fuel cells, and batteries in order to provide traction power.
Assessment Score	51%
Assessment Summary	There are significant technical, financial and regulatory challenges that must be overcome before HFC technology becomes a viable candidate for all rail applications in Canada. With an adequate availability of renewable electricity for green hydrogen production and significantly scaled up production of heavy-duty HFC systems in the future, hydrail would be expected to reach cost parity with diesel locomotives for passenger and yard applications in the long term. However, it is not expected to be cost-competitive with diesel for freight under any existing scenarios (largely due to the need for tenders resulting from hydrogen's low volumetric energy density). The GHG reduction potential of hydrogen depends on the production method and carbon intensity of local electrical grids, with major variances in the potential of different methods. In summary, there are many uncertainties with hydrail stemming from its novel and complex nature.

Table 13: Hydrogen Fuel Cell Assessment Score

	COST				CARBON REDUCTION POTENTIAL		CHALLENGES		
	Develop	**Implement-Capital Cost**	**Implement-Infrastructure Requirements**	**Operate**	**Reduction Potential**	**Uptake/ Applicability**	**Operation**	**Refueling**	**Safety & Regulatory Compliance**
RATING					5				
			3			3	3		
	2								2
		1		1				1	
Weight	6.7%	6.7%	6.7%	13.3%	16.7%	16.7%	11.1%	11.1%	11.1%
	32% (10.7/33.3)				**80% (26.7/33.4)**		**40% (13.3/33.3)**		

4. DEVELOPING A ROADMAP

4.1 TECHNOLOGY ROADMAP

Section 2.2 introduced the concept of technology waves aligning with the timing of Canada's 2030 and 2050 targets. The roadmap is informed by this concept, but with significant overlap among waves.

> **Wave 1: Efficiency aligns with near-term:** Many measures in this category are in use in the rail sector now, and new efficiency measures will continue to be developed.

Efficiency measures should continue to be leveraged to their full capacity to reduce the overall energy required to power trains. This in turn will reduce the challenges associated with all other decarbonization technology options. Measures that show particular promise for further implementation and RD&D include: lightweighting and enhanced aerodynamics for both locomotives and railcars, data optimization tools and energy management software (e.g., Trip Optimizer, Wi-Tronix, ALTRIOS), onboard energy storage and regenerative braking, the use of APUs in conjunction with automatic engine start-stop systems (AESS), energy efficient driving strategies and training, distributed power management and control technologies, common rail fuel injection and control system upgrades, increased automation at ports and shipping hubs, and the retrofitting or replacement of lower-tier diesel engines. All efficiency measures require RD&D in Canada before widespread implementation can begin, as the efficiency enhancement claims of OEMs must be validated and cold weather performance verified.

> **Wave 2: Alternative fuels align with the medium-term:** These are in use in low blend rates now, and the technology to allow for the use of higher blend rates is in development and expected to be commercially available in the context of rail application by 2030.

Testing of biodiesel in blends of 5% to 20% should be an immediate priority. This will require partnerships between locomotive OEMs and rail companies to assess enhanced maintenance requirements, engine modifications and operational capabilities including cold weather operations.

As availability of HDRD increases, the focus of testing and development should shift to HDRD30. HDRD30 has potential to be blended with biodiesel to increase overall renewable content of fuel, and both of these alternative fuels have great potential to be used alongside alternative propulsion options as discussed below.

- **Wave 3: Alternaitve propulsion aligns with the long-term:** While some alternative propulsion options are in use now, wide-spread commercial availability across all Canadian rail applications is now expected until after 2030.

With their limited operating areas and more manageable duty cycles, switcher locomotives operating in rail yards present an excellent opportunity to test alternative propulsion technologies. These should be a key focus of demonstrations to test durability, refueling/charging infrastructure, performance, and costs. This would have the additional benefit of helping to address local air quality issues around railyards, which as noted in Section 15.4 would be expected to have beneficial impacts on the health and well-being of nearby residents, a disproportionate number of which are racialized and low-income Canadians. Rail yards are also excellent sites to generate information for developing more robust codes and standards for safety (e.g., designs for storage tanks, refining the rules and guidelines for monitoring leaks, flames, electrical shocks, etc., and for instructing people on how to act around hydrogen and high voltage electrical equipment).

Once proven in this context, testing should be scaled up and rolled out in more energy-intensive applications. Unit trains are proposed as a useful interim step, as the supporting infrastructure required would be limited to a smaller geographic area.

All three alternative propulsion options: battery, catenary and hydrogen fuel cell must also be tested in mainline freight applications. Freight represents 93% of rail emissions in Canada, and has the highest number of associated challenges, so any technology that can be proven effective in the context of mainline freight will be equally applicable to short line and passenger rail applications. Bi-mode options present another suitable interim step to full mainline operation.

Bi-mode options combine two propulsion technologies to further reduce or eliminate the use of petroleum diesel. Due to inherent limitations associated with both alternative fuel and alternative propulsion technologies, bi-mode options are expected to be necessary until at least 2050 and likely beyond in certain applications.

COMBINING ALTERNATIVE FUEL WITH ALTERNATIVE PROPULSION

As alternative propulsion technology continues to mature, the use of bi-mode consists (multiple unit trains that include both traditional and electric/ hydrogen-fueled locomotives) will likely be required. Availability of biofuels is limited; and while alternative propulsion technologies are promising, they either cannot yet fully power most Canadian trains, or will take time to build out. In the short to medium term, combining combustion and electric technologies can allow for the benefits of both to be maximized, while minimizing limitations around power, costs and infrastructure.

There could therefore be a key long-term role for biofuels to play in rail sector decarbonization, through their use in bi-mode consists in conjunction with one of the three primary alt propulsion technologies. Such bi-mode trains could be useful on low-traffic lines where stand-alone alternative propulsion is not economically viable. They could fill gaps where alternative propulsion options are less favourable, including in railyards. They would provide a back-up solution in cases of power outages or constrained fuel availability. Finally, in the case of catenary rail, they could reduce the need for upgrades to infrastructure such as tunnels and bridges. Bi-mode trains that combine alt propulsion and biofuel (blended or neat) surmount some of the current barriers to alternative propulsion as follows:

- For catenary, trains could run on electricity in the high-use corridors where catenary makes more economical and practical/ logistical sense, and on biofuel (blends, or neat) in areas where catenary is challenging to install or where traffic levels do not support it economically.
- For battery/ hydrogen fuel cell operation, if used in a consist with biofuel burning locomotives, the fuel could boost the power that can be delivered to operate heavier trains and could allow sufficient locomotive power to reach fueling/ charging locations, thus eliminating range anxiety and reducing demands on tenders.

Combining biofuels with alternative propulsion would allow railways to leverage the benefits of biofuels within the availability limitations and would also allow for reduced CAC emissions in populated areas such as in and near rail yards and urban locations. While combining multiple propulsion technologies can be costly and may pose certain technical challenges, it should be noted that both battery and hydrogen tenders currently cost significantly more than diesel locomotives that utilize biofuels. Bi-mode options could therefore become the most cost-effective net zero option for rail in certain scenarios. At the very least, they can provide the opportunity to integrate new technologies into the rail network in a way that is progressive, measured, and sustainable.

COMBINING ALTERNATIVE PROPULSION OPTIONS

All alternative propulsion options have inherent limitations. Combining them strategically can reduce those limitations while maximizing the benefits of both. The pairing of catenary and batteries is an excellent example of optimizing the benefits of two complementary technologies.

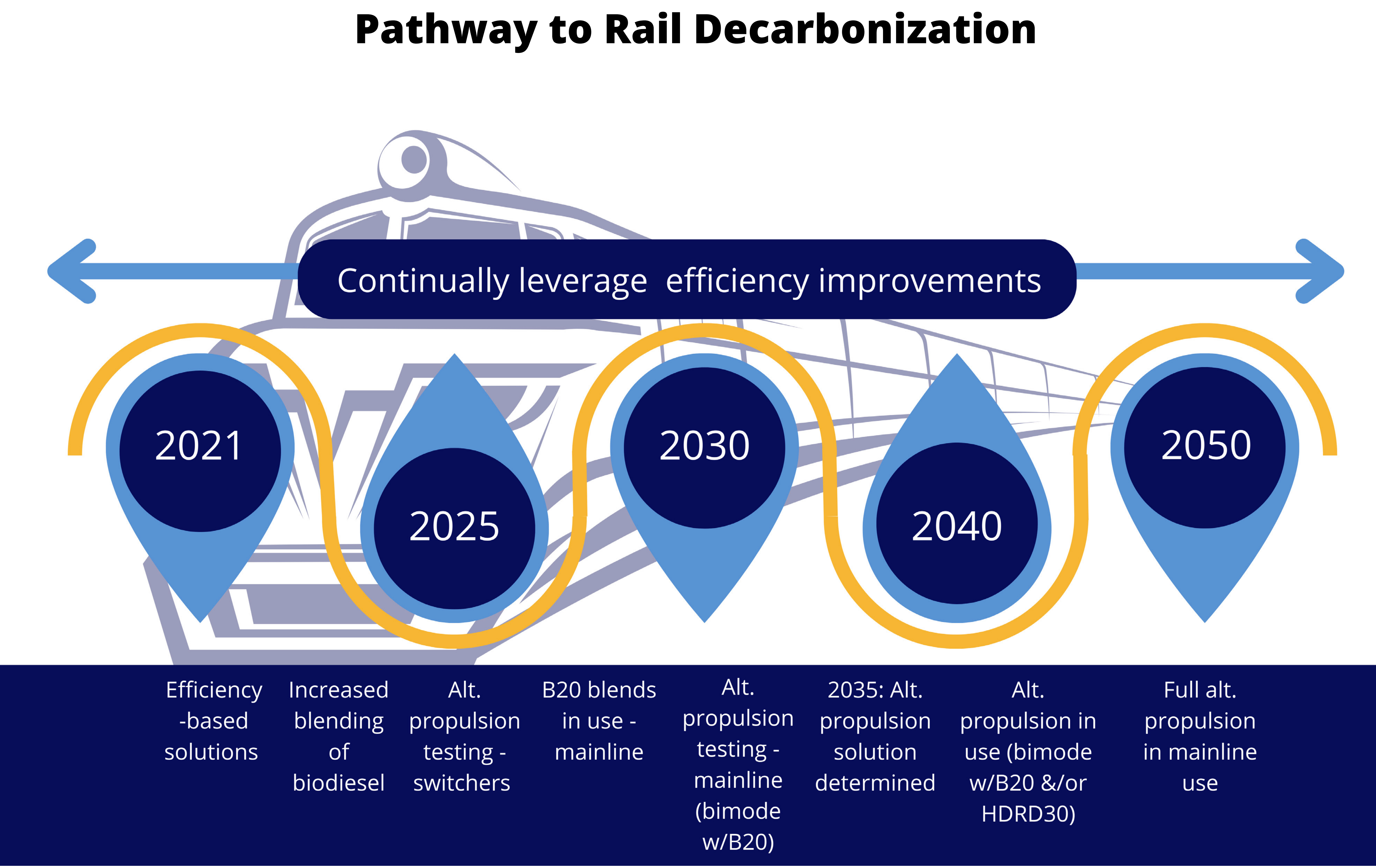
Given the heightened challenges of building catenary infrastructure in some areas (for example, on less trafficked portions of track, or through difficult terrain such as the Rockies) and with some types of existing infrastructure (for example, tunnels and bridges), catenary alone would be unlikely to be able to power the entire sector. If paired with battery technology, however, this limitation could be reduced or completely eliminated. Catenary could be used in high traffic areas, while trains could use battery power on lesser used portions of track. Further, battery power could be used in yards to address safety or loading concerns around catenary in these environments. Batteries could be recharged during catenary operation and could also capture power from regenerative braking. Further, batteries could serve as a backup power option during power outages, to ensure trains do not become stranded in unsafe or inconvenient areas, and that essential services are maintained for passengers and crew.

Combining hydrogen fuel cell with electric technology is less applicable on a per-train basis (i.e., in a bi-mode train), but there is opportunity to combine these on a larger scale (i.e., outside of a bi-mode option). For example, catenaries on high volume mainlines could be combined with hydrail on lower-traffic short lines. While in the current context, this solution would not seem to address the challenges as effectively as in the example above, these technologies are all evolving rapidly and as such the associated use-case scenarios also remain in flux.

ONGOING ASSESSMENT REQUIRED

As testing progresses, technology assessments should be conducted regularly – particularly for each of the three alternative propulsion options. As each of these technologies are developed further and can be tested in the Canadian/ North American context, the overall scores for each of the technologies will shift. This is expected to be particularly true for less mature technologies. The relative trajectories of the three technologies can then be compared against one another to identify which option(s) have the most promise for decarbonizing rail.

Figure 3: Illustrates a proposed high-level technology pathway to rail decarbonization



4.2 NON-TECHNOLOGY RELATED CONSIDERATIONS

While technical feasibility is a key component of the pathway to decarbonization for rail, the design of the pathway must also account for additional criteria including economic and practical considerations.

4.2.1 EVOLVING COST MODELS

To date, decarbonizationof rail has largely relied on improvements to fuel efficiency. This approach has included measures to enhance operating practices and to implement fuel saving technologies, refurbishment of existing locomotives and rail cars, and the purchase of more fuel efficient trains, including Tier 4 locomotives and new generation railcars.

The cost model associated with fuel efficiency improvements relies on investments by both OEMs (to develop the technology) and railways (to test, purchase and install the technology) that are recouped via sales and operational savings, respectively. Fuel efficiency measures reduce operating costs to generate savings for railways.

As the rail sector moves beyond efficiency improvements into increasing decarbonization of fuel, and towards implementation of alternative propulsion technologies, the cost profile will also evolve. Development and implementation costs may increase beyond what can be reasonably expected to be recouped, and further, there may be incremental costs to operate rather than savings. This points to the need for a different cost-sharing profile(or cost model)than has been seen in the past.

FUNDING OPTIONS FOR TECHNOLOGY DEVELOPMENT

While potential actors include academic or government research institutions, OEMs and railways, there is not an existing model for collaboration between these parties, so development costs may be borne by any of them. Where development costs are very high, this could present an insurmountable obstacle to the successful development of a particular decarbonization measure –even one that has considerable promise.

The following three examples of efforts to develop hydrogen fuel cell technology for use in rail applications illustrate that there is not a uniform approach to funding rail technology development in Canada at the national level.

Industry funded

Hydrogen fuel cell line haul freight locomotive (CP Rail)

Canadian Pacific (CP) recently announced that it plans to retrofit an existing diesel-electric line haul locomotive using hydrogen fuel cell modules that it has purchased from Ballard Power Systems. Once the locomotive is operational (by the end of 2022), CP plans to "conduct rail service trials and qualification testing to evaluate the technology's readiness for the freight-rail sector." Its longer term vision is to partner with an OEM to produce the locomotives, which would then be available for purchase by other railways.[24]

In November 2021, CP announced that it will be expanding its hydrogen locomotive program by retrofitting two additional locomotives for switching applications, and by installing an electrolysis plant at its Calgary yard and an SMR hydrogen production unit at its Edmonton yard. This expanded effort was made possible in part through a 50-50 matching grant from the Government of Alberta, in the amount of $15 million.[25]

Government funded

Hydrogen fuel cell switcher locomotive (ECCC)

Environment and Climate Change Canada (ECCC) engaged an engineering service firm in partnership with railway equipment overhaul and refurbishment specialists, a hydrogen fuel cell manufacturer and a transportation energy efficiency consultant to assess the potential to retrofit a diesel switcher locomotive to use hydrogen fuel cells as the prime mover. Finding no significant barriers, the resulting recommendations were to partner with industry and other key stakeholders to scale the technology up to commercial application.[26]

Academic/ Industry Collaboration with Government Funding

Hydrogen fuel cell-lithium ion battery switcher locomotive (UBC & SRY)

Funded in part by an NSERC Engage grant, the School of Engineering at University of British Columbia's Okanagan Campus worked with Southern Railway of British Columbia (SRY) to assess the potential of retrofitting a switcher locomotive to a hybrid hydrogen fuel cell -lithium ion battery unit, including examining performance of the proposed power systems given typical load dynamics, and assessing sizing of the different subsystems vis-à-vis the existing locomotive frame. This represented Phase 1 of a multi-phase study.

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24 Railway Age, 2021(https://www.railwayage.com/mechanical/locomotives/cp-hydrogen-locomotive-pilot-powered-by-ballard/)

25 CP Rail, 2021. (https://www.cpr.ca/en/media/canadian-pacific-expands-hydrogen-locomotive-program-to-include-additional-locomotives-fueling-stations-with-emissions-red)

26 Change Energy Services, 2020 (https://tcdocs.ingeniumcanada.org/sites/default/files/2020-08/Assessment%20of%20the%20Design%2C%20Deployment%20Characteristics%20and%20Requirements%20of%20a%20Hydrogen%20Fuel%20Cell%20Powered%20Switcher%20Locomotive.pdf)

In North American jurisdictions outside of Canada, technology development models rely heavily on both government funding and on collaborations:

- Sierra Northern Railway, a small short line railway that operates 120 km of track in Northern California has received nearly $4 million USD in funding from the California Energy Commission (CEC) to build and test a hydrogen fuel cell switching locomotive. It is partnering with GTI Energy, Railpower Tech LLC, Ballard Power Systems, Optifuel Systems LLC, UC Davis Institute of Transportation Studies, Valley Vision, Velocity Strategies, Southern California Gas Co. and the Sacramento Metropolitan Air Quality Management District.[27]

- As part of a $22.6 million USD grant awarded to BNSF Railway and the San Joaquin Valley Air Pollution Control District by the California Air Resource Board, BNSF Railway is partnering with Wabtec to test its FLXdrive battery electric locomotive in a battery-electric hybrid consist. BNSF partnered with Wabtec on the development of the locomotive, which includes an overall energy-management system and onboard energy storage.

The current rail decarbonization model – OEMs develop and sell technology to railways – may not be tenable for the higher cost/ higher potential decarbonization measures. Given that the deeper decarbonization options being demonstrated are pre-commercial and market uptake levels are uncertain, the traditional OEM-driven model is less applicable. OEMs will need partners to develop, demonstrate and provide financial support for emerging technologies so they can be proven effective before production ramps up. Rail companies are expected to require funding support to implement the technologies once commercialized, as operational savings are not expected to cover initial costs.

FUNDING OPTIONS FOR TECHNOLOGY IMPLEMENTATION

In the context of the efficiency improvements that have constituted the bulk of the decarbonization efforts to date, these costs have typically been borne by railway companies as they replace or refurbish equipment and infrastructure or introduce efficiency measures. As described for the development of new decarbonization measures in Section 4.1, however, this cost model may need to be adjusted to accommodate significantly higher incremental costs, particularly for electric or hydrogen powered locomotives and the respective required charging/ refueling infrastructure. The issue here is primarily one of timing: if deep decarbonization of the rail sector is to occur within the timelines required to support Canada's net zero target, railway companies are likely to require funding partners.

27 Sierra Northern, 2021. (http://sierranorthern.com/news/articles/california-energy-commission-awards-sierra-northern-railway-team-nearly-4-000-000-to-build-and-test-hydrogen-switcher-locomotive/)

LEVERAGING PARTNERSHIPS

As noted, there is a need for a different cost-sharing profile (or cost model) than has been seen in the past. Governments in particular have a role to play in terms of cost-sharing, especially with regard to shared, long-lived infrastructure that will offer substantial benefits to Canada's environment and economy. The rail sector provides a low-cost means of shipping vital bulk commodities that help to bolster Canada's export markets and keep the cost of living low for Canadian consumers. Government support for rail infrastructure is warranted given the vital role it plays in Canada's economy.

Government support for the rail sector, and for freight movement more broadly, can take many forms. Canada's updated 2020 climate plan, A Healthy Environment and a Healthy Economy,[28] notes that a key role for government in greening the heavy-duty vehicle sector is to support technology development through R&D, but also to support pilot projects and the implementation of commercially ready solutions across all modes, including rail. Due to its high efficiency, rail is already a low-carbon mode relative to alternatives such as on-road transportation. This means that government investments in rail efficiency will be proportionally more impactful as they can help to maintain high rates of utilization.

Further, as all modes of transportation decarbonize, there are potential synergies to be leveraged in infrastructure development and energy supply. A key role for government in addition to infrastructure and R&D funding is convening a wide variety of stakeholders across modes to identify mutual benefits that could be achieved through collaboration on decarbonization efforts. The convening power of government should not be understated, as it can play a vital role in helping to forge partnerships between rail sector stakeholders, between modes, and across borders.

4.2.2 North American Interoperability

Interoperability across North America is a key requirement. North American railways have shared assets and horsepower agreements, and trains must travel between Canada, the United States, and Mexico. Any solution must not only be equally applicable across North America, but it must also be decided upon jointly by all North American stakeholders. This points to the requirement for close collaboration among North American railways, along with standards and regulatory consistency between all countries.

An additional role for governments would be to continue to decarbonize electricity generation throughout the continent. That would offer carbon benefits to all of the three leading types of alt propulsion.

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28 ECCC, 2020. (https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climateplan/healthy_environment_healthy_economy_plan.pdf)

4.2.3 Competition for Resources and Between Modes

Due to factors such as aggressive government decarbonization policies, heightened impacts from climate change, pressure from shareholders seeking to green and de-risk their portfolios, and a growing sustainability mindset among the general public, the race to decarbonize is gaining momentum. Not only are all modes of transport increasingly implementing low-carbon solutions, but other economic sectors are as well. This push to decarbonize is likely to cause near- and mid-term bottlenecks in the production and supply of renewable, low-carbon commodities and products.

Hydrogen, for example, is not only useful in fuel cell applications to power vehicles but is also sought-after as a feedstock in petroleum and metals refining as well as in ammonia, fertilizer and methanol production. Hydrogen is also emerging as a potential low-carbon fuel in sectors such as space and water heating, electricity generation and energy storage. Likewise, batteries with relatively high energy density and strong charge-discharge performance, such as those based on lithium-ion chemistries, are not only useful in transportation applications but in building and grid-scale energy storage, and in a wide range of consumer and industrial electronics.

If the rail sector is to advance on a decarbonization pathway in the most expedient manner possible, it may be advisable for it to avoid competition for technologies and fuels with other modes and economic sectors to the greatest extent possible.

Aside from resource availability, another factor to consider is the pace of decarbonization in the modes that the rail

sector competes with for business – most notably on-road trucking. While most on-road trucking remains reliant on carbon-intensive petroleum diesel, the sector turns over its assets much faster than rail (roughly 10-15 years versus 30-50), and low-carbon solutions that have already been commercialized for smaller vehicles are now becoming viable for freight trucks. These factors mean the trucking sector has a much shorter potential timeline to decarbonization. From the perspective of shippers, who like other actors are facing increasing pressure to decarbonize operations, the value proposition of trucking will grow as its carbon intensity decreases.

Such factors may threaten the profitability of the rail sector going forward, in lieu of decisive action that places it on a clear decarbonization trajectory.

4.2.4 Social Equity

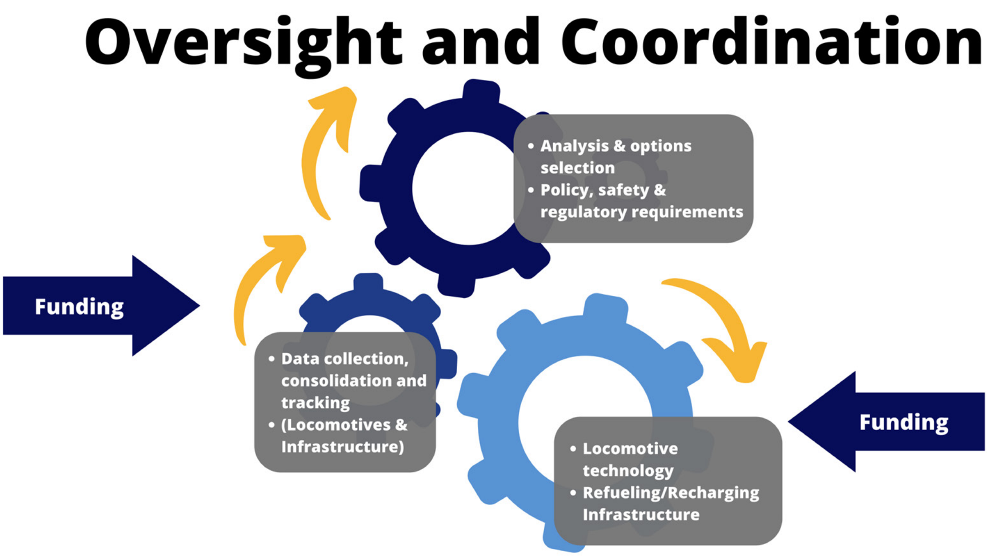
Peer-reviewed studies have found that there are significant diesel exhaust exposure disparities among residents living in close proximity to major rail yards. Further, research has shown that a disproportionate number of these residents belong to ethnic minority and low-income households. While the focus of this study is on decarbonization, most of the measures included here are also expected to reduce CAC emissions from rail operations, including in rail yards.[29] At the same time, some measures have the potential to increase at least the perception of risk, and possibly the overall level of risk in and around rail yards, for workers and nearby residents alike, due to the novel nature of certain technologies. A wide variety of industries have been using high-density batteries, high-voltage electrical systems, and hydrogen for a long time in a manner that has proven to be very safe. The use of these technologies in the Canadian rail sector is untested, however, which may cause perceived risks to be elevated. Consultations and educational campaigns with support from both the public and private sectors should be key elements of the rollout of alternative propulsion technologies. A focus of these efforts could be knowledge transfer from other industries which validate that appropriate risk mitigation measures have been taken by rail stakeholders. The involvement of academia can also be used to provide independent perspectives, conduct innovative research, and generally lend credibility to decarbonization measures implemented.

4.3 RAIL DECARBONIZATION ROADMAP: IMPLEMENTATION PLAN

The Decarbonization Roadmap has identified potential technology pathways to rail decarbonization, as well as non-technology related considerations. The pursuit of these pathways will require collaboration between all key stakeholder groups. Areas of collaboration are outlined in Section 4.3.1, and roles of key stakeholder groups are outlined in the Workplan included in Section 4.3.2.

29 Caveat: as noted in section 3.2, the use of biodiesel can increase NOx emissions and biofuel use may therefore be restricted within densely populated areas in the future.

Recommendations for next steps are included in Section 4.3.3.



4.3.1 KEY ELEMENTS FOR COLLABORATION

TECHNOLOGY

Pilots and demonstration projects to test alternative fuels and alternative propulsion technologies have been announced, and in some cases are already underway, led by railways in both Canada and the United States. In Canada, CP Rail has announced that it will design and build two line-haul hydrogen-powered locomotives (North America's first) and a yard switcher using fuel cells and batteries to power the electric traction motors. CN Rail has announced that it is partnering with Wabtec to put into service its FLXdrive battery-electric freight locomotive, the first 100% battery heavy-haul locomotive for the country. Via Rail is replacing its core fleet with dual mode trains that can operate on either diesel or catenary electric power where it is available.

Railways and OEMs will be collecting and analysing data from this testing to inform further development of each technology. As the technologies advance, the assessment framework should be re-applied at regular intervals. The changing scores will uncover the relative trajectories of each of the technologies as they evolve. Pilot project data from across North America should be accounted for, given differences in both geography and climate.

Given the significant infrastructure requirements for alternative propulsion technologies, and the interoperability of railways across North America, some degree of alignment across Class 1 railways operating in Canada, the United States and Mexico is essential. Competition, corporate confidentiality, and proprietary information may limit what can be shared, however. **As such, Canadian-American policy alignment is a necessary complement to technology alignment.**

REGULATION

The technology roadmap is but one component: the regulatory/ safety landscape must evolve to enable the use of these new technologies. The introduction of new fuels and technologies may require new or updated regulations or rules. In other cases, existing regulations or rules could continue to apply but could, for example, be amended to require updated emissions testing procedures which would support implementation. Safety management systems may need to be revised. Training and certification requirements may need to be revised or developed.

Policy-makers for the North American rail sector should be kept abreast of the results of pilot testing. This will help to ensure that regulatory development keeps pace with technology development, will allow for alignment of regulations across national and provincial/ state borders, and will promote early identification of safety-related barriers and challenges. Further, they should be apprised of evolving safety practices and designs that result from these trials, so that new data can be incorporated into regulations and rules as appropriate.

POLICY AND PROGRAM DEVELOPMENT

There is a need for both policies and supporting programs that target the rail sector explicitly, in recognition of the vital role it plays in freight and passenger movement, and the unique decarbonization barriers it faces.

As noted in Section 4.2.1, a new funding model is required to make rail decarbonization a reality. In North American jurisdictions outside of Canada, technology development models rely heavily on both government funding and on collaborations. Government support for the rail sector, and for freight movement more broadly, can take many forms. Canada's updated 2020 climate plan, A Healthy Environment and a Healthy Economy, notes that a key role for government in greening the heavy-duty vehicle sector is to support technology development through R&D, but also to support pilot projects and the implementation of commercially ready solutions across all modes, including rail. Due to its high efficiency, rail is already a low-carbon mode relative to alternatives such as on-road transportation. This means that government investments in rail decarbonization may not achieve the same level of carbon reduction per dollar invested as for on-road but will potentially be more impactful through helping to maintain high utilization rates of the most efficient ground-based mode of transport.

The Canadian pilots announced by both CP and CN Rail are both being supported by existing funding programs. Emissions Reduction Alberta (ERA) is providing a $15 million grant to CP's Hydrogen Locomotive Program, and Pennsylvania's Department of Environmental Protection (DEP) is contributing funds to support CN's purchase of the Wabtec battery-electric locomotive. The positive investments by the state government of Pennsylvania and the provincial government of Alberta to these demonstration projects is very positive and can be a foundation for further investments by governments.

Transportation functions as a system. As such, policy and programs designed to address one modality may impact on others, for example by shifting uptake. Transportation policy has the opportunity to address barriers to rail decarbonization, but it may unintentionally have the opposite effect if the possible impacts on the rail sector are not considered. For example, in excluding rail as a credit generator, the Clean Fuel Standard (CFS) has the potential to incentivize the use of trucks over rail for shipping freight.

4.3.2 Stakeholder Workplan

Table 14 identifies rail decarbonization stakeholders and explores how they could contribute to developing and testing technology options; tracking, and analysing key data; and developing policy, safety and regulatory frameworks to support the transition to zero-emissions technology for the rail sector. The table reflects roles that stakeholders could play to help overcome barriers to rail decarbonization. In many cases the groups identified are already playing active roles in advancing the areas indicated as being within their purviews.

Legend			
Symbol	L	S	F
Role	Lead	Support	Fund/Finance

	Fuels, Technology and Infrastructure Development		Locomotives			Recharging/ Refueling			Oversight		
STAKEHOLDER GROUP	R&D	Testing/ Demonstration	Locomotive Retrofits & Enhanced Maintenance	Locomotive Manufacturing	Locomotive Purchase and Use	Fuel/ Electricity Supply	Identification of Shared Infrastructure Opportunities	Infrastructure Deployment	Policy Development	Safety and Regulatory Requirements	Data Collection, Tracking and Direction-Setting
RAC	S	S					S	S	S	S	L
Railways	L	L	L		L	S	S	L		S	L
Federal Government	F	F			F	F	L	F	L	L	L
Provincial Governments		F			F	S	S	F	L		
OEMs	L	S	S	L						S	S
Clean Tech Companies*	L	S	S								
Standards Development Organizations	S	S	S	S						L	
Research Insistutions	L	S					S		S	S	S
Alt Fuel Producers	S	S				L	S	S			
Banks/ NBFIs		F			F	F		F			
Utilities		S				L	S	S		S	
Hydrogen producers		S				L	S	S		S	
Supply-Chain Partners						S	S	S			

** Including providers of hydrogen storage solutions, batteries, etc.*

4.3.3 Recommendations

TECHNICAL ASSESSMENTS

Regular application of the assessment framework in Section 2.6 is the key to implementing the Roadmap. The framework is intended to provide a rating that captures the current status of each technology option with regard to cost, carbon reduction potential and challenges. The value of these ratings will be realized as the framework is applied at regular intervals to map out the relative trajectories of each option to 2030 and 2050. This in turn is expected to allow for early identification of the technologies that show the most promise. As illustrated in the Pathway to Rail Decarbonization graphic in Section 4.2, in order to achieve net-zero by 2050, it will be necessary to identify the most promising technology or technologies by 2035 and begin building out the required infrastructure.

The Rail Decarbonization Committee (discussed below) should be tasked with ensuring regular updates of the detailed technology assessments, using the framework in this roadmap. It is recommended that this occur every two to five years. At each iteration, a report should be developed to track and report on the results. Unless limited by privacy concerns, these reports should be made public. Updated data, based on the results of ongoing and future pilot projects, could be collected from railways by the RAC and anonymized prior to being applied to the assessment framework. It is important that the assessments include data from operations in Canada, so emerging technologies, fuels and practices can be assessed and rated based on performance in Canada's unique climate.

Recommendation I: Complete assessments of technology options every 2-5 years using the Assessment Framework included in Section 2.6. Report on the relative trajectories of each option to 2030 and 2050. The results of each assessment should be published and shared broadly with rail stakeholders throughout North America if it is possible to do so while respecting confidentiality of railways and other private sector stakeholders.

Timeframe: Regular interval to be determined.

OVERALL PATHWAY IMPLEMENTATION OVERSIGHT

Given that this project involved extensive public and private sector consultations, and reflects the priorities identified by both of these broad stakeholder groups, the recommendations in this section should be captured in a renewed 2022 MOU between TC and the RAC. Including these recommendations will help to enable government to work with the rail industry in achieving further emissions reductions and will also help to ensure that industry has a basis for securing public sector financial support which complements its own investments into decarbonization measures.

The roles and responsibilities of key stakeholder groups, as specified in Table 17 of this report, should also be incorporated into the renewed MOU to ensure all stakeholders are actively working towards the deep decarbonization of the sector.

> ***Recommendation II:*** Renew the MOU between TC and RAC in 2022. Reference the findings of both Phases 1 and 2 of the Rail Pathways work, including the assessment framework, the recommendations, and the stakeholder roles and responsibilities from this report.
>
> *Timeframe:* 2022

A dedicated body is required to provide oversight and coordination - overseeing implementation of the Roadmap and coordinating all stakeholders. A Rail Decarbonization Committee should be established, based on the stakeholder groups represented in the Roles and Responsibilities Matrix (possibly U.S. representation as well) and should be responsible for: arranging regular technology assessments; monitoring results and proposing appropriate short- to mid-term actions (which could include, as examples: making recommendations for additional testing, providing input on a funding model to support the transition (discussed further below); investigation of shared charging/ fueling infrastructure opportunities, and identification of possible partnerships within the rail sector and between modalities). In the longer term, the Committee should set decarbonization targets and track progress towards them. To support this Committee, a Project Manager should be engaged to serve as the secretariat on Roadmap implementation.

> ***Recommendation III:*** Establish a national Rail Decarbonization Committee. The Committee can lead on setting decarbonization targets, tracking progress towards them, overseeing future applications of the assessment framework, identifying optimal areas for government support, proposing appropriate short- to mid-term actions, as well as engaging with U.S. counterparts to align high level approaches and actions.
>
> *Timeframe:* Establish role of the Decarbonization Committee in 2022, with Committee operational through duration of the next and subsequent MOUs (beyond 2035).

> ***Recommendation IV:*** Create a Project Manager function to support the Rail Decarbonization Committee.
>
> *Timeframe:* Establish the function in 2022, Project Manager to support the Committee throughout its operations.

PROGRAM DEVELOPMENT

A joint government-industry funding model is required to realize deep decarbonization. Appropriate funding mechanisms for rail must be identified. Triaging the funding needs and finding gaps in already available government funding are the recommended next steps. In some cases, the decarbonization options assessed in this report are being piloted by Canadian railways in the US. This is in large part due to state and federal funding support for rail decarbonization efforts. A comparable level of support from Canadian governments would help to incentivize additional pilots and demonstrations in Canada. This would in turn ensure that data from operations in Canada is generated, allowing for the assessment of emerging technologies, fuels and practices in the context of Canada's unique climate and geography.

Further, the Government of Canada should consider hosting exercises with Canadian railways, as well as counterparts in the US and Mexico, to explore what level of government funding would be required to support a shift to any of the three propulsion modes that are capable of deep decarbonization. Such exercises could help to shed light on the most important cost and technical barriers and could ultimately serve to expedite the decarbonization timeline for rail.

A key role for government in addition to funding is convening a wide variety of stakeholders across modes to identify synergies and mutual benefits that could be achieved through collaboration on decarbonization efforts. The convening power of government should not be understated, as it can play a vital role in helping to forge partnerships between rail sector stakeholders, between modes, and across borders. Deployment of infrastructure is expected to present opportunities for collaboration with supply chain partners at locations including ports and intermodal facilities. Other modalities such as trucking and marine shipping may implement alternate technology pathways, which would limit the opportunity to collaborate (but would be favourable for rail in terms of competition for energy-based resources.)

Recommendation V: Establish a joint government-industry program to support and realize the decarbonization opportunities identified in this Roadmap. This program should have an exclusive focus on rail in recognition of its inherent efficiency benefits over other modes and the vital role it plays in Canada's economy. It should include both a funding component and a convening component intended to support collaboration.

Timeframe: 2023-2030

APPENDIX A – LIST OF INTERVIEWS CONDUCTED

Name	Title, Organization
Research	
Steve Fritz	Manager, Medium-Speed Diesel Engines, Southwest Research Institute
Paul Blomerus	Independent Consultant
Peter Eggleton	Independent Consultant
Josipa Petrunic	Executive Director & CEO, CUTRIC
Dr. Gordon Lovegrove	Associate Professor, School of Engineering, Faculty of Applied Science, UBC
Clean Tech and OEMs	
Bob Oliver	CEO, Tech-K.O. and Acting CEO, H2GO Canada
Nicolas Pocard	VP Marketing and Strategic Paternships, Ballard
Jerainne Heywood	Technical Leader, Fluid Technology, Wabtec
Fuel Producers	
Fred Ghatala	Director Carbon & Sustainability, Advanced Biofuels Canada
Matt Leuck	Renewable Diesel Fuel Technical Manager, Neste
Dayne Delahoussaye	North American Public Policy, Neste
Government	
Kyle Beauliua	A/Engineer Environmental Programs, Transport Canada
Daniel Fairbairn	Manager/Senior Policy Advisor, Transport Canada
Paul Izdebski	Policy Analyst, Environment and Climate Change Canada
Stephen Healey	Policy Analyst, Environmental Policy, Transport Canada
Lorri Thompson	Manager, Clean Fuel Standard, Environment and Climate Change Canada
Eddy Zuppel	Program Lead, Vehicle Propulsion Technologies, National Research Council
Albert Wahba	Program Lead, Resilient Ground Transportation, National Research Council
Richard Holt	Head, Clean Transportation, Environment and Climate Change Canada
Ursula Green	Senior Engineer, Rail Safety Operations, Transport Canada
Railways	
Chantale Despres	Assistant Vice-President of Sustainability, CN
David Huck	Director, Sustainability, CP
Matthew Findlay	Director, Locomotive Maintenance, CP
Laszlo Czihaly	Chief Mechanical Officer, Southern Railway of British Columbia (SRY)

APPENDIX B – REDUCTION MEASURES IDENTIFIED

The following measures are presented in alphabetical order within each category. They represent potential decarbonization solutions identified through interviews or literature review.

Efficiency	Alternative Fuel	Alternative Propulsion
Aerodynamics-Locomotives	Alcohol	Battery+diesel generator (to rechard the battery)
Aerodynamics-Rail cars	Ammonia	Battery electric (tenders)
Anti-idling/Idle reduction devices	Biodiesel	Catenary
Automated throttle management	FAME (fatty acid methyl esters)	Catenary+ Battery
Automation/ Tended automation	HDRD (hydrogenation-derived renewable diesel)	Catenary +Hydrogen Fuel cell
Data driven solutions (System efficiency to minimize wasted kms) - e.g., Trip Optimizer	Hydrogen Co-combustion (H_2+ diesel)	Diesel + On-board Battery-Augmented (with or without aftertreamtment systems)
Engine mapping	HVO (Renewable hydro-treated vegetable oil)	Hybrid solid oxide fuel cell-gas turbine (SOFC-GT)
Lightweighting	Lignin-derived biodiesel	
Reduced leakage of compressed air	LNG (liquefied natural gas)/ CNG (compressed natural gas)	Hydrogen Fuel Cell (HFC)
Track-whell interface	Methanol	Proton exchange membrane fuel cell (PEMFC) + on-board traction battery
Ultracapacitors/ rengerative braking	RNG (renewable natural gas)	

APPENDIX C – DETAILED TECHNOLOGY ASSESSMENT: BIODIESEL (B20)

1. COST

A. DEVELOP

Score	Description	Selection
5	Commercially available: no development cost	✓
4	Nearing commercial availability: development costs <$10 million	
3	$10-50 million	
2	$50-70 million	
1	Significant development required including complex challenges: >$75 million	

Summary:

Total cost to develop, test and certify biodiesel is nil, as it has been commercially available throughout Canada for many years. However, it is likely that additional costs will be required to further develop second and third generation biodiesel in the medium and long term.

Notes:

- Biodiesel production has been technically mature and cost-effective for many years. Its use is currently required nationally at blend rates of at least 2% with petroleum diesel, though some provinces mandate higher average blend rates (e.g., Manitoba already requires renewable diesel blend rates of 5%, and Ontario requires 4% blends).

- In Canada, most commercially available biodiesel is still produced from edible food crops, most often soybeans, which presents a distinct set of challenges and limitations. Biodiesel production from non-food products such as waste cooking oil and animal fat, and even from cultivated algae, is possible yet some related technologies are still in their infancy and feedstock availability is limited, which limits uptake and GHG reduction potential.

- It is expected that there will be a reduced demand for first generation biofuels in the future, due to concerns over food security and the carbon intensity of production.

- Locomotive OEMs are aware that the typical 5% limit on biodiesel blending will limit railways in their efforts to decarbonize and are open to testing higher blends. Progress Rail recently approved B20 blends for its lineup of 645 and 710 EMD engines to help its customers achieve climate targets. SRY has submitted a grant application so it can test neat biodiesel (B100) use.

- Railways stated that they require a better line of sight on the precise blending ratios of different batches of diesel fuel that they purchase. There are currently no requirements on the part of fuel providers to disclose this, so long as they meet mandated annual average blending requirements. This information would help railways validate the efficacy and impacts of different blends, report more accurately on the carbon intensity of their operations and gauge the effects of higher blends on fuel prices.

Reference(s):

- Consultations: SRY, Neste, TC, CN
- Literature review:
  - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
  - US DOE, 2020 (https://afdc.energy.gov/fuels/biodiesel_benefits.html)
  - Progress Rail, 2021 (https://www.progressrail.com/en/Company/News/PressReleases/ProgressRailApprovesB20BiodieselFuelforUseinEMDEngines.html)

B. IMPLEMENT — CAPITAL COST

Score	Description	Selection
5	No incremental cost	
4	Up to $1 million	✓
3	$1-3 million	
2	$3-5 million	
1	>$5 million	

Summary:

Incremental capital cost per locomotive to allow for the use of B20 is estimated to be well below $1 million.

Notes:

- Biodiesel blends of up to 20% are technically feasible to use in many existing diesel locomotives, however upgrades to some components such as rubber gaskets may be required in some cases (especially for pre-2004 locomotives). Blends of up to 7% should be feasible for all existing diesel locomotives with no upgrades required.

- A UK study found that purpose-built neat biodiesel locomotives should be technically feasible by 2030 or 2040. Converting existing fleets to run on neat biodiesel should also be technically feasible by 2030, however biodiesel supply would be a major constraint (one which is not expected to be overcome).

- If biodiesel blends are used in excess of levels specified by warranties, railways may need to purchase and install upgrading kits.

Reference(s):

- Consultations: CP, ECCC, CN
- Literature review:
    - Rail Safety and Standards Board (RSSB), 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)

C. IMPLEMENT — INFRASTRUCTURE REQUIREMENTS

Score	Description	Selection
5	No additional infrastructure required	
4	Existing infrastructure can be used, with modifications	✓
3	Significant new infrastructure required in yards only.	
2	Significant new infrastructure required in yards and other locations	
1	Significant new infrastructure required over entire net-work	

Summary:

Additional refueling/ charging infrastructure requirements for the use of B20 include:

- Biodiesel storage tanks may require increased maintenance relative to petroleum diesel, as water content can lead to biological growth.

- Railways may choose to add in-house blending facilities and equipment to meet any future biodiesel targets.

Notes:

- Biodiesel is safer and easier to transport than petroleum diesel and can utilize existing refueling infrastructure and dispensing equipment with minimal modifications.

- Biodiesel has a lower energy density relative to petroleum diesel (roughly 9% lower). For a B20 blend, this is a small difference (under 2%). As such, it is unlikely to result in a requirement for additional refueling locations at this blend rate.

Reference(s):

- Consultations: TC, Wabtec, Waterfall Group
- Literature review:
  - Navius Research, 2020 (https://www.naviusresearch.com/publications/2020-biofuels-in-canada/)
  - US DOE, 2020 (https://afdc.energy.gov/fuels/biodiesel_benefits.html)

D. OPERATE

Score	Description	Selection
5	>20% savings	
4	Up to 20% savings	
3	Par with diesel	✓
2	Up to twice the cost of diesel	
1	>2x	

Summary:

Incremental cost to operate is roughly on par with petroleum diesel.

Notes:

- While biodiesel is considered a drop-in fuel at low blend rates (<20%), it does tend to cost slightly more than petroleum diesel, and additional fuel is required based on the lower energy content. This is expected to be balanced in varying degrees based on the increasing carbon tax.

- Refueling equipment and practices are very similar to petroleum diesel. However, in some cases railways may choose to blend biofuels at their own facilities, which would require the use of specialized blending equipment.
- Biodiesel has greater water content than other fuels, and railways need to use additives such as methanol to address issues resulting from this. In some cases, this water content can lead to corrosion in a variety of engine and fuel system components, leading to higher maintenance costs.
- The use of biodiesel in blend rates greater than 2% may lead to higher maintenance costs and blends greater than 5% will almost certainly lead to increases in maintenance frequency as engine reliability timelines would be altered. Biodiesel derived from different types of vegetable oils will have different impacts on engine performance and maintenance. More research is needed on the mechanical impacts of higher blend rates.
- Updated service contracts with engine OEMs will likely be required with the use of biodiesel blends in excess of 5%. Fuel filters are particularly likely to require increased maintenance and replacement as a result of biodiesel use, particularly in early stages of the transition.
- As credits for the use of biodiesel expire in the future, the economic case for using it may be diminished. This transitory economic benefit of using biodiesel is viewed as a risk by some experts.
- California currently requires that 40% of all diesel distributed in the state be HDRD or biodiesel. As a result, fuel costs are significantly higher and railways operating in the state go out of their way to buy fuel elsewhere.

Reference(s):

- Consultations: CP, SRY, Wabtec, Paul Blomerus, SWRI, Waterfall Group
- Literature review:
    - Navius Research, 2020 (https://www.naviusresearch.com/publications/2020-biofuels-in-canada/)
    - Rail Safety and Standards Board (RSSB), 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)

2. CARBON REDUCTION POTENTIAL

A. GHG REDUCTION POTENTIAL

Score	Description	Selection
5	>80%	
4	50-80%	
3	30-50%	
2	10-30%	✓
1	<10%	

Summary:

As compared with a baseline of diesel, GHG reductions on a per-equipment basis is estimated at up to 80% for neat biodiesel, or up to roughly 16% for B20.

Notes:

- At the system level, biodiesel alone is not a credible option for the deep decarbonization of rail, primarily due to the scale of supply that would be needed to supplant the majority of petroleum diesel currently in use.
- The GHG reduction potential of biodiesel can vary greatly, and depends on the feedstock(s) used, the location, the GHG intensity of their cultivation and transport, production processes, and the blend rate. Several experts stated that the net GHG reduction potential of neat biodiesel ranges from 20-80%, though it tends to be in the higher ranges in North America.
- Life cycle analysis completed by Argonne National Laboratory found that B100 use reduces GHG emissions by an average of 74% compared with petroleum diesel. The GREET model is used to assess the carbon intensity of biodiesel in the US, while Canada uses GHGenius.
- More research is needed on biofuel production processes to determine narrower windows of GHG reduction potential.
- First generation biofuels, which are produced from edible food crops such as soybeans, are the main source of biodiesel, which presents a distinct set of challenges and limitations. For example, many countries have caps on the amount of first generation biofuels that can be produced, in order to protect food supplies. Although third generation biofuels (those produced from cultivated algae) are an option for biodiesel production, they are still in their infancy which limits GHG reduction potential.

- Like HDRD, biodiesel use can address net GHG emissions but does not address emissions of CACs. Blends of 20% biodiesel (i.e., B20) have actually been shown to increase NOx emissions by roughly 5%. The use of biodiesel would likely do little to address air quality concerns in and around rail yards.

- While GHG reductions of up to 100% are theoretically possible with biodiesel, this assumes that cultivation/production, processing and transportation are achieved at near zero carbon which is highly unlikely.

- Biofuel use for surface transport may be phased out in the 2030s, and many see the use of biofuels as a stepping stone in the transition away from combustion engines and towards deep decarbonization.

Reference(s):

- Consultations: SRY, Peter Eggleton, TC, SWRI
- Literature review:
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - Southwest Research Institute, Low-Carbon Fuels for Locomotives: Biodiesel and Renewable Diesel (information received from SWRI)
    - Rail Safety and Standards Board (RSSB), 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)
    - US DOE, 2020 (https://afdc.energy.gov/fuels/biodiesel_benefits.html)

B. UPTAKE/ APPLICABILITY

Score	Description	Selection
5	Well-suited to mainline freight rail	✓
4	Partially suited to mainline freight rail	
3	Suited to yard equipment	
2	Well suited to passenger rail	
1	Not suited to mainline freight rail, only partially suited to passenger rail	

Summary:

Biodiesel is well-suited to all types of rail with only minor modifications to existing equipment, infrastructure and practices. Its properties are very similar to petroleum diesel. A critical caveat, however, is that the use of neat biodiesel (B100) for applications such as mainline freight is unlikely due to the scale of production that would be required.

Notes:

- The use of neat biodiesel should be feasible by 2030 or 2040, for all rail modes.

- The use of B2 and B5 blends have been tested in temperatures as low as -40°C in Canada, with no significant adverse impacts reported. Some experts believe that the use of blends as high as B20 should be feasible throughout Canada, year-round. CN is currently testing the feasibility of using B10 blends.

- A recent RSSB study found that biodiesel is currently the only realistic alternative fuel to petroleum diesel that would provide the sort of power and on-board energy required for self-powered freight locomotives.
- In some jurisdictions, railways have to meet renewable fuel blending requirements, in others they have to meet carbon lifecycle requirements. HDRD is better in latter scenario (due to its higher energy density and the fact that it can be produced from a broader range of low-carbon feedstocks), and biodiesel is better in former (due to its lower costs).

- Some experts stated that biodiesel may have a role to play in deep rail decarbonization where alternative propulsion technologies cannot have a major impact (e.g., on low-volume, short-haul lines).

Reference(s):

- Consultations: ECCC, TC, CN, CP
- Literature review:
    - Rail Safety and Standards Board (RSSB), 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)

3. CHALLENGES

A. OPERATION

Score	Description	Selection
5	Equal to or better than diesel	
4	Low level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	✓
3	Moderate level of complexity in maintaining system reliability and exisiting infrastructure and/or maintaining equipment.	
2	High level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	
1	Significant risk to reliability. Significant risk of loss of an asset.	

Summary:

The characteristics and composition of biodiesel from different sources are not uniform, presenting a series of technical challenges which are relatively straightforward to address. Additives or practices such as pre-heating fuel tanks may be necessary for the use of high (>20%) biodiesel blends in cold temperatures. Altered engine maintenance regimes and standards will also be required for higher blends.

Notes:

- Biodiesel has performance issues in cold weather related to clouding, which is why it is not mandated for use in Canadian regions north of 60° latitude. These issues can be addressed in part through the use of fuel additives, but these typically come with their own series of unique challenges. In general, performance issues tend to be proportional to blend rates.

- Biodiesel alters the cold start properties of fuels. In blends greater than 10%, there could be issues with starting locomotives in extreme cold temperatures. In such cases, fuel tanks would have to be heated prior to start up to ensure the biodiesel component is liquefied.

- Due to cold weather issues, blend rates are mandated on an annual average basis, meaning that fuel suppliers provide higher blend rates in the summer months and lower blend rates in the winter. For example, the State of Minnesota allows blend rates of up to 10% to be sold in the summer to meet an annual average blend requirement of 5%.

- Warranties from locomotive OEMs may be voided if biodiesel blend rates exceed a certain threshold. This issue was identified by one railway as the biggest challenge associated with increased biodiesel use. OEMs interviewed indicated that they are willing to work with railways to test higher blend rates than are currently warrantied, however, and to adjust specifications based on the results of those studies.

- Biodiesel can cause rubberized/elastomer gaskets and seals in engines to expand, posing a risk of fuel leaks upon shrinkage, which in turn can lead to excessive engine wear. This can be addressed through the addition of aromatic additives to biodiesel, or through the replacement of the seals. Most post-2003 engines have seals that are not susceptible to swelling.

- Biodiesel is not expected to be available in sufficient quantities to have meaningful decarbonization impacts.

- The chemical composition of biodiesel can vary, and standards have room for improvement.

- Biodiesel produced from different types of vegetable oils will change states (e.g., liquid to solid) at different temperatures, which will impact engine performance.

- Biodiesel is heavier than petroleum diesel, so it requires higher temperatures to burn. Due to the way engines are designed, temperatures are often not high enough leading to incomplete combustion. This can lead to the clogging of fuel injection nozzles and fuel leaks which can cause excessive engine wear.

- Engine OEMs such as Wabtec have developed recommendations around the use of different biodiesel blends for different regions, engine types and biodiesel sources/ feedstocks. They are aware that customers are seeking to use higher biodiesel blends and are working to validate different engine platforms and establish engine maintenance frequencies per platform because they will vary.

Reference(s):

- Consultations: CP, Neste, Wabtec, SWRI, Waterfall Group
- Literature review:
    - Southwest Research Institute, Low-Carbon Fuels for Locomotives: Biodiesel and Renewable Diesel (information received from SWRI)
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)

B. REFUELING

Score	Description	Selection
5	Equal to or better than diesel	
4	Moderate complexity to supply chain and/or refueling requirements	✓
3	Complex supply chain, >2x refuel/recharge time/frequency	
2	Intermittent availability issues, up to 2x refuel/ recharge time/ frequency	
1	Frequent availability issues, >2x refuel/rechg. time/ frequency	

Summary:

Refueling infrastructure, equipment and practices are very similar to that used for petroleum diesel. However, in the context of using biodiesel to achieve deep decarbonization, availability will become an increasingly prominent challenge with increasing blend rates. Availability would rapidly present a prohibitive barrier if the rail sector were to begin a wholesale shift to biodiesel, primarily due to conflicts with food production and a finite amount of arable land. For these reasons, this assessment is focused on the use of B20.

Notes:

- The energy content of biodiesel is roughly 9% lower than petroleum diesel, meaning that for higher blend rates, additional onboard fuel storage capacity (possibly including fuel tenders) or fueling points may be required to enable the use of high biodiesel blends on routes that have been optimized for petroleum diesel. This is unlikely to be an issue for B20 blends which would be under 2% less energy intensive than petroleum diesel.

- To use biodiesel at higher than mandated blend rates a consistent, reliable sources will be necessary and availability could quickly become a constraint. New sources and supply chains for vegetable oils and animal fats will need to be created. These will conflict with food production needed to feed a growing population, and could be exacerbated by climate change.

- Relatively high water content in biodiesel can lead to biological growth in fuel systems, including onboard and stationary fuel storage tanks. This can necessitate more stringent maintenance and cleaning of fuel systems.

- Canada currently produces enough biodiesel to meet domestic demand, however it exports much of its biodiesel to the US due to the higher prices it can garner there.

- As of 2019, Canada sourced 55% of national biodiesel demand domestically, and relies on imports to supply current renewable diesel consumption. The US is by far the largest supplier of biodiesel to Canada, but some is also imported from Europe, primarily Germany, and also from Argentina.

- At blend rates greater than 20%, there are expected to be major supply constraints which could necessitate the retrofitting of existing petroleum refineries. The retrofitting process is easier for HDRD than for biodiesel.

Reference(s):

- Consultations: CP, Wabtec, ECCC, TC
- Literature review:
    - Navius Research, 2020 (https://www.naviusresearch.com/publications/2020-biofuels-in-canada/)
    - Canadian Association of Petroleum Producers (CAPP), 2020 (https://www.capp.ca/wp-content/uploads/2020/11/Availability-of-Biofuels-Clean-Fuel-Standard-Supply-and-Demand-Implications-377511.pdf)

C. SAFETY & REGULATORY COMPLIANCE

Score	Description	Selection
5	Equal to or better than diesel	
4	Some additional training and/or regulatory development required	✓
3	Additional training & certification and/or regulatory development required	
2	Safety concerns and/or significant regulatory development required	
1	Significant safety concerns, including to public and/or complete regulatory development required	

Summary:

The use and transport of biodiesel is safer than the use of petroleum diesel. Minimal additional regulatory development is required to facilitate higher blend rates.

Notes:

- Overall, biodiesel is expected to require minimal regulatory development, even if used at higher blend rates than those currently mandated or warrantied.

- It is possible that the use of biofuels for surface transport will be phased out through regulations during the 2030s or 2040s. One expert suggested the use of biodiesel could remain viable for the next 5-10 years, however beyond that things become much less certain.

- Neat biodiesel causes far less damage than petroleum diesel if spilled or released to the environment. It is safer than petroleum diesel because it is less combustible. The flashpoint for biodiesel is higher than 130°C, compared with about 52°C for petroleum diesel. Biodiesel is generally safe to handle, store, and transport.

- ASTM D975 is the fuel specification which allows for the use of up to 5% biodiesel blends in the US, and treats these blends as functionally identical to petroleum diesel. In Canada, the Canadian General Standards Board (CGSB) has opted for separate specifications between petroleum diesel and blends up to B5. The Canadian standards for petroleum diesel and blends up to B5 are CAN/CGSB-3.517 and CAN/CGSB-3.520, respectively. The biodiesel used in Canadian blends must meet US or European standards for B100, which are ASTM D6751 or EN 14214, respectively. The BQ-9000 Quality Management Program is used to verify that producers and marketers of biodiesel sold in North America meets the ASTM D6751 standard. A Canadian specification for blends in the B6 to B20 range is currently being developed.

Reference(s):

- Consultations: CP, Wabtec, SWRI, CN
- Literature review:
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)
    - US DOE, 2020 (https://afdc.energy.gov/fuels/biodiesel_benefits.html)
    - DieselNet, 2021 (https://dieselnet.com/standards/ca/fuel_biodiesel.php)
    - Government of Canada, 2020 (https://publications.gc.ca/site/eng/9.884945/publication.html)
    - Natural Resources Canada, 2015 (https://www.nrcan.gc.ca/energy/alternative-fuels/fuel-facts/biodiesel/3523)
    - National Biodiesel Board, 2021 (https://www.bq-9000.org/)

APPENDIX D – DETAILED TECHNOLOGY ASSESSMENT: HYDROGENATION-DERIVED RENEWABLE DIESEL (HDRD 30)

1. COST

A. DEVELOP

Score	Description	Selection
5	Commercially available: no development cost.	
4	Nearing commercial availability: development costs <$10 million	✓
3	$10-50 million	
2	$50-75 million	
1	Significant development required including complex challenges: >$75 million	

Summary:

Total cost to develop, test and certify is estimated to be less than $10 million. The majority of these costs are expected to be borne by fuel producers, locomotive OEMs and certification bodies. Alternative fuels such as HDRD are being developed for sectors including not only rail, but also on-road trucking, school and transit buses, marine, and off-road vehicles and equipment.

Notes:

- There is currently no HDRD production taking place in Canada. Neste is the only major producer in North America, and most supply currently goes to California due to aggressive emissions standards and renewable fuel blending requirements, as well as a profitable compliance credit market.

- Production in Canada would require purpose-built biorefineries or the conversion of existing petroleum refineries. NRCan's Fuels of the Future program will incentivize the development of renewable fuels such as HDRD in Canada.

- Lignin-derived biodiesel is chemically similar to HDRD and has similar performance metrics but is produced through a different pathway. There are a small number of companies in Canada that produce it in limited quantities. While HDRD can be produced from lignocellulosic feedstocks such as forestry and agricultural residues, the production processes for these pathways remain immature.

- Purpose-built commercial HDRD refineries were found to cost anywhere from $130 million to $1 billion in 2012 dollars.

Reference(s):

- Consultations: Waterfall Group, Neste, TC
- Literature review:
    - Government of Canada, 2019 (https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/national-renewable-diesel-demonstration-initiative/nrddi-final-report/nrddi-fr-introduction/3669)
    - Natural Resources Canada, 2012 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/transportation/alternative-fuels/resources/pdf/HDRD_Final_Report_eng.pdf)

B. IMPLEMENT — CAPITAL COST

Score	Description	Selection
5	No incremental cost	✓
4	Up to $1 million	
3	$1-3 million	
2	$3-5 million	
1	> $5 million	

Summary:

HDRD30 is already warrantied for use in locomotives. Incremental capital cost per locomotive to accommodate the use of HDRD30, then, is estimated to be negligible for post-2003 locomotive engines, and minor for older engines. Incremental capital costs to accommodate the use of neat HDRD are anticipated to be well below $1 million, though further testing is required to determine if this is a possibility, and if so, what the range of costs per unit would be.

Notes:

- Many stakeholders consulted stressed that HDRD is not a pure drop-in fuel, though it is close to being chemically identical to petroleum diesel. Minor upgrades to older, pre-2004, engines (e.g., replacement of rubberized gaskets and seals in engine fuel systems, as high HDRD blends can cause these to expand and leak due to its lack of aromatics) will be required for HDRD blends exceeding 20%. Additional maintenance could also be required by the use of neat HDRD, as its use will have impacts on engine timing on account of its lower energy density relative to petroleum diesel (roughly 6% lower).

- Locomotive engine OEMs certify their engines to run on HDRD blends of 20 or 30%. The use of blends exceeding these levels can potentially void engine warranties. This issue is complicated by the fact that there are currently no disclosure requirements for renewable content blend rates, so railways are never sure of the exact blend rates of fuels in use.

Reference(s):

- Consultations: CP, CN, Neste, Wabtec
- Literature review:
  - Navius Research, 2020 (https://www.naviusresearch.com/publications/2020-biofuels-in-canada/)
  - University of Toronto, 2019 (https://www.toronto.ca/legdocs/mmis/2019/ie/bgrd/backgroundfile-130965.pdf)

C. IMPLEMENT — INFRASTRUCTURE REQUIREMENTS

Score	Description	Selection
5	No additional infrastructure required	✓
4	Existing infrastructure can be used, with modifications	
3	Significant new infrastructure required in yards only.	
2	Significant new infrastructure required in yards and other locations	
1	Significant new infrastructure required over entire network	

Summary:

Additional refueling/ charging infrastructure requirements are not anticipated for blends of 30% HDRD. If this fuel were to be used neat, requirements may include:

- Additional refueling locations due to the lower energy density of HDRD as compared to petroleum diesel (roughly 6% lower); or
- Additional onboard fuel storage capacity
- Railways may choose to add in-house blending facilities and storage equipment to meet any future HDRD targets.

Reference(s):

- Consultations: CP, Wabtec
- Literature review:
  - Navius Research, 2020 (https://www.naviusresearch.com/publications/2020-biofuels-in-canada/)

D. OPERATE

Score	Description	Selection
5	>20% savings	
4	Up to 20% savings	
3	Par with diesel	
2	Up to twice the cost of diesel	✓
1	>2x	

Summary:

Incremental costs to operate, as compared with a baseline of petroleum diesel, are currently 3-4 times greater for neat HDRD, or up to two times greater for HDRD30. This could change, however, if economies of scale (i.e., HDRD refineries are built or existing refineries are retrofitted) and/or lower-cost feedstocks and production processes emerge. Another extenuating factor is carbon pricing and compliance credit markets, although it was stated that a carbon price of $170 per tonne (Canada's 2030 target) would not be adequate to make HDRD cost-competitive with petroleum diesel.

Notes:

- There is currently limited availability and use of HDRD in Canada due to a lack of production capacity (what is being used is produced in the US). Increasing this capacity would likely require wholesale refinery conversions, as has occurred in the US. Further, its costs are significantly greater than petroleum diesel, currently 3-4 times more expensive. Demand for HDRD is expected to outpace supply for the next 15 years.

- When fuel producers in North America sell HDRD, they are actually selling two products – a diesel fuel and a compliance credit. If a railway does not have an obligation to reduce carbon, they do not need to buy the credit component. Fuel producers can split those two commodities, and sell carbon credits to a fuel provider, then sell the fuel itself to a railway, which would only pay for the fuel component, thus lowering the price paid.

- The lack of both sulphur and aromatics in HDRD reduces its lubricity, necessitating the use of fuel additives.

- Aside from the incremental costs of fuel, additional operational costs are expected to be negligible.

- Unlike biodiesel, HDRD is very stable and poses no more risk of microbial growth, precipitation and water formation during storage than petroleum diesel.

Reference(s):

- Consultations: CP, CN, ECCC, Waterfall Group, Neste, SWRI
- Literature review:
    - Southwest Research Institute, Low-Carbon Fuels for Locomotives: Biodiesel and Renewable Diesel (information received from SWRI)
    - University of Toronto, 2019 (https://www.toronto.ca/legdocs/mmis/2019/ie/bgrd/backgroundfile-130965.pdf)

2. CARBON REDUCTION POTENTIAL

A. GHG REDUCTION POTENTIAL

Score	Description	Selection
5	>80%	
4	50-80%	
3	30-50%	
2	10-30%	✓
1	<10%	

Summary:

As compared with a baseline of diesel, GHG reductions on a per-equipment basis for HDRD30 is estimated at 27%. This is based on carbon intensity estimates for HDRD from GHGenius 4.03a, which are 89% lower than petroleum diesel. The GHG reduction potential is heavily dependent on the fuel sources/feedstocks and production processes, both of which can vary significantly.

Notes:

- Fuel providers are exploring the use of novel feedstocks to produce HDRD (as opposed to vegetable oils and animal fats), such as algae, municipal solid waste, forestry residues, and carbon captured from the atmosphere. This could impact prices as well as GHG reduction potential from a life-cycle perspective. HDRD can be produced from a broader range of feedstocks than biodiesel.

- HDRD has greater GHG reduction benefits than biodiesel as it has slightly greater (~3%) energy density and can be blended with petroleum diesel at higher rates using existing equipment.

- The Government of Canada is calling for 11% HDRD use in all heavy-duty diesel applications by 2030 to help meet its climate targets.

- In California, blends of 20% biodiesel and 80% HDRD are being marketed as carbon neutral, though this is not based on a universal life-cycle assessment methodology. Further, there are no ASTM specifications on HDRD composition, and some stakeholders suspect that some of the fuel being sold as HDRD is simply raw vegetable oil. It is difficult and costly to determine the exact composition and source of a given batch of HDRD.

- Lifecycle carbon intensity in 2018 was 10.4 g CO2e/MJ for the combined weighted average of biodiesel and HDRD (which assumes that the same feedstocks were used). This is 89% less carbon intensive than petroleum diesel.

Reference(s):

- Consultations: Neste, ECCC, Wabtec, SWRI
- Literature review:
    - Natural Resources Canada, 2012 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/transportation/alternative-fuels/resources/pdf/HDRD_Final_Report_eng.pdf)
    - Southwest Research Institute, Low-Carbon Fuels for Locomotives: Biodiesel and Renewable Diesel (information received from SWRI)
    - Navius Research, 2020 (https://www.naviusresearch.com/publications/2020-biofuels-in-canada/)

B. UPTAKE/ APPLICABILITY

Score	Description	Selection
5	Well-suited to mainline freight rail	✓
4	Partially suited to mainline freight rail	
3	Suited to yard equipment	
2	Well suited to passenger rail	
1	Not suited to mainline freight rail, only partially suited to passenger rail	

Summary:

HDRD is suitable for all rail applications. It is close to being a drop-in fuel for post-2003 locomotive engines, and it is expected that only minor upgrades will be required for its use as a neat fuel or in blend rates greater than 20 or 30%.

Notes:

- HDRD can play a key role in decarbonizing rail in applications where alternative propulsion technologies are not well-suited. In theory it can be carbon-neutral on a life-cycle basis. In California, certain blends of 20% biodiesel and 80% HDRD are currently being sold as carbon-neutral.

- Despite its strong GHG reduction potential and compatibility with existing rail equipment and infrastructure, HDRD availability is expected to be constrained by either the limited availability of feedstocks (food and non-food crops and suitable triglyceride-rich waste materials) or the immaturity of production processes utilizing more abundant feedstocks (e.g., agricultural and forestry residues). This constraint, along with competition for HDRD from other heavy-duty diesel applications, is likely to limit the use of HDRD in rail applications (i.e., prevent the wholesale replacement of petroleum diesel with HDRD).

- In the context of deep decarbonization HDRD may play a role in low-volume rail lines as a petroleum diesel alternative in bi-mode consists, complemented by a zero emission propulsion technology.

- It should be noted that despite HDRD's low carbon intensity, its use will still result in emissions of air pollutants, which may limit its potential in the context of rail yards or other operations in densely populated areas. However, HDRD is virtually free of metal contaminants as well as ash-forming compounds which leads to relatively clean combustion.

Reference(s):

- Consultations: TC, Neste, SRY
- Literature review:

  - Rail Safety and Standards Board (RSSB), 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)
  - Natural Resources Canada, 2012 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/transportation/alternative-fuels/resources/pdf/HDRD_Final_Report_eng.pdf)
  - University of Toronto, 2019 (https://www.toronto.ca/legdocs/mmis/2019/ie/bgrd/backgroundfile-130965.pdf)
  - Government of Canada, 2019 (https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/national-renewable-diesel-demonstration-initiative/nrddi-final-report/nrddi-fr-introduction/3669)

3. CHALLENGES

A. OPERATION

Score	Description	Selection
5	Equal to or better than diesel	
4	Low level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	✓
3	Moderate level of complexity in maintaining system reliability and exisiting infrastructure and/or maintaining equipment.	
2	High level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	
1	Significant risk to reliability. Significant risk of loss of an asset.	

Summary:

The use of HDRD30 can lead to low severity mechanical issues and increased maintenance requirements. Mechanical issues are primarily limited to pre-2004 locomotive engines that have rubberized gaskets and seals that can expand and then shrink, leading to fuel leakages, due to the use of fuels that lack aromatics such as HDRD. Maintenance issues with higher blend rates in newer engines are a possibility yet are not currently well-understood due to a lack of field testing of neat HDRD. Engine OEMs are currently testing different blends of HDRD derived from a variety of feedstocks on different engine platforms and in different climates to develop maintenance regimens and update warranty limits.

Notes:

- HDRD is not typically formulated for use in cold climates, and cold weather performance remains an issue requiring further study. However, unlike biodiesel, its cloud point can be adjusted by varying production processes and blend components. HDRD supplied to the Alberta Renewable Diesel Demonstration (ARDD) was successfully tested in temperatures as low as -27°C.

- For older engines, because HDRD has a high cetane number (meaning it burns more quickly than petroleum diesel) it impacts the timing of engines. It can therefore cause instability in older engines, as all engines are optimized for certain timing. Conventional fuels have cetane numbers between 40 and 48, but when numbers go higher, into the 50s, it disrupts engine timing. There are a lot of older engines still running in Canada, although they tend to get overhauled every 7 to 10 years. It is possible to go beyond 30% blend rates even for older engines, but there are mechanical and maintenance implications.

- Engine OEMs are actively seeking partnerships with North American railways to better understand how higher blend rates of renewable diesel impact different types of engines in different climates.

Reference(s):

- Consultations: Neste, Wabtec, SWRI
- Literature review:
  - Southwest Research Institute, Low-Carbon Fuels for Locomotives: Biodiesel and Renewable Diesel (information received from SWRI)
  - University of Toronto, 2019 (https://www.toronto.ca/legdocs/mmis/2019/ie/bgrd/backgroundfile-130965.pdf)

B. REFUELING

Score	Description	Selection
5	Equal to or better than diesel	
4	Moderate complexity to supply chain and/or refueling requirements	
3	Complex supply chain, >2x refuel/recharge time/frequency	
2	Intermittent availability issues, up to 2x refuel/ recharge time/ frequency	✓
1	Frequent availability issues, >2x refuel/rechg. time/ frequency	

Summary:

Overall, refueling requirements for HDRD are very close to being equal to those for petroleum diesel. However, there are major availability issues which are expected to persist out to 2035.

Notes:

- Added supply chain complexity and supply issues along with validation requirements around the source and composition of HDRD may pose modest complications to railways.

- As has been mentioned previously, feedstock availability, immature production processes for alternative feedstocks, and limited refining capacity present significant availability challenges for HDRD.

Reference(s):

- Consultations: CP, Wabtec
- Literature review:
    - Government of Canada, 2019 (https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/national-renewable-diesel-demonstration-initiative/nrddi-final-report/nrddi-fr-introduction/3669)
    - University of Toronto, 2019 (https://www.toronto.ca/legdocs/mmis/2019/ie/bgrd/backgroundfile-130965.pdf)

C. SAFETY & REGULATORY COMPLIANCE

Score	Description	Selection
5	Equal to or better than diesel	
4	Some additional training and/or regulatory development required	✓
3	Additional training & certification and/or regulatory development required	
2	Safety concerns and/or significant regulatory development required	
1	Significant safety concerns, including to public and/or complete regulatory development required	

Summary:

Specifications around the composition of HDRD are required in order to determine its environmental and mechanical impacts and thresholds. Work in this area is underway and is not expected to be burdensome, however. There are no requirements for fuel providers to disclose the blend rates of a given batch of fuel to railways, which presents an issue with regard to environmental performance and reporting as well as the testing and validation of different fuel blends in active service.

Notes:

- There are currently no definitive regulatory specifications for what constitutes HDRD in North America or globally. This is problematic as some rail sector stakeholders treat it like a pure drop-in fuel (i.e., chemically identical to petroleum diesel) when in fact it is not, and its composition can vary significantly. Standards are needed to ensure HDRD consistency and quality.

- The ASTM D975 diesel standard currently uses a broad enough definition for diesel so as to treat petroleum diesel and HDRD as chemically identical.

- Although Canadian General Standards Board (CGSB) diesel standards do not currently explicitly state that HDRD can be blended at any level, HDRD nonetheless already meets the definition for diesel in CAN/CGSB 3.517, and so the CGSB diesel standard implicitly allows for HDRD blending at any level. Some stakeholders are concerned with respect to ensuring adequate lubricity additive levels in HDRD, although section 6.22 of CAN/CGSB-3.517 does state the requirement for lubricity and how it is to be achieved and tested. As a result, it is not expected that HDRD will require a significant amount of regulatory development to facilitate its widespread use in Canada.

- HDRD has impacts on engine reliability and other impacts that require further study. Such explorations should be the starting point for the development of regulatory specifications. There are a lot of misconceptions around HDRD and some sellers are selling fuels that are quite chemically different from petroleum diesel. Currently different types of fuels with different environmental and performance impacts are all being marketed under the umbrella of HDRD.

- Once HDRD-specific standards are developed, it can be better incorporated into lifecycle assessment models in order to determine its net environmental impacts and decarbonization potential.

Reference(s):

- Consultations: CP, CN, Wabtec, SWRI
- Literature review:
    - University of Toronto, 2019 (https://www.toronto.ca/legdocs/mmis/2019/ie/bgrd/backgroundfile-130965.pdf)

APPENDIX E – DETAILED TECHNOLOGY ASSESSMENT: BATTERY ELECTRIC

1. COST

A. DEVELOP

Score	Description	Selection
5	Commercially available: no development cost.	
4	Nearing commercial availability: development costs <$10 million	
3	$10-50 million	✓
2	$50-75 million	
1	Significant development required including complex challenges: >$75 million	

Summary:

Total cost to develop, test and certify battery electric propulsion for mainline service is estimated to be between $20 and 50 million.

Notes:

- Progress Rail has developed a battery switcher locomotive, the EMD Joule, with capacity of 1.9-2.4 MWh (up to 3,000 HP). It has been commercially available since 2020. Further R&D is required to improve charging times and test impacts of frequent charge-discharge cycles on battery degradation.

- Wabtec's FLXdrive heavy-haul battery electric locomotive is undergoing testing on a BNSF railway in California. The FLXdrive has run over 16,000 km and delivered an average of 10% reduction in fuel consumption when used in active service as part of a diesel-battery electric consist. While the locomotive being tested delivers 2.4 MWh of energy, a larger 6+ MWh unit could reduce fuel consumption and emissions by up to 30%.

- A multi-year battery electric demonstration would likely be well-suited to a short line or dedicated route. It would likely cost in the range of $20-100 million.

- Wabtec stated that its FLXdrive demonstration would not have been possible without financial support from the government (through the California Air Resources Board). Partnerships, external funding, and technology development will all have to work in concert to make battery electric technologies viable for the rail sector.

- While the technology is technically mature and commercially available for passenger rail and yard applications, more R&D is required to make it a feasible option for mainline railway service. Key goals of R&D include reducing the weight and size of battery tenders, reducing charging times and developing optimal charging infrastructure for a variety of in-use and yard scenarios, testing battery degradation over extended use, improving overall train efficiency to reduce demands on batteries, and reducing battery costs.
- Wabtec, Genesee & Wyoming (G&W) and Carnegie Mellon University are seeking to collaborate with the US government to form and co-fund a public-private partnership that will focus on zero-emission railway technology research, demonstration and commercialization, with a focus on battery and hydrogen fuel cells and on-site hydrogen generation solutions. This proposed Freight Rail Innovation Institute would commit to developing the technologies through the partnership by 2030.

Reference(s):

- Consultations: CP, CUTRIC, Wabtec, CN
- Literature review:
    - Progress Rail, 2021 (https://www.progressrail.com/en/Segments/RollingStock/Locomotives/FreightLocomotives/EMDJoule.html)
    - House Committee on Transportation and Infrastructure, 2021 (https://transportation.house.gov/imo/media/doc/Santana%20Testimony.pdf)

B. IMPLEMENT — CAPITAL COST

Score	Description	Selection
5	No incremental cost	
4	Up to $1 million	
3	$1-3 million	
2	$3-5 million	
1	> $5 million	✓

Summary:

Incremental capital cost per high horsepower (HHP) locomotive is estimated at $9 million. Capital costs are significantly lower for lower-horsepower passenger or yard switching locomotives. Incremental capital costs for yard switching locomotives (compared to Tier 4 gensets) are approximately $1 million.

Notes:

- Batteries are by far the most expensive component of battery electric locomotives. As of 2019, costs for battery cells were $160 per kWh, while battery packs were $350 per kWh. By 2035 however, these costs are expected to be $62 and $125 per kWh for cells and packs, respectively. During the last decade, lithium-ion battery prices decreased by roughly 10% each year.

- Although battery tenders are not in production in North America, the estimated cost per (6.2 MWh) tender is $4.2 million.

- Based on 2015 numbers, high horsepower locomotives (~4,400 HP) would each need to be replaced with 3 battery tenders with capacities of approximately 6 MWh (with the intent to only utilize 50% of their capacity to ensure depletion never occurs) to match performance metrics. So if a 100 car freight train used 2-4 locomotives, it would need 6-12 battery tenders (this estimate is based on 2015 numbers, and battery energy density has markedly improved since then, so the low-end of tender estimates should be considered). This would mean that a significant number of cars in each trainset would be non-revenue generating. At 3 battery tenders per HHP locomotive, incremental capital costs per locomotive would be roughly $9 million.

- Incremental capital cost estimates do not include charging or electrical transmission infrastructure at rail yards.

- The availability of raw materials (e.g., lithium, cobalt, nickel, manganese, graphite) needed to produce batteries will become a more pressing issue going forward, as there will be increasing competition for these materials from a growing number of transportation and other applications. However, alternative battery chemistries may allow for future battery production using alternative raw materials with greater availability.

- The energy density of lithium-ion batteries is expected to double by 2035, meaning battery size and weight will be halved.

- Most railways tend to use old, low-cost locomotives as yard switchers, so shifting from these to expensive low/zero emissions technologies would represent a significant opportunity to reduce GHG emissions, but at a high cost to railways.

Reference(s):

- Consultations: SRY, CP
- Literature review:
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)

- California Air Resources Board, 2016 (https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf)
- Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
- IEA, 2019 (https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The_Future_of_Rail.pdf)

C. IMPLEMENT — INFRASTRUCTURE REQUIREMENTS

Score	Description	Selection
5	No additional infrastructure required	
4	Existing infrastructure can be used, with modifications	
3	Significant new infrastructure required in yards only.	
2	Significant new infrastructure required in yards and other locations	✓
1	Significant new infrastructure required over entire network	

Summary:

Additional refueling/ charging infrastructure requirements include:

- Additional electricity transmission infrastructure servicing rail yards and other charging points
- Charging equipment at rail yards and other charging points (including en-route), which can include any combination of catenary, third rail, or discrete plug-in or DC connection charging infrastructure.
- Possible use of stationary storage systems (likely battery) to reduce demand charges (peak power consumption) at charging sites and reduce the carbon intensity of electricity used.

Notes:

- Batteries can be recharged while trains are in motion, using catenary or third rail contact systems on select stretches of track, or at rail yards using catenary, third rail, or discrete plug-in or DC connection charging infrastructure. If contact systems are sufficiently widespread on rail lines, it could mitigate the need for dedicated, plug-in charging infrastructure at rail yards.

- Association of American Railroads and Canadian railways recently launched a taskforce to assess overhead charging infrastructure for battery locomotives (due largely to safety requirements); however it was stated these systems would be difficult to implement on a widespread basis due to costs.

- Grid power requirements for charging batteries at rail yards can range from hundreds of kW to several MW, meaning that grid connections can be smaller than those needed for continuous contact (i.e., catenary) systems. Dedicated, slow-charge batteries can be used at rail yards to draw power from the grid and discharge it rapidly to battery tenders when required. Either way, significant grid upgrades will be required at rail yards and other charging sites. Utilities and battery OEMs will be key stakeholder groups to involve in any electrification implementation efforts.

- Due to the multi-modal nature of transport systems, opportunities exist to provide coordinated, shared battery recharging hubs (e.g., at transload terminals), potentially leading to economies of scale and reduced battery charging infrastructure costs to railways (through partnerships with on-road trucking companies and other stakeholders). Electrifying other equipment at shipping hubs could also improve the value proposition of charging infrastructure.

Reference(s):

- Consultations: CP, CN, NRC
- Literature review:
  - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
  - IEA, 2019 (https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The_Future_of_Rail.pdf)

D. OPERATE

Score	Description	Selection
5	>20% savings	
4	Up to 20% savings	✓
3	Par with diesel	
2	Up to twice the cost of diesel	
1	>2x	

Summary:

Costs to operate battery electric trains are expected to be roughly on par with diesel based on current equipment and fuel prices. By 2030, operational costs for battery electric trains are expected to offer significant cost savings relative to diesel.

Notes:

- Over a 15 year useful life of a 6.2 MWh battery tender, CARB's 2016 estimate suggests two rounds of battery cell replacement would be required, at a cost of $2.2M each. These costs are expected to decrease significantly by 2030. A more recent estimate from Network Rail suggests that battery cells should last up to 10 years before requiring replacement. In general, battery cell replacement is recommended when energy capacity declines to 80% of rated capacity (used batteries could be repurposed for stationary storage applications). As 3 battery tenders are estimated to be required to replace each HHP diesel locomotive, costs of battery cell replacement over a 15-20 year period would be ~$13.2 million. Diesel locomotives tend to be overhauled every 10-15 years (to improve fuel efficiency, reduce maintenance costs and downtime, improve tractive effort, and, in some cases, comply with regulations) at a cost of roughly $1.5-2 million. This means that incremental costs for maintaining equipment (excluding routine maintenance, which is expected to be less for battery propulsion) would be roughly $11.5 million based on current prices.

- Vehicles that draw power from electricity grids are significantly less expensive to power than those that use diesel. Battery powered rolling stock has the potential to reduce overall fuel costs by ~75% compared to diesel. Electricity prices also offer the advantage of having far less variability than diesel (making budgeting for fuel costs more predictable and straightforward). Average annual fuel costs for mainline freight locomotives operating in Canada are roughly $850,000 as of 2019 ($13 million over 15 years), assuming an average of 730,000 litres of diesel consumed per locomotive. Comparatively, electricity would be expected to cost roughly $3 million over 15 years, for a total fuel savings of roughly $10 million (or almost $14 million over 20 years).

- The incremental costs of equipment maintenance are estimated to be offset by reduced fuel costs over a 15-20 year timeframe. Excluding operational costs such as routine maintenance, labour, insurance, and reduced cargo capacity due to non-revenue railcars, the operational costs of battery electric are anticipated to be roughly on par with diesel. However, it should be noted that costs associated with diesel technologies are likely to increase over the long term (due to more stringent emissions standards, carbon pricing, etc.), while costs associated with battery electric technologies are expected to decrease (due to economies of scale, R&D, etc.).

- The cold and hot weather performance of lithium-ion batteries is expected to improve markedly by 2035. Currently, batteries can operate reliably in temperatures ranging from -20 to +60°C. By 2035, however, this is expected to improve to -40 to +80°C.

- Diesel locomotives have a significant number of moving parts (and over 200,000 internal parts) which require extensive and regular maintenance. Battery electric powertrains provide greater simplicity of equipment required to provide traction. Greater simplicity results in reduced downtime, a reduced need for depot stabling and reductions in the storage of spare locomotives. However, the benefits of reduced downtime for routine maintenance offered by battery electric could be offset by downtime required for recharging. Demonstrations could shed light on this and other operational issues.

- Battery charging infrastructure could have unforeseen maintenance costs, which will need to be assessed through demonstrations and factored into total operational costs.

- Conductors, technicians, and yard staff would need to undergo training related to maintenance, fueling and safety of battery electric technology, but associated costs are not expected to significantly influence total operational costs on an ongoing basis.

Reference(s):

- Consultations: CP, SRY, CN
- Literature review:
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - California Air Resources Board, 2016 (https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf)
    - Railway Association of Canada, Locomotive Emissions Monitoring Report, 2019
    - Railway Age, 2020 (https://www.railwayage.com/mechanical/locomotives/does-rebuilding-locomotives-beat-buying-new/)

2. CARBON REDUCTION POTENTIAL

A. GHG REDUCTION POTENTIAL

Score	Description	Selection
5	>80%	✓
4	50-80%	
3	30-50%	
2	10-30%	
1	<10%	

Summary:

As compared with a baseline of diesel, GHG reductions on a per-equipment basis are estimated at more than 80%.

Notes:

- As with catenary electric systems, GHG reduction potential is largely dependent on the carbon intensity of local electricity grids. As of 2018, roughly 82% of electricity generated in Canada was emissions-free, and this number is expected to grow as coal phase-outs and renewable energy deployments continue to accelerate.[30]

- Life-cycle accounting should incorporate the net impact of required battery production and decommissioning. Recent estimates, which include raw material extraction and refining (the most carbon-intensive link in battery supply chains), suggest a global average of 65 kg of CO2e emissions for every kWh of battery produced.[31] For each 6.2 MWh tender, this would equate to roughly 400 t of GHG emissions. However, the GHG emissions intensity of battery production decreases eight-fold in scenarios where electricity and transportation networks are powered by renewable energy. This suggests that battery supply chains in Canada would have a significant GHG advantage over most other countries, including the US in which only 40% of electricity generation is emissions-free.[32]

- Battery-powered trains would significantly reduce or eliminate CAC emissions from rail operations. They would also significantly reduce noise and vibration issues. While these factors are not captured by the assessment framework, they are highly important from social and health perspectives. Rail yards are often located in or near disadvantaged communities that suffer heavy burdens from air pollution. The US EPA's Tier 4 emission standard for locomotives, which took effect in 2015, will return more than ten times the cost of locomotives through improved public health.

- Wabtec's FLXdrive 2.4 MWh battery electric locomotive has reduced fuel consumption by 10% when used in active service as a supplemental power source in a diesel-battery electric consist. A 6+ MWh unit used in the same role would be expected to reduce fuel consumption and emissions by 30%.

- Progress Rail's EMD Joule yard switcher locomotive has no in-service emissions.

- Capturing power through regenerative braking could enhance train fuel efficiency by up to 15%. Efficiency gains are most pronounced on routes with frequent starts and stops (e.g., passenger, short-haul) or changes in gradient, so long-haul freight may not see these levels of efficiency benefits from regenerative braking.

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30 NRCan, 2020. https://www.nrcan.gc.ca/science-and-data/data-and-analysis/energy-data-and-analysis/energyfacts/energy-and-greenhouse-gas-emissions-ghgs/20063

31 Hoekstra A. (2019). The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions. Joule, Vol 3. Issue 6. (https://www.sciencedirect.com/science/article/pii/S2542435119302715#)

32 IEA, 2021. https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

- Electric locomotives are 90-95% efficient (i.e., 90-95% of the energy allocated to them is converted into tractive force), even accounting for line losses and engine transformers. Modern conventional diesel locomotives (which are technically diesel-electric hybrids), by comparison, are roughly 40% efficient (with most energy lost as waste heat).

- A US study found that increasing the utilization of rail by 50% for the movement of freight over 800 km would reduce GHG emissions by 60 Mt per year. The combination of zero-emission locomotives and shifting more freight to rail would reduce GHG emissions by up to 120 Mt per year. Reducing the carbon intensity of the US electricity grid would lead to even greater reductions.

Reference(s):

- Consultations: CN, Wabtec, NRC, SWRI
- Literature review:
    - California Air Resources Board, 2016 (https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf)
    - Network Rail, 2020 (https://www.networkrail.co.uk/wpcontent/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-InterimProgramme-Business-Case.pdf)
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)
    - House Committee on Transportation and Infrastructure, 2021 (https://transportation.house.gov/imo/media/doc/Santana%20Testimony.pdf)
    - Progress Rail, 2021 (https://www.progressrail.com/en/Segments/RollingStock/Locomotives/FreightLocomotives/EMDJoule.html)
    - Solutionary Rail, 2017 (https://www.solutionaryrail.org/buybook)

B. UPTAKE/ APPLICABILITY

Score	Description	Selection
5	Well-suited to mainline freight rail	
4	Partially suited to mainline freight rail	
3	Suited to yard equipment	✓
2	Well suited to passenger rail	
1	Not suited to mainline freight rail, only partially suited to passenger rail	

Summary:

While battery electric trains are technically feasible for all types of rail, key constraints revolve around battery energy density and resulting issues around size, weight, costs, and the total number of tenders required for long haul freight and passenger service. Current applications are limited to switching and yard service, and potentially short haul (<400 km), low-speed routes with ample dwell time (for both passenger and freight).

Notes:

- Due to the volume of energy storage required, battery electric trains are currently cost prohibitive for mainline freight. They are not expected to be feasible prior to 2030 or 2035. Their feasibility rests largely on advances in battery and charging technologies, both of which could be assisted by developments in the road transport or stationary storage sectors.

- Due to extreme power requirements, mainline freight will likely be the last rail mode for which the adoption of battery electric propulsion is feasible. As over 90% of rail emissions in Canada stem from freight line-haul services, this limits the ability of battery electric to contribute to deep rail decarbonization in the near and medium terms. Batteries can play key decarbonization roles in hybrid applications, however (e.g., through supplemental propulsion, idle reduction and regenerative braking). Battery tenders can be added to conventional electric trains for propulsion on stretches of track that lack continuous contact systems (e.g., tunnels, spurs, etc.).

- Green Goat yard switching locomotives have been demonstrated in a variety of scenarios since 2001. Some have been retired due to battery replacement costs and operational issues (they utilize lead-acid batteries comparable to those used in heavy-duty trucking). Battery replacements were required in some cases due to improper thermal fittings.

- It was noted that for highly trafficked corridors (e.g., Toronto-Montreal), battery electric freight rail could be feasible if catenary-based "opportunity" charging could take place in select areas while trains are in motion.

- Bi-mode trains using batteries in a limited capacity are currently available for all rail applications. Wabtec's FLXdrive has seen 16,000 km of active freight service in a diesel-battery electric consist.

- Top speeds of battery trains are currently limited to approximately 160 km/h to optimize the efficiency of batteries. While this poses a barrier to high speed rail, this limit is consistent with the top speeds employed across Canada's rail network.

- Yard switching tends to represent a small share of emissions for mainline freight railways, yet a relatively large share of emissions for short lines. On a company level, battery electric yard switchers would therefore offer the biggest emissions benefits to short lines. Costs, however, remain a major challenge, and one expert noted that short lines could be the last railways to implement zero emission technologies.

- Interoperability of propulsion technologies across the entire continent is essential for mainline railways.

Reference(s):

- Consultations: SRY, CN, CP, UBC, CUTRIC, Bob Oliver, NRC, Paul Blomerus, SWRI
- Literature review:
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)
    - California Air Resources Board, 2016 (https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf)
    - Railway Association of Canada, Locomotive Emissions Monitoring Report, 2019
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - Rail Safety and Standards Board, 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)
    - House Committee on Transportation and Infrastructure, 2021 (https://transportation.house.gov/imo/media/doc/Santana%20Testimony.pdf)

3. CHALLENGES

A. OPERATION

Score	Description	Selection
5	Equal to or better than diesel	
4	Low level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	✓
3	Moderate level of complexity in maintaining system reliability and exisiting infrastructure and/or maintaining equipment.	
2	High level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	
1	Significant risk to reliability. Significant risk of loss of an asset.	

Summary:

Key operational challenges include range, downtime required for charging, charging infrastructure, and flexibility of operation/interoperability.

Notes:

- In the initial years of deployment, it can be assumed that each battery tender would only be allowed a depth of discharge of 50% to account for railway industry operating and safety margins.
- There is a trade-off between range and total trainset weight related to total battery capacity (i.e., more weight leads to shorter ranges). This can be compounded by the weight of battery tenders themselves relative to the total weight of a trainset. Battery weight can decrease maximum payloads on certain routes which have weight limits based on rail gauge and/or type of substrate.
- A major challenge is enhancing the overall efficiency of battery electric trainsets and the energy density of batteries. Enhanced efficiency and battery energy density will mean that fewer and/or smaller tenders will be required, which in turn will reduce costs.
- The energy density of lithium-ion batteries is expected to double by 2035, meaning battery size and weight will be halved.
- The roll out of technologies such as battery electric propulsion for mainline freight would have to be coordinated at a continent-wide scale. There are horsepower agreements between railways throughout the continent as well as shared assets (which must be compatible with propulsion technologies deployed). Yards owned by railways must also be capable of servicing and refueling trains from other railways, so extensive coordination would be required.
- Operational challenges can be addressed in part through the use of ultracapacitors to complement battery electric technology. These are able to capture all braking power (which can be too much, too fast for batteries alone) and can reduce the size and capacity demands of battery tenders by providing some of the power required for acceleration.

Reference(s):

- Consultations: SRY, CP, CN, Peter Eggleton, SWRI
- Literature review:
    - California Air Resources Board, 2016 (https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%20 20200117.pdf)

- Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)

B. REFUELING

Score	Description	Selection
5	Equal to or better than diesel	
4	Moderate complexity to supply chain and/or refueling requirements	
3	Complex supply chain, >2x refuel/recharge time/frequency	✓
2	Intermittent availability issues, up to 2x refuel/ recharge time/ frequency	
1	Frequent availability issues, >2x refuel/rechg. time/ frequency	

Summary:

For applications aside from yard switching and some short hauls, most experts agree that charging/refueling would have to take place both at yards and while in transit. There are many possible pros and cons to this approach. Pros include the ability to utilize low-carbon, low-cost electricity wherever it is most abundant, and cons include costs associated with a decentralized charging network, and the number of partnerships required to secure an adequate amount of power across a national (and continental) network.

Notes:

- Refueling/charging infrastructure would need to be capable of charging multiple tenders simultaneously. Switching depleted tenders with fully charged tenders at rail yards would not be feasible due to the high costs of additional/redundant assets.

- Downtime related to charging presents a significant barrier. Unless a significant amount of charging can occur while trains are in transit, this barrier may be prohibitive. However, battery power density is expected to increase four-fold by 2035, meaning recharging time will decrease significantly.

- In cases of power outages, battery tenders can be used to supply power to catenary networks and to “rescue” stranded trains. They can also be used to reduce peak loads in rail yards by serving as a supplemental power source.

- Overnight charging at rail yards could take advantage of off-peak baseload electricity, which tends to have lower carbon intensity (and sometimes lower prices) than electricity produced during the day.

- Progress Rail has developed a commercially available battery electric switcher, the EMD Joule. However railways consulted stated that downtime required for charging is currently prohibitive. Though the batteries perform well in terms of acceleration and deceleration, another concern was that frequent charge-discharge cycles could degrade batteries. Battery chemistry used in the Joule is currently LiFePO.

Reference(s):

- Consultations: CP, CN, Paul Blomerus, SWRI
- Literature review:
    - California Air Resources Board, 2016 (https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf)
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - Progress Rail, 2021 (https://www.progressrail.com/en/Segments/RollingStock/Locomotives/FreightLocomotives/EMDJoule.html)

C. SAFETY & REGULATORY COMPLIANCE

Score	Description	Selection
5	Equal to or better than diesel	
4	Some additional training and/or regulatory development required	
3	Additional training & certification and/or regulatory development required	✓
2	Safety concerns and/or significant regulatory development required	
1	Significant safety concerns, including to public and/or complete regulatory development required	

Summary:

High voltage equipment can pose safety hazards, which will require a variety of training methods and safety measures to address. Safety management systems for battery electric propulsion will need to be developed and adopted by governments throughout North America prior to meaningful deployment.

Notes:

- High voltage equipment can pose significant safety hazards for yard workers. Depending on the design of equipment, however, required levels of safety may be met using passive design and/or detection and control systems.

- Train operators and technicians need safety manuals on emerging technologies like battery electric propulsion. Railways expressed the need for more information on safety standards and best practices related to charging batteries by third-rail, overhead wires or plug-in technologies.

- Safety management systems for emerging rail technologies can take 10-20 years to get through regulatory agencies in the US. The Canadian process is more targeted and streamlined, but technologies would have to be approved on both sides of the border prior to meaningful implementation.

- One battery-related challenge that will likely be addressed by 2035 is the elimination of the risk of thermal runaway, which can pose a safety issue by potentially leading to fires. This risk has been largely mitigated already.

- The Locomotive Maintenance Committee provides guidance on interoperability and safety issues in North America. TTCI (Transportation Technology Centre Inc.) is a US institute that conducts trials to ensure locomotives and cars are safe and robust enough to be deployed. TTCI is currently testing both the EMD Joule and FLXdrive battery electric locomotives.

Reference(s):

- Consultations: CP, CN, Bob Oliver
- Literature review:
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)

APPENDIX F – DETAILED TECHNOLOGY ASSESSMENT: CATENARY ELECTRIC

1. COST

A. DEVELOP

Score	Description	Selection
5	Commercially available: no development cost.	
4	Nearing commercial availability: development costs <$10 million	✓
3	$10-50 million	
2	$50-75 million	
1	Significant development required including complex challenges: >$75 million	

Summary:

Total cost to develop, test and certify the technologies required is estimated to be roughly $10 million in a North American context. In general, the technologies associated with catenary electrification of all types of rail are technically mature.

Notes:

- Catenary systems are in use in freight rail networks in Europe, Asia, Africa and Australia. These networks support some of the biggest, heaviest trains in operation globally. Based on current usage, the technical requirements in the Canadian context may be slightly different due to additional power requirements in regions such as the Rockies, and the generally lower frequency of rail service.

- Costs associated with the development of technologies appropriate for use in Canadian catenary systems are expected to be under $10 million.

- Due to the integrated nature of North American rail networks, a variety of stakeholders would be required to contribute to development solutions, including national governments, electrical utilities and associations, railway OEMs, and railways themselves.

Reference(s):

- Consultations: CN, CUTRIC, Paul Blomerus
- Literature review:
    - CUTRIC, 2019 (https://cutric-crituc.org/wp-content/uploads/2020/06/FINAL-Rail-Innovation-in-Canada-Top-10-Technology-areas-for-Passenger-and-Freight-Rail-EA-2.pdf)

- Paul Blomerus, Electrification of Freight Rail Sector in Canada, 2019 (provided by Transport Canada)
- Solutionary Rail, 2020 (https://www.solutionaryrail.org/what_types_of_locomotives_will_be_required_for_u_s_long_haul_freight_trains)

B. IMPLEMENT — CAPITAL COST

Score	Description	Selection
5	No incremental cost	
4	Up to $1 million	✓
3	$1-3 million	
2	$3-5 million	
1	> $5 million	

Summary:

Incremental capital costs per locomotive are estimated at less than $1 million for retrofitted diesel locomotives, to up to $3 million for new electric locomotives, until the market becomes established in North America.

Notes:

- Infrastructure costs would be prohibitive for Canadian rail companies to bear alone. However, if the infrastructure was in place the costs to convert existing locomotive fleets would be manageable, and would rapidly be recouped through fuel savings. Diesel engines could be downsized for use in limited applications within catenary networks (e.g., loading/unloading zones, certain sidings), as is often done in Europe.

- In India, diesel locomotives are typically refurbished once they see 18 years of service. India's new decarbonization strategy would see diesel locomotives retrofitted for electric catenary systems during scheduled refurbishment. Estimated costs per locomotive are $330,000 using a customized process, which is less than half of the cost of refurbishing a diesel engine.

- The cost of new electric locomotives is currently 20-30% less than the cost of new diesel locomotives in mature markets (e.g., EU, UK). However, costs in North America would likely currently be greater than Tier 4 diesel locomotives (which currently cost roughly $3-4 million each) until the market grows.

Reference(s):

- Consultations: CP, SRY
- Literature review:
    - Solutionary Rail, 2017 (https://www.solutionaryrail.org/buybook)
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - Business Standard, 2018 (https://www.business-standard.com/article/indian-railways/how-railways-plans-to-convert-diesel-locos-to-electric-at-cheaper-cost-118092400949_1.html)
    - Train Conductor Headquarters, 2018 (https://www.trainconductorhq.com/how-much-do-locomotives-cost/)

C. IMPLEMENT — INFRASTRUCTURE REQUIREMENTS

Score	Description	Selection
5	No additional infrastructure required	
4	Existing infrastructure can be used, with modifications	
3	Significant new infrastructure required in yards only.	
2	Significant new infrastructure required in yards and other locations	
1	Significant new infrastructure required over entire network	✓

Summary:

Additional refueling/ charging infrastructure requirements include:

- 50 kV catenary systems would be required for freight rail, while 25 kV or 50 kV lines would be appropriate for passenger.
- High-voltage transmission lines with capacities of 115 to 345 kV.
- New electrical sub-stations would likely need to be built every 32-80 km of track to supply the required power. New electricity generation and/or storage infrastructure could be required in certain regions. High voltage transmission towers may need to be constructed in remote regions, as local grids could lack adequate power.
- Tunnels, bridges, sidings and other existing rail infrastructure would require extensive modifications to accommodate overhead wires. Onboard batteries or the selective use of third rail systems could mitigate the need for such modifications in some circumstances.
- Additional railway switches might be required to mitigate potential disruptions from power outages.

Notes:

- In a 2020 UK assessment, the infrastructure costs per km of track for shared freight and passenger rail lines were estimated to be $1.7-4.3 million (with the lower end expected outside of major cities). These numbers are consistent with a GO Rail electrification feasibility study which found estimated costs per km for passenger rail to be $2 million (in 2018 dollars). The IEA estimated freight rail infrastructure costs per km at $1.6 million, however this was based on global averages, and most countries employ smaller, lighter freight trains than those used in North America (which may require higher voltage lines that come with higher costs).

- Total lifecycle costs for catenary systems are projected to be lower than battery electric or hydrogen fuel cell on intensively-used rail lines (in Europe, this means lines where four or more three-car DMU's operate per hour). The IEA projected catenary systems could be cost-competitive with diesel over a ten year period on lines where traffic levels are more than two trains per hour.

- A 2019 assessment for Transport Canada found that infrastructure costs associated with electrifying over 10,000 km of the most heavily-trafficked freight lines between Vancouver and Montreal would total roughly $10.5 billion, yet would offer Canada's Class 1 freight railways over $750 million per year in fuel savings, with an estimated payback period of roughly 14 years.

- Costs are currently prohibitive for rail lines in remote regions, and many experts state that infrastructure costs are prohibitive for the majority of Canada's rail network, especially given its vast extent and lack of density. Infrastructure costs to electrify mainline freight would be in the billions of dollars. However, because catenary technology is already deployed in many parts of the world, cost estimates should be more accurate than for other alternative technologies such as hydrail.
- Infrastructure costs for heavily used corridors, such as Windsor to Quebec City, could be economically feasible. In such cases, catenary systems would have to be paired with complementary modes of propulsion (e.g., diesel bi-mode, hydrogen fuel cell, battery electric) for trains operating outside of an electrified corridor.

- 50 kV AC catenary systems have been successfully deployed in Canada before, on the Tumbler Ridge dedicated coal mine route in BC.

Reference(s):

- Consultations: VIA Rail, CP, CN, CUTRIC, TC, Bob Oliver, Peter Eggleton
- Literature review:
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - Paul Blomerus, Electrification of Freight Rail Sector in Canada, 2019 (provided by Transport Canada).
    - Solutionary Rail, 2017 (https://www.solutionaryrail.org/buybook)
    - IEA, 2019 (https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The_Future_of_Rail.pdf)
    - 995 Days - Construction of the Tumbler Ridge Branch Line, 2014 (https://www.youtube.com/watch?v=Uw8WZ7pBF1k)

D. OPERATE

Score	Description	Selection
5	>20% savings	✓
4	Up to 20% savings	
3	Par with diesel	
2	Up to twice the cost of diesel	
1	>2x	

Summary:

As compared with a baseline of diesel, catenary rail would be expected to generate an operational savings of 25-50%.

Notes:

- In addition to electricity and maintenance costs, training and certification for staff would add to operational costs.

- New infrastructure required for catenary electric and other alternative propulsion technologies would likely entail additional and ongoing costs to maintain (e.g., maintaining catenary tension, flood prevention in areas with third rails).

- Electric locomotives would be expected to have significantly lower maintenance costs than diesel platforms. Electric motors are well established in rail applications, and last for decades with minimal maintenance. Electric units have a greatly reduced number of moving parts relative to diesel counterparts, which reduces downtime and costs related to spare parts and redundant backup units. A Hungarian study found that they break down 40% less than diesel counterparts, and multiple European studies found that overall operating costs are reduced by 25-35%. Over the long term, following the build out of required infrastructure, they are expected to offer railways significant operational savings relative to diesel.

- Catenary systems could offer the potential for railways to return excess power (e.g., from regenerative braking) to the grid, which could reduce net fuel costs. Excess power could also be transferred to stationary energy storage systems, especially in areas with steep gradients.

- Relative to diesel, catenaries are expected to offer Canadian railways fuel cost savings between 71 and 85%, depending on the region. The cost of diesel is expected to grow in the future, further widening this divide. The use of regenerative braking can reduce electricity costs further.

- The average mainline freight locomotive in Canada consumes roughly 730,000 L of diesel fuel each year, at an estimated cost of $850,000. At a 75% reduction in costs, a fuel savings of roughly $637,500 per locomotive could be realized each year. Over a 30 year timeframe, this would equate to fuel savings of over $19 million per freight locomotive. As Canada's current fleet of Class 1 freight locomotives currently numbers approximately 2,660, the combined savings in fuel costs through a switch from diesel to catenary over a 30 year timeframe would be over $50 billion. That does not factor in projected increases in the price of diesel, changes in GTK (which has seen a compound annual growth rate of 2.4% since 1990), or efficiency improvements in diesel locomotives. The US EIA projects that petroleum diesel prices will increase by 21% by 2030 and by 27% by 2035. By comparison, electricity prices tend to be much more stable over long timeframes.
- With catenary systems, railways would essentially be paying for long-term fuel costs upfront, as part of capital costs. It is possible that creative financing mechanisms from government could help to bridge this divide and spread out costs over long timeframes.

Reference(s):

- Consultations: CP, CUTRIC, Peter Eggleton, NRC
- Literature review:
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - Solutionary Rail, 2017 (https://www.solutionaryrail.org/buybook)
    - US DOE, 2020 (https://www.hydrogen.energy.gov/pdfs/review20/ta034_ahluwalia_2020_o.pdf)
    - Railway Association of Canada, 2021. Locomotive Emissions Monitoring Report: 2019
    - Paul Blomerus, Electrification of Freight Rail Sector in Canada, 2019 (provided by Transport Canada)

2. CARBON REDUCTION POTENTIAL

A. GHG REDUCTION POTENTIAL

Score	Description	Selection
5	>80%	✓
4	50-80%	
3	30-50%	
2	10-30%	
1	<10%	

Summary:

As compared with a baseline of diesel, GHG reduction on a per-equipment basis is estimated at more than 80%.

Notes:

- Reduction potential is largely dependent on the carbon intensity of Canada's electricity grid. As of 2018, roughly 82% of electricity generated nationally was emissions-free, and this number is expected to grow as coal phase-outs and renewable energy deployments continue to accelerate.[33]

33 NRCan, 2020. (https://www.nrcan.gc.ca/science-and-data/data-and-analysis/energy-data-and-analysis/energyfacts/energy-and-greenhouse-gas-emissions-ghgs/20063)

- Life-cycle accounting should incorporate the impact of cement and steel production needed to facilitate catenary construction, as these are both carbon-intensive industries. If onboard or stationary storage batteries are required to complement catenary systems, their production should also be factored into life-cycle assessment. However, a comparative benefit of conventional catenary systems is that they avoid the use of large onboard batteries, which can have significant carbon footprints and will potentially face supply bottlenecks due to competition from other transport modes and economic sectors. Catenary systems represent a decarbonization solution unique to the rail sector.

- Catenary systems would significantly reduce or eliminate CAC emissions from rail operations. They would also significantly reduce noise and vibration issues. While these factors are not captured by the assessment framework, they are highly important from social and health perspectives. Rail yards are often located in or near disadvantaged communities that suffer heavy burdens from air pollution. The US EPA's Tier 4 emission standard for locomotives, which took effect in 2015, will return more than ten times the cost of locomotives through improved public health (suggesting a role for public investment in clean rail infrastructure).

- Capturing power through regenerative braking could enhance train fuel efficiency by 15%, although this would require the use of batteries or bi-directional energy flow between trains and local electrical grids.

- Electric locomotives tend to be significantly lighter than diesel, battery electric, or hydrogen fuel cell units as they do not have to carry their own power sources. This reduced axle load can translate into reduced track wear and reduced infrastructure renewal frequency. A UK study found that the reduced weight of catenary electric locomotives meant that they could carry 20% more cargo than diesel equivalents and complete journeys 10% faster.

- Electric locomotives are 90-95% efficient (i.e., 90-95% of the energy allocated to them is converted into tractive force), even accounting for line losses and engine transformers. Modern conventional diesel locomotives (which are technically diesel-electric hybrids), by comparison, are up to 40% efficient (with most energy lost as waste heat).

- The UK's Rail Industry Decarbonisation Taskforce stated that catenary electrification is currently the only viable solution to get the rail sector to net zero by 2050.

- A US study found that increasing the utilization of rail by 50% for the movement of all freight on routes over 800 km would reduce GHG emissions by 60 Mt per year. The combination of zero-emission locomotives and shifting more freight to rail would reduce GHG emissions by up to 120 Mt per year. Reducing the carbon intensity of the US electricity grid would lead to even greater reductions.

Reference(s):

- Consultations: SRY, CN, CP, Paul Blomerus, Bob Oliver
- Literature review:
    - Rail Industry Decarbonisation Taskforce, 2019 (https://www.researchgate.net/publication/334671578_Rail_Industry_Decarbonisation_Taskforce_FINAL_REPORT_TO_THE_MINISTER_FOR_RAIL)
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - Solutionary Rail, 2017 (https://www.solutionaryrail.org/buybook)
    - House Committee on Transportation and Infrastructure, 2021 (https://transportation.house.gov/imo/media/doc/Santana%20Testimony.pdf)

B. UPTAKE/ APPLICABILITY

Score	Description	Selection
5	Well-suited to mainline freight rail	✓
4	Partially suited to mainline freight rail	
3	Suited to yard equipment	
2	Well suited to passenger rail	
1	Not suited to mainline freight rail, only partially suited to passenger rail	

Summary:

Electric catenary systems are suitable for all types of rail and are currently deployed throughout much of the world in both freight and passenger applications. They are optimal for highly trafficked routes due to financial considerations however they are technically feasible for any rail application.

Notes:

- Well-suited to high-traffic passenger rail corridors (e.g., Windsor to Quebec City).

- Potential applications in yards, short lines and on specific, dedicated runs (e.g., loops between primary resource hubs and ports).

- Catenary systems can be used to charge battery/hybrid locomotives on certain sections of track.

- The interoperability of the entire North American freight rail network is of critical importance. Alternative propulsion technologies deployed cannot be limited to Canada. Current freight rail assets have been standardized to the greatest extent possible to optimize flexibility (in terms of commodities, access to different regions, shared rail assets, etc.), and a comparable level of flexibility would need to be maintained.

Reference(s):

- Consultations: VIA Rail, SRY, CN, CP, CUTRIC, TC
- Literature review:
    - Paul Blomerus, Electrification of Freight Rail Sector in Canada, 2019 (provided by Transport Canada).

3. CHALLENGES

A. OPERATION

Score	Description	Selection
5	Equal to or better than diesel	
4	Low level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	
3	Moderate level of complexity in maintaining system reliability and exisiting infrastructure and/or maintaining equipment.	
2	High level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	✓
1	Significant risk to reliability. Significant risk of loss of an asset.	

Summary:

For mainline freight rail, a shift to electric catenary systems would have to be coordinated on a continent-wide basis, otherwise operational challenges would be prohibitively complex. As in other parts of the world, a rollout of catenary systems might best be reserved for high-volume rail lines, and complemented by other low-carbon technologies on lower-volume lines. On dedicated, closed loop routes or for highly trafficked passenger routes, operational challenges would be expected to be only slightly greater than those of diesel locomotives, assuming that required equipment and infrastructure was in place. There are a wealth of global examples of smoothly functioning electric catenary rail networks, however they would necessitate an overhaul of infrastructure, equipment and practices in North America that would take time to refine and optimize.

Notes:

- Compatibility challenges with catenaries and other infrastructure such as tunnels, bridges, rail sidings servicing warehouses or manufacturing plants, loading/unloading sites, etc., can be significant. Such challenges would significantly complicate, and add to the costs of, a network-wide roll out of catenary systems. It was suggested that electrified third rail systems could be used in certain situations, or batteries that could power trains over short distances and capture power from regenerative braking. Dual-mode/bi-mode (electric and diesel) locomotives could offer flexibility but come with added costs and added weight.
- Overhead wires could limit or negate the use of tri-level, bi-level and double-stacked railcars. However there are examples of rail networks that use catenary systems that can accommodate double-stacked railcars, including a stretch of CSX's US east coast network, and almost 4,000 km of track in Indian Railways' network (with more expansions planned) In such networks, which are more costly than conventional catenary networks, overhead wires are suspended roughly 8 metres above track level.
- Use of catenaries could complicate climate adaptation by railways, as there are reported issues with icing in the winter and of sagging wires in extreme heat.
- Continent-wide rail infrastructure and propulsion interoperability is critical for freight rail. Technologies deployed in Canada would have to be adopted in the US as well to see widespread uptake. If catenary electrification were to roll out on a piecemeal basis it could lead to bottlenecks at sites where electric locomotives have to be swapped for conventional diesel-electric hybrids, or vice-versa.
- Starting up multiple locomotives at the same site at the same time could cause short outs within local electricity grids, so significant coordination with local electrical utilities would be required. The uneven use of high voltage electricity could create significant challenges from a load balancing perspective.
- Catenary electric units are susceptible to local power outages, which can lead to significant and costly delays.
- Many of these challenges were identified by the Association of American Railroads (AAR) in a recently published fact sheet on electric catenary systems. Some of the issues identified by AAR were rebutted by railway experts (e.g., here and here), though it is agreed that many of the issues pose significant operational challenges.

Reference(s):

Consultations: VIA Rail, CP, Paul Blomerus, SRY, NRC, TC
Literature review:

- Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
- California Air Resources Board, 2016 (https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf)
- Solutionary Rail, 2017 (https://www.solutionaryrail.org/buybook)
- Association of American Railroads (AAR), 2020 (https://www.aar.org/wp-content/uploads/2020/12/AAR-Electrification-Fact-Sheet.pdf)
- International Railway Journal, 2020 (https://www.railjournal.com/freight/indian-railways-launches-electric-double-stack-container-operation/)

B. REFUELING

Score	Description	Selection
5	Equal to or better than diesel	
4	Moderate complexity to supply chain and/or refueling requirements	
3	Complex supply chain, >2x refuel/recharge time/frequency	
2	Intermittent availability issues, up to 2x refuel/ recharge time/ frequency	✓
1	Frequent availability issues, >2x refuel/rechg. time/ frequency	

Summary:

While "refueling" in the case of catenary electric systems is simply a matter of maintaining a connection to live wires, supplying adequate power to those wires on a consistent basis presents a series of challenges unique to this propulsion technology. While the technology also presents a series of unique opportunities related to the "electrify everything" movement, it would require the creation of a novel fuel supply chain for the rail sector.

Notes:

- Power demands for freight rail in North America could exceed those deployed in other parts of the world that use catenary systems to power rail networks. However, countries such as China, Russia, South Africa and Australia currently utilize catenary-powered freight trains that are heavier than typical line-haul freight trains used in North America. All of those networks use either 25 or 50 kV systems, the latter of which are used to provide additional power or lengthen the distance between electrical sub-stations.

- Local power outages could lead to significant delays and congestion.
- Bi-directional energy technology could allow trains to deliver excess power (e.g., from regenerative braking) back to the grid, but this technology is still pre-commercial.
- Certain areas might require additional generation capacity or sub-stations to deliver necessary power to catenary systems. Significant coordination with electrical utilities would be necessary.

Reference(s):

- Consultations: TC, NRC
- Literature review:
    - California Air Resources Board, 2016 (https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf)
    - Solutionary Rail, 2020 (https://www.solutionaryrail.org/what_types_of_locomotives_will_be_required_for_u_s_long_haul_freight_trains)

C. SAFETY & REGULATORY COMPLIANCE

Score	Description	Selection
5	Equal to or better than diesel	
4	Some additional training and/or regulatory development required	
3	Additional training & certification and/or regulatory development required	
2	Safety concerns and/or significant regulatory development required	✓
1	Significant safety concerns, including to public and/or complete regulatory development required	

Summary:

Rail yard workers, technicians and crew would require training on the safe operation and maintenance of high voltage equipment. Updated regulatory standards and certifications would be required for catenary systems powering North American freight trains. Educational campaigns and safety messaging for the general public would need to be delivered.

Notes:

- The Canadian Standards Association (CSA) published the standard *Railway Electrification Guidelines* (CAN/CSA-C22.3 NO. 8-M91) in 1992 and revised it in 2003.
- High voltage catenary systems can pose significant safety hazards for yard workers. Likewise, electrified third rail systems would pose safety hazards to anyone able to access rail infrastructure. Safety standards for staff and the general public, as well as education campaigns, would be required.
- Close coordination with US and Mexican policy-makers and railways would be essential to facilitate the rollout of catenary systems for freight rail.
- Along with safety standards, feasibility studies and demonstrations will likely need to precede commercial rollout. One estimate suggested that it could be 15 years before meaningful implementation can begin. Another suggested that the funding, design, permitting and construction of a freight catenary system nationally could take 30 years.
- Because catenary systems are already deployed globally, safety and compliance standards from other jurisdictions could be used as a starting point for Canada.

Reference(s):

- Consultations: SRY, CN, CUTRIC, TC
- Literature review:
    - Paul Blomerus, *Electrification of Freight Rail Sector in Canada*, 2019 (provided by Transport Canada).

APPENDIX G – DETAILED TECHNOLOGY ASSESSMENT: HYDROGEN FUEL CELL

1. COST

A. DEVELOP

5	Commercially available: no development cost.	
4	Nearing commercial availability: development costs <$10 million	
3	$10-50 million	
2	$50-75 million	✓
1	Significant development required including complex challenges: >$75 million	

Summary:

Total cost to develop, test and certify is estimated at $50-75 million,[34] although there is a great deal of uncertainty surrounding hydrail development costs required for the technology to reach commercial readiness for all rail applications in North America.

Notes:

- Hydrogen fuel cell technology is already viable for passenger and yard applications (see section 2B), as well as other transportation modes, but has yet to be trialled for mainline freight. Even if the testing of hydrail technologies for mainline applications were to begin today, it would likely be 4-5 years minimum before a hydrogen train could be approved for mainline use. One expert noted that while HFCs are at a high state of technological readiness, HFC locomotives are not.

- CP is currently retrofitting a former diesel-electric linehaul freight locomotive into an HFC switcher locomotive, replacing its diesel engine and traction alternator with a fuel cell stack (six 200 kW modules) and battery technology to power its electric traction motors. The HFCs will be manufactured by Ballard. The locomotive should be ready to begin active service by the end of 2022. CP is seeking partnerships with rail OEMs for further hydrail development.

- Retrofitting existing locomotives with HFCs and batteries is a viable option in lieu of purpose-built HFC locomotives. Diesel engines tend to be rebuilt every 10-15 years, so retrofitting could occur at these junctures. Removing diesel engines should provide enough space for HFCs and batteries (hydrogen storage space is a constraint which is discussed in sections 2B and 3B). Retrofits make sense in the near and medium terms,

34 All monetary figures in this assessment have been converted to CAD for ease of comparison.

and can be used to inform the development of a new generation of locomotives in the long term. However, retrofitting is expected to cost almost as much as purpose-built HFC locomotives. As with other technologies, production costs are expected to decline significantly with scale.

- Wabtec, Genesee & Wyoming (G&W) and Carnegie Mellon University are seeking to collaborate with the US government to form and co-fund a public-private partnership that will focus on zero-emission railway technology research, demonstration and commercialization, with a focus on battery electric and HFCs with on-site hydrogen generation solutions. This proposed Freight Rail Innovation Institute would commit to developing the technologies through the partnership by 2030.

- Experts are divided on the longevity of fuel cell stacks in rail applications. Several suggested they would require replacement every 5-10 years, while others stated they should last as long as diesel engines. More RD&D is required to determine a more precise replacement timeline under real-world duty cycles. CAD Railway Industries in Montreal was suggested as a possible site for endurance testing HFC locomotives.

- Section 3C details some of the testing and certification challenges posed by hydrail. In some cases, standards and practices developed for hydrail in jurisdictions such as the EU can be used as a starting point.

- Canada is a globally-leading manufacturer of HFC technology, so hydrail development would be likely to offer economic development benefits nationally.

Reference(s):

- Consultations: CP, Bob Oliver, UBC, Ballard, CUTRIC, Peter Eggleton, TC
- Literature review:
    - TELLIGENCE Group, 2020 (https://static1.squarespace.com/static/5b193e81cef372d012efda72/t/5f7b42e1a96b3a18f431f9f1/1601913574512/Hydrail+Prerequisites+-+2020+Final+Revision-converted.pdf)
    - House Committee on Transportation and Infrastructure, 2021 (https://transportation.house.gov/imo/media/doc/Santana%20Testimony.pdf)
    - Railway Age, 2021 (https://www.railwayage.com/mechanical/locomotives/cp-hydrogen-locomotive-pilot-powered-by-ballard/)

B. IMPLEMENT — CAPITAL COST

Score	Description	Selection
5	No incremental cost	
4	Up to $1 million	
3	$1-3 million	
2	$3-5 million	
1	> $5 million	✓

Summary:

Incremental capital cost per locomotive is currently estimated at $6.5 million for mainline freight locomotives, roughly $300,000 for passenger locomotives (with no tenders) and roughly $200,000 for switcher locomotives. In the long term, assuming significantly scaled up production of HFC technology and green hydrogen, capital costs could reach parity with diesel for passenger and yard locomotives and be reduced to as low as $1 million for freight.

Notes:

- The US DOE estimates that currently, the capital costs of HFC freight locomotives comprise 31% of total cost of ownership (TCO) and are roughly 2.7 times greater than capital costs for diesel locomotives. Each HFC locomotive costs roughly $3.2 million, each fuel cell system costs roughly $1 million, and each 100 kWh battery pack costs roughly $125,000. This sums to roughly $4.3 million per hydrogen locomotive suitable for switching service. Each hydrogen tender is expected to cost roughly $6.2 million, though they are not currently in production. A tender would be required to meet the specs of a single HHP freight locomotive. Costs for a hydrogen freight locomotive would therefore be expected to be in the range of $10.5 million. All component costs except those for HFC locomotives (which will remain constant) are expected to decline by half in the medium term (for a total of ~$7 million) and by three quarters in the long term (for a total of roughly $5 million), assuming necessary production levels are reached (>100,000 heavy-duty vehicle fuel cell systems produced in the US per year).
- Capital costs for inter-city passenger HFC locomotives are expected to be much lower, as they are not likely to require a hydrogen tender, they travel at lower average speeds, and have more frequent stops than freight. Capital costs for HFC passenger locomotives are only expected to be roughly 7% higher than for diesel. These costs assume these locomotives will carry 500 kg of cryogenic liquid, as opposed to gaseous, hydrogen, although a tender may not be required with gaseous hydrogen at 350 bar, depending on the route (see section 3B for more information on fueling).

- In Germany, railway supplier Alstom produced self-powered HFC passenger cars for a cost of approximately $10 million each, although this included a mobile refueling unit. These costs are significantly higher than estimates from the US DOE. The Government of Germany contributed 40% of the cost differential between hydrogen and diesel power units. Estimated lifetime is 30+ years, although fuel cell stacks and batteries (at least 100 kWh each) will likely require multiple replacements over that timeframe.

- The US DOE estimates current storage system costs at $1,400 per kg of liquid hydrogen (at roughly -200°C), potentially decreasing to $340 per kg in the long term, with sufficient scale of production. With storage capacities of 500 kg per hydrogen multiple unit, this would mean current costs of $700,000 per onboard storage system, decreasing to as low as $170,000 in the future.

- Retrofitting diesel locomotives and replacing engines with HFC technology is viable and cost-effective compared to purpose-built HFC locomotives (which are not yet available in North America). Cost reductions are expected with a scale up of production.

- Batteries, ultracapacitors (which can be used to provide supplemental propulsion and capture energy from braking), hydrogen storage tanks and fuel cell stacks (with cooling) have high capital costs but can lead to energy-related cost containment if durable/long-lived.

- Refueling equipment will require high upfront capital costs, but demonstrations are required to determine accurate price ranges. At scale, hydrogen locomotives and fueling infrastructure are projected to be cost effective, however getting to scale will be a major challenge for the rail sector. These capital cost estimates do not include refueling, compression, storage, or electrical transmission equipment and infrastructure at rail yards.

- It was suggested that railways would have more interest in adopting novel technologies like HFC locomotives if Canada increased capital cost allowance (CCA) rates for new rail assets. Lowering the appreciation time would likewise offer capital cost benefits to railways. Limiting taxes for hydrogen (such as the 4 cent per litre excise tax on petroleum diesel) could also encourage adoption.

Reference(s):

- Consultations: Ballard, Peter Eggleton, UBC
- Literature review:
    - Hydrogen Strategy for Canada, 2020 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)

- Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
- TELLIGENCE Group, 2020 (https://static1.squarespace.com/static/5b193e81cef372d012efda72/t/5f7b42e1a96b3a18f431f9f1/1601913574512/Hydrail+Prerequisites+-+2020+Final+Revision-converted.pdf)
- RSSB, 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)
- US DOE, 2020 (https://www.hydrogen.energy.gov/pdfs/review20/ta034_ahluwalia_2020_o.pdf)

C. IMPLEMENT — INFRASTRUCTURE REQUIREMENTS

Score	Description	Selection
5	No additional infrastructure required	
4	Existing infrastructure can be used, with modifications	
3	Significant new infrastructure required in yards only.	✓
2	Significant new infrastructure required in yards and other locations	
1	Significant new infrastructure required over entire network	

Summary:

Additional refueling/ charging infrastructure requirements may include:

- Hydrogen storage, compression, and dispensing equipment and infrastructure would likely be required at rail yards and fueling sites serving HFC locomotives. Distribution infrastructure such as pipelines may be used in cases where a hydrogen source is nearby.

- Electrical sub-stations and high voltage transmission infrastructure will be required if electrolyzers are installed at rail yards or fueling sites. Hydrogen compression, liquefaction and cooling are also energy-intensive and would likely require electrical system upgrades in yards.

Notes:

- Hydrogen trains require little change to existing rail infrastructure. However, they require new fuelling systems (and potentially hydrogen production systems) to be constructed. The limited existing hydrogen infrastructure to support deployment requires concurrent investment in both supply and demand, presenting a "chicken and egg" scenario which can make initial investments challenging.

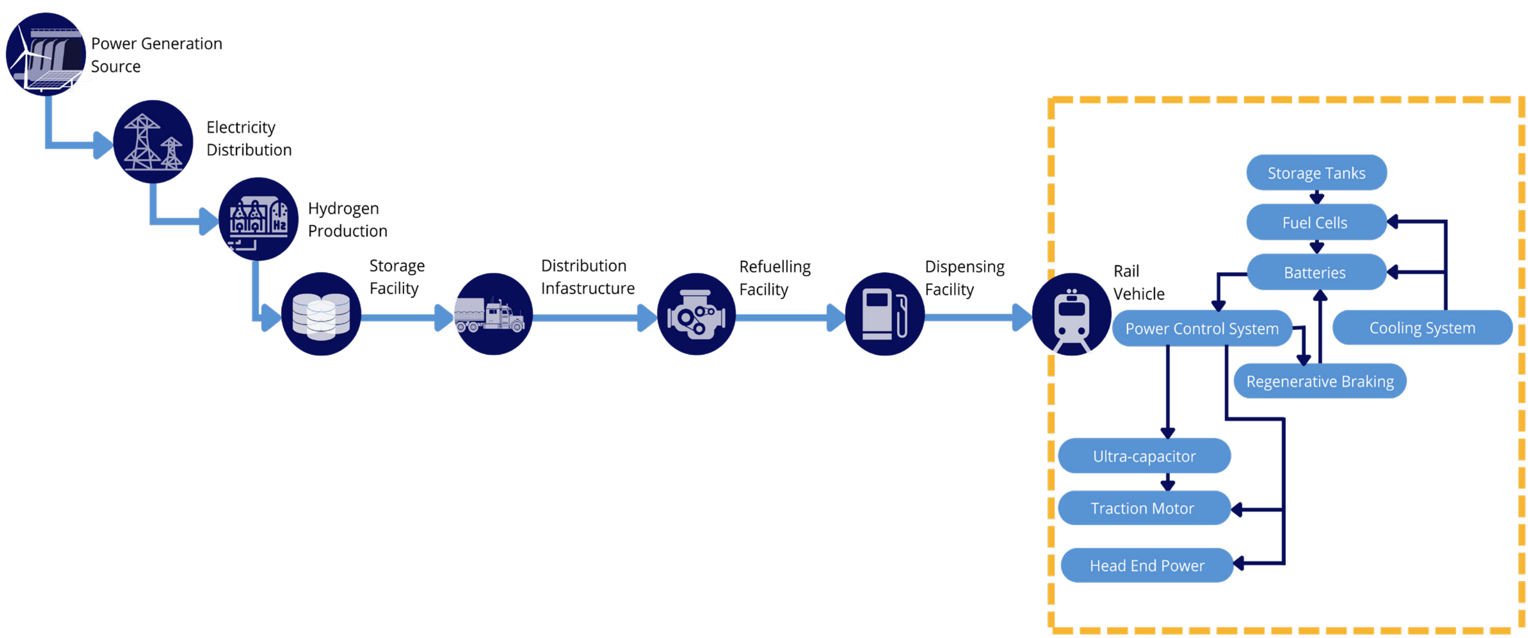
- Because HFC technology does not require major modifications to railway infrastructure outside of yards and fueling points, HFC locomotives can be phased into existing fleets gradually, on routes where hydrogen is available.

- In Germany, costs for mobile trackside hydrogen dispensing units for Coradia iLint HFC passenger trains were included with the purchase of each HFC power unit. Mobile refueling is being used to reduce capital and infrastructure costs during initial hydrail deployments. This entails green hydrogen produced onsite via electrolysis and stored in a mobile storage tank trailer, and is expected to be able to refuel a train in the same time as it would take to refuel a diesel train.

- Hydrogen production via electrolysis could cause disruptions in electricity generation systems, and sufficient power needs to be allocated to meet consistent demands. This could increase costs to railways (if producing hydrogen at refueling facilities) or could lead to higher fuel prices. See Figure 1 for an overview of key elements of a hydrail ecosystem.

- A Metrolinx feasibility study from 2018 found that the costs of building and operating an HFC system for passenger rail are equivalent to that of a conventional catenary system.

Figure 1: Components of a Hydrail System (source: TELLIGENCE Group, 2020)



Reference(s):

- Consultations: CP, Ballard
- Literature review:
    - o Hydrogen Strategy for Canada, 2020 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)
    - o Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - o TELLIGENCE Group, 2020 (https://static1.squarespace.com/static/5b193e81cef372d012efda72/t/5f7b42e1a96b3a18f431f9f1/1601913574512/Hydrail+Prerequisites+-+2020+Final+Revision-converted.pdf)

D. OPERATE

Score	Description	Selection
5	>20% savings	
4	Up to 20% savings	
3	Par with diesel	
2	Up to twice the cost of diesel	
1	>2x	✓

Summary:

Incremental cost to operate, as compared with a baseline of diesel, is roughly three times greater for freight and passenger, and roughly twice as great for yard switchers. These costs are expected to decline significantly in the long term, if hydrogen and HFC technology production is scaled up significantly.

Notes:

- According to the US DOE, hydrogen fuel costs currently make up 44-63% of TCO (63% for freight, 52% for passenger, 44% for switchers), maintenance makes up 7-18% (7% for freight, 10% for passenger, 18% for switchers), and capital costs comprise the remainder.[35]

35 For reference, in the case of diesel locomotives, fuel costs currently make up roughly 53% of TCO for freight, 32% for passenger, and about 25% for switchers. Maintenance TCO costs for diesel are 13%, 14%, and 20% for freight, passenger and switchers, respectively.

- Total TCO for hydrail is almost three times greater than diesel in the case of freight, about 80% greater for passenger (with no tenders) and 51% greater for switchers. These numbers, however, are expected to decline to 36% greater in the long term for freight (assuming sufficient scale is reached), and to near cost parity for both passenger and switcher locomotives.

- When hydrogen fuel production is scaled up significantly, fuel costs are expected to be 50% higher than diesel for freight and passenger, and 21% higher for switchers.

- A major challenge is posed by the costs required to store, compress, transport and dispense hydrogen (see section 3B). Hydrogen is the most energy dense fuel by mass, but the least energy dense by volume, which makes its storage and transport very expensive. The energy density of hydrogen by mass is roughly 2.6 times greater than petroleum diesel, 33.6 kWh/kg versus 13 kWh/kg.

- A 2018 study for Metrolinx found that maintenance costs of HFC locomotives and infrastructure were comparable to those of electric catenary systems. However, it also found that the complexities of hydrail presented a unique set of risks relative to catenary electrification which could impact costs.

- The Hydrogen Strategy for Canada puts the cost estimate range per kg of dispensed gaseous or liquid hydrogen at roughly $3-10. A 2019 UK study put cost estimates between $9.50 and $15.40 per kg. A 2020 study from the US DOE reported hydrogen costs for passenger buses in California ranging from $6.50 to $17.50 per kg (or 2x to over 5x more expensive than diesel).

- Fuel costs depend to a large degree on the process used to produce hydrogen, and are currently negatively correlated with the GHG emissions reduction potential of different classes of hydrogen (i.e., lower costs come with lower GHG reduction potential; more on this in section 2A). Significant reductions in fuel costs are expected as the scale of production increases.

- Based on US estimates and diesel prices as of 2020, the break-even price for hydrogen to reach cost parity with diesel is $2.75 per kg for freight applications, about $4.50 per kg for passenger, or $5.00 per kg for switching services. However this may change as the US EIA expects diesel prices to increase by 21% between 2020 and 2030, and by 27% by 2035.

- In addition to being transported by tanker truck, rail, or pipeline, hydrogen can be produced on-site at fueling depots using electrolyzers. This requires a high voltage grid connection and a source of water. Hydrogen can be stored in bulk in low or medium pressure vessels. A compressor then transfers the hydrogen to high pressure vessels which are used to refuel trains with a flexible hose. Electrolysis is currently the most expensive production pathway for hydrogen, but costs are expected to come down as scale of production increases.

- A number of other transportation modes (e.g., heavy-duty trucking, buses, marine, off-road) are currently exploring the use of hydrogen as a fuel. This could lead either to competition and increased prices for hydrogen, or to increased production and economies of scale. Opportunities exist for shared fueling infrastructure (and therefore lower costs) at intermodal hubs between rail, trucking, marine, passenger buses and/or terminal equipment such as cranes and forklifts.

- Liquefying hydrogen is more expensive and energy intensive than compressing, but insulated storage reservoirs for liquid hydrogen (which must be kept at -253°C) might be less expensive than compressed gas cylinders (at 350 bar). Liquid hydrogen is also more space efficient, but if storage space is not a constraint, compressed hydrogen may be more economical.

- Industrial gas supply companies and others have commercial interest in supplying hydrogen for rail applications due to the size and long-term stability of the requirements. Partnerships with gas and electric utilities will likely be key to reducing fuel costs.

- HFC locomotives have far fewer moving parts as compared to diesel. This greater simplicity is expected to result in reduced downtime and maintenance, reduced need for depot stabling, and reductions in the storage of spare power units.

- Major maintenance issues with fuel cell systems tend not to be related to the stacks themselves, but to air handling/compressors, blowers, cooling pumps and plumbing. 30-40% of maintenance costs for diesel locomotives are associated with the engine. Fuel cells themselves have no moving parts and there is no wear from friction. They also operate cooler than diesel engines, which can lead to reduced maintenance requirements.

- Fuel cell systems for hydrail have an expected lifetime of roughly 10 years (assuming 10-12 hours of operation per day). As each system costs roughly $1 million, this would add $3 million in operating costs over a 30 year lifespan per power unit.

- A European study found that for passenger rail, hydrogen could be cost-competitive with diesel, though the total cost of ownership was higher (by 4-35%). This was despite hydrail having lower maintenance costs. A caveat to the cost-competitiveness is that renewable energy must be abundant and cheap (as it is in places like Scandinavia and Canada). Cost-competitiveness is further improved as the cost of diesel increases, with a key threshold for Europe being roughly $1.80 per litre.

- Insurance rates for hydrail may be high enough to pose a barrier to adoption.

Reference(s):

- Consultations: Ballard, CP, SWRI, Bob Oliver, UBC, Peter Eggleton
- Literature review:
    - Hydrogen Strategy for Canada, 2020 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)
    - Rocky Mountain Institute, 2019 (https://rmi.org/run-on-less-with-hydrogen-fuel-cells/)
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - TELLIGENCE Group, 2020 (https://static1.squarespace.com/static/5b193e81cef372d012efda72/t/5f7b42e1a96b3a18f431f9f1/1601913574512/Hydrail+Prerequisites+-+2020+Final+Revision-converted.pdf)
    - Shift2Rail, 2019 (https://shift2rail.org/wp-content/uploads/2019/05/Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment_final.pdf)
    - US DOE, 2020 (https://www.hydrogen.energy.gov/pdfs/review20/ta034_ahluwalia_2020_o.pdf)
    - Transport Canada Innovation Centre, 2019 (https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-belluz.pdf)

2. CARBON REDUCTION POTENTIAL

A. GHG REDUCTION POTENTIAL

Score	Description	Selection
5	>80%	✓
4	50-80%	
3	30-50%	
2	10-30%	
1	<10%	

Summary:

As compared with a baseline of diesel, GHG reduction potential on a per-equipment basis is estimated at over 80% in the case of green hydrogen, 30-50% for blue hydrogen, and marginal to negligible for grey hydrogen.

Notes:

- HFC locomotives have no emissions at point of use. The carbon intensity of operation depends on the method(s) used to produce, store and distribute the hydrogen. There are three methods currently employed for production, resulting in three corresponding classes of hydrogen:
    - Green hydrogen is made by extracting hydrogen from water using electrolysis powered by renewable energy. With the lowest carbon intensity, it offers the greatest climate benefit, but also comes with the greatest production costs. If electrolysis is powered by non-renewable electricity, climate benefits decline significantly. Nationally, 82% of electricity generation in Canada is emissions-free.[36]

    - Blue hydrogen is made by extracting hydrogen from natural gas, and then using carbon capture and sequestration technology to store the remaining carbon. It has a low to moderate carbon intensity.

    - Grey hydrogen is made by extracting hydrogen from natural gas using thermal processes such as steam methane reformation. It offers little to no climate benefit. A large majority (one expert claimed 99% in the case of the US) of hydrogen currently used is grey, due to lower production costs.

- The ideal GHG scenario is using excess, off-peak, low-cost electricity from emissions-free sources for all hydrogen production. In this scenario, hydrogen would essentially serve as a renewable energy storage medium, similar to batteries, but without any degradation or losses over time. Canada's hydro-power provinces, namely BC, Manitoba and Quebec, are particularly well-suited for green hydrogen production.

- In Alberta, roughly 2,250 t of hydrogen is produced daily, and is earmarked for industrial purposes such as fertilizer production, bitumen upgrading, and oil refining. Roughly 58% of this is grey hydrogen, and 42% is blue.

- A UK study found that GHG benefits of hydrogen relative to diesel were 5% for grey hydrogen and 75% for green hydrogen (based on the UK grid's carbon intensity, which is higher than Canada's).

- Green hydrogen currently costs roughly three times more than grey hydrogen, which could limit the GHG reduction potential of hydrail.

- The combined efficiency of electrolysis, compression and fuel cells lead to total energy consumption around three times that of conventional electric trains. When fuel supply chains are factored in, the overall efficiency of HFC locomotives using green hydrogen is roughly 40%, compared to 30-35% for diesel. However the in-use efficiency of HFC

36 NRCan, 2020. (https://www.nrcan.gc.ca/science-and-data/data-and-analysis/energy-data-and-analysis/energyfacts/energy-and-greenhouse-gas-emissions-ghgs/20063)

locomotives is significantly greater than diesel – up to 30% greater in the case of freight, or 76% in the case of switchers.

- HFC locomotives would significantly reduce or eliminate CAC emissions from rail operations. They would also significantly reduce noise and vibration issues. While these factors are outside the scope of this analysis and are therefore not captured by the assessment framework, they are highly important from social and health perspectives. Rail yards tend to be located in or near disadvantaged communities that suffer heavy burdens from air pollution. Rail yard staff health would also be enhanced through the use of HFC propulsion.

- A US study found that increasing the utilization of rail by 50% for the movement of all freight on routes over 800 km would reduce GHG emissions by 60 Mt per year. The combination of zero-emission locomotives and shifting more freight to rail would reduce GHG emissions by up to 120 Mt per year. Reducing the carbon intensity of the US electricity grid would lead to even greater reductions.

- Regarding hydrogen co-combustion, existing diesel engines can be retrofitted to burn up to 30% hydrogen blends, with a proportional GHG emission reduction potential in the case of green hydrogen (i.e., up to 30%). However, hydrogen co-combustion can lead to increases in NOx emissions and is unlikely to contribute to deep decarbonization.

- One expert noted that increased demand for green hydrogen could catalyze a faster shift to renewables like wind, hydro and solar for electricity generation.

Reference(s):

- Consultations: Bob Oliver, SWRI, CN, Peter Eggleton, TC, NRC,
- Literature review:

  - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
  - Pembina Institute, 2020 (https://www.pembina.org/reports/hydrogen-climate-primer-2020.pdf)
  - House Committee on Transportation and Infrastructure, 2021 (https://transportation.house.gov/imo/media/doc/Santana%20Testimony.pdf)
  - Hydrogen Strategy for Canada, 2020 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)
  - Transition Accelerator, 2020 (https://transitionaccelerator.ca/wp-content/uploads/2020/11/Building-a-Transition-Pathway-to-a-Vibrant-Hydrogen-Economy-in-the-Alberta-Industrial-Heartland-November-2020-5.pdf)

- TELLIGENCE Group, 2020 (https://static1.squarespace.com/static/5b193e81cef372d012efda72/t/5f7b42e1a96b3a18f431f9f1/1601913574512/Hydrail+Prerequisites+-+2020+Final+Revision-converted.pdf)
- Shift2Rail, 2019 (https://shift2rail.org/wp-content/uploads/2019/05/Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment_final.pdf)
- RSSB, 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)

B. UPTAKE/ APPLICABILITY

Score	Description	Selection
5	Well-suited to mainline freight rail	
4	Partially suited to mainline freight rail	
3	Suited to yard equipment	✓
2	Well suited to passenger rail	
1	Not suited to mainline freight rail, only partially suited to passenger rail	

Summary:

HFC switchers, shunters and passenger locomotives are currently technically and economically feasible. To date, no HFC locomotives capable of hauling freight have been developed.

Notes:

- On average, yard locomotives have daily ranges of roughly 120 km, pull loads of roughly 500 t, and operate for 12-16 hours a day. They are amenable to daily refueling in yards. Rail yards are coming under increasing public pressure as sources of air pollutants, so demonstrating technologies like hydrail in them could be a good starting point.

- CP is currently retrofitting a former linehaul diesel locomotive into an HFC switcher, with active service set to begin by the end of 2022.

- Europe now uses an electric multiple unit (EMU) concept for most of its passenger rail. This concept is beginning to roll out in North America (e.g., Ottawa O-Train), but most passenger service is still dominated by large, powerful diesel trains. EMUs can use any type of propulsion technology as drop-in power units (e.g., HFC, battery, diesel). Passenger HFC locomotives in North America would likely need more than 1MW of power, which is a challenge from a cost containment perspective for HFC technology. In Europe passenger trains require roughly 200kW of power, which is feasible for hydrogen.

- Hydrail is well suited to duty cycles with frequent starts and stops (e.g., switchers, commuter), due to its use of regenerative braking.

- Fuel cell trains have relatively short refueling times (roughly 15-30 minutes for inter-city passenger applications) which are comparable to diesel. One expert noted that this, along with the fact that hydrail requires little in the way of new infrastructure, makes it an attractive option for mainline freight service in the long term. Despite the need for tenders in long-haul and HHP applications, hydrogen is still viewed as having more portability than battery electric.

- Fuel cell locomotives are already in use in certain countries for passenger applications, typically on shorter, low-traffic sections of track where electrification is not cost-effective. They can be configured for use in bi-mode systems, with either catenary or diesel.

- In 2018 rail OEM Alstom launched passenger service of two Coradia iLint trains in Germany, produced with fuel cells made by Canadian company Hydrogenics (now a subsidiary of Cummins). The trains can carry up to 300 passengers, reach speeds of up to 160 km/h, and have ranges up to 1,000 km. The trains are fueled from a mobile filling station. Dozens more of these trains have been pre-ordered by European rail operators, and deliveries will begin in 2022. Their primary application is on lightly-used passenger lines. The main competition with hydrogen for zero-emission rail in such applications is battery electric.

- One expert stated that approvals, funding, design, permitting, construction, etc., mean that while technically feasible, actually implementing HFCs for freight rail is likely 30+ years away.

- A study out of Europe found that by 2030, hydrogen multiple units could replace up to 30% of existing diesel locomotives (particularly in areas with an abundance of renewable electricity). However the study found that a lack of prototype testing and available products is a barrier to shunter and mainline uptake. Hydrail could be a viable option for retrofitting shunter fleets, where space and weight requirements can be managed; however it was noted that due to the high idle times of some shunters, battery trains could be the cheaper option in these cases.

- It was suggested that hydrail rollout would be best-suited to initially take place in hubs, especially those where low-cost hydrogen can be produced at scale. A good approach is the creation of regional hubs, such as the one Transition Accelerator is spearheading in Alberta, which entail the use of hydrogen in a variety of sectors and transportation modes. Eventually, multiple hubs could be linked to create broad networks of integrated hydrogen technologies.

- The fuel cell stacks used in HFC locomotives are similar to those used in buses, marine vessels, and other heavy-duty vehicle applications. Most use 200kW modules, which are stacked to meet power demands. The rail sector will benefit from cost reductions that will come from building out hydrogen into other transport modes.

- Passenger rail stations are often space-constrained and may lack the storage space required for hydrogen.

Reference(s):

- Consultations: Ballard, UBC, Peter Eggleton, TC, Paul Blomerus, Bob Oliver
- Literature review:

  - Hydrogen Strategy for Canada, 2020 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)
  - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
  - Railway Technology, 2019 (https://www.railway-technology.com/projects/coradia-ilint-regional-train/)
  - TELLIGENCE Group, 2020 (https://static1.squarespace.com/static/5b193e81cef372d012efda72/t/5f7b42e1a96b3a18f431f9f1/1601913574512/Hydrail+Prerequisites+-+2020+Final+Revision-converted.pdf)
  - Transition Accelerator, 2020 (https://transitionaccelerator.ca/wp-content/uploads/2020/11/Building-a-Transition-Pathway-to-a-Vibrant-Hydrogen-Economy-in-the-Alberta-Industrial-Heartland-November-2020-5.pdf)
  - Shift2Rail, 2019 (https://shift2rail.org/wp-content/uploads/2019/05/Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment_final.pdf)
  - Ballard, 2020. Fuel cell solutions for zero emission rail (presentation provided by Ballard).

3. CHALLENGES

A. OPERATION

Score	Description	Selection
5	Equal to or better than diesel	
4	Low level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	
3	Moderate level of complexity in maintaining system reliability and exisiting infrastructure and/or maintaining equipment.	✓
2	High level of complexity in maintaining system reliability and existing infrastructure and/or maintaining equipment.	
1	Significant risk to reliability. Significant risk of loss of an asset.	

Summary:

The low volumetric energy density of hydrogen poses a major challenge, requiring the use of heavy, bulky tanks for on-board and fueling depot storage. This limits range and will necessitate the use of tenders for long-haul and HHP applications. Other significant challenges include network interoperability, and a lack of testing in real-world duty cycles.

Notes:

- The energy density of hydrogen poses a major challenge, especially for freight linehaul applications. It will likely necessitate the use of tenders, and increased refueling points.

- Relatedly, interoperability is a major challenge, as Canadian railways and their assets operate throughout the US and Mexico. The rollout of technologies such as hydrail for mainline freight would have to be coordinated at a continent-wide scale. There are horsepower agreements between railways throughout the continent as well as shared assets (which must be compatible with propulsion technologies deployed). Yards owned by railways must also be capable of servicing and refueling trains from other railways, so extensive coordination would be required.

- HFC locomotives currently have power limitations that make them unsuitable for freight service. Roughly 75% of hydrogen is consumed in throttle notches 6, 7 and 8, where diesel engines are most efficient. This lack of applicability may limit the GHG reduction potential and adoption levels of HFC locomotives.

- Hydrogen tenders and additional multiple units in trainsets would make hydrail more viable for freight, however tenders have yet to be developed (due to connectivity, weight and cost issues) and would limit maximum payloads.

- HFC performance is not expected to be negatively impacted by Canada's cold climate, however cold weather testing is needed to validate this assumption.

- Hydrail technologies are more complex and novel than catenary or battery electric propulsion, which could pose additional and unforeseen operational challenges and risks.

- There are many commonalities between the equipment, infrastructure and regulations used for compressed natural gas (CNG) and hydrogen. If railways adopted CNG technology in the near term the transition to hydrogen in the longer term would be easier and more affordable. Some experts suggested, however, that a near term switch to CNG or LNG would be a distraction given that net zero is the ultimate objective.

Reference(s):

- Consultations: CP, SRY, CN, Bob Oliver, UBC, CUTRIC, TC
- Literature review:
    - Hydrogen Strategy for Canada, 2020 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)
    - RSSB, 2019 (https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26141)
    - US DOE, 2020 (https://www.hydrogen.energy.gov/pdfs/review20/ta034_ahluwalia_2020_o.pdf)
    - Transport Canada Innovation Centre, 2019 (https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-belluz.pdf)

B. REFUELING

Score	Description	Selection
5	Equal to or better than diesel	
4	Moderate complexity to supply chain and/or refueling requirements	
3	Complex supply chain, >2x refuel/recharge time/frequency	
2	Intermittent availability issues, up to 2x refuel/ recharge time/ frequency	
1	Frequent availability issues, >2x refuel/rechg. time/ frequency	✓

Summary:

A major challenge stems from the nascent nature of hydrogen supply chains and the lack of refueling infrastructure throughout Canada. Lack of fuel availability was identified by most experts consulted as a major challenge. Uncertainty around the ideal state of hydrogen (i.e., liquid versus gaseous) for storage, distribution, and use, poses another major challenge.

Notes:

- Refueling capacity is likely required before mainline demonstrations and HFC locomotive production can begin, and uncertainties with regard to future fueling demand could hinder this.
- Hydrogen can be transported in either a liquid or gaseous form. To maintain a liquid state, which has much higher energy density than a gaseous state, hydrogen must be kept at a temperature of -253°C. Liquefying hydrogen is very energy intensive, and consumes roughly 30% of the energy value of the hydrogen itself (which decreases efficiency and adds to costs). Liquid hydrogen is typically vaporized and dispensed in its gaseous form for most transportation applications, however energy-intensive applications such as freight rail would likely require the on-board storage of liquid hydrogen.
- Gaseous hydrogen is compressed and stored in high pressure cylinders. Hydrogen vehicles typically store it on-board at pressures of 350 or 700 bar. At 350 bar, onboard hydrogen storage consumes eight times the space of diesel to cover the same distance. Long range or HHP applications would likely require hydrogen tenders (which have yet to be developed) or additional power units which would also represent non-revenue generating cars. 700 bar storage is preferable for rail, and is possible if stronger components are used in fuel tanks. This would provide additional range but at greater cost.
- Researchers in China, who are hosting discussions with UBC researchers, are looking into the viability of storing hydrogen in small, low-pressure (50 bar or less) tanks at ambient temperatures, which would allow for storage in the existing frames of switcher locomotives.
- Hydrogen fuel would ideally be produced locally to the refuelling point due to the costs associated with transfer using a pipeline network (unless suitable infrastructure already exists) and both the difficulty and associated carbon emissions of transportation by road.
- It is expected that HFC trains that lack tenders will require refueling daily, possibly during overnight stabling. However this could require an expanded network of fueling stations. Each hydrogen multiple unit should be able to store 500 kg of liquid hydrogen at 500 bar and temperatures of roughly -200° C, or 100 kg of gaseous hydrogen at 350 bar and room temperature.
- Chemical carriers can be used to store and transport hydrogen, and can address challenges related to its low volumetric energy density (for example, 1 litre of gasoline contains more hydrogen than 1 litre of liquid hydrogen). Liquid chemical carriers such as methylcyclohexane (MCH) and ammonia (NH3) are easier to handle and contain relatively large quantities of hydrogen by volume. However carriers such as ammonia

come with significant downsides such as being flammable and highly toxic as an airborne or waterborne pollutant.

- Currently, most gaseous hydrogen is transported via steel tube trailer trucks at pressures of up to 250 bar. Higher pressures would make transport more economical, however the trucks come up against maximum allowable weights due to the thickness of the steel required to contain the hydrogen. The use of trailers made of composite materials is being explored.

- Transporting gaseous hydrogen using existing natural gas pipelines should be technically feasible with blend rates of up to 20% (this is being trialled globally, though not yet in Canada). Separating the hydrogen from natural gas is currently a technical challenge, although a lot of ongoing R&D is focused on this. Higher blend rates are a challenge due to the small size of the hydrogen molecule (which means it can pass through certain materials) and due to risks associated with the embrittlement of steel (which means it can cause failures in pipelines composed of certain steel alloys). Purpose-built hydrogen pipelines could potentially reduce transportation costs, although they come with substantial capital costs.

- One expert noted that both governments and utilities need to provide investments for hydrogen production to help to establish supply chains.

- Direct-to-locomotive refueling could be a viable option for HFC locomotives. Diesel is currently ferried over rail networks, and there is no reason why hydrogen could not be as well. This would allow hydrogen production to be focused in areas where it is low-carbon and low-cost.

Reference(s):

- Consultations: CP, SWRI, CN, UBC, Ballard, CUTRIC, NRC
- Literature review:

    - Hydrogen Strategy for Canada, 2020 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)
    - Transition Accelerator, 2020 (https://transitionaccelerator.ca/wp-content/uploads/2020/11/Building-a-Transition-Pathway-to-a-Vibrant-Hydrogen-Economy-in-the-Alberta-Industrial-Heartland-November-2020-5.pdf)
    - Network Rail, 2020 (https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf)
    - Shift2Rail, 2019 (https://shift2rail.org/wp-content/uploads/2019/05/Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment_final.pdf)
    - US DOE, 2020 (https://www.hydrogen.energy.gov/pdfs/review20/ta034_ahluwalia_2020_o.pdf)

C. SAFETY & REGULATORY COMPLIANCE

Score	Description	Selection
5	Equal to or better than diesel	
4	Some additional training and/or regulatory development required	
3	Additional training & certification and/or regulatory development required	
2	Safety concerns and/or significant regulatory development required	✓
1	Significant safety concerns, including to public and/or complete regulatory development required	

Summary:

Development of hydrogen regulations and standards, or amendments to existing regulations and standards to incorporate hydrogen, are required prior to commercialization in Canada. In some cases, existing standards for CNG/LNG or petroleum may be adaptable for hydrogen, or standards from other jurisdictions can be used to expedite development.

Notes:

- Transport Canada regulates the transport of gaseous hydrogen through the Transport of Dangerous Goods (TDG) Regulations.
- Transport Canada's Transportation Safety Board Regulations should be updated to account for hydrogen transport by pipeline, rail and marine vessel.
- Standards for dispensing, through amendments to Canada's Weights and Measures Act, will be required for hydrogen. As part of this, Measurement Canada will need to test and certify hydrogen dispensing, compression and storage equipment.
- Examples of related legislation that may require amendments to incorporate the use of HFC locomotives include: Canada Shipping Act (Transport Canada), Canadian Transportation Accident Investigation and Safety Board Act (Transport Canada), Canadian Environmental Protection Act (Environment and Climate Change Canada), and Railway Safety Act (Transport Canada). The Railway Safety Act regulates facilities on railway properties, and hydrogen storage and dispensing equipment will need to be incorporated into the Act. It was suggested that the Liquefied Petroleum Gases Bulk Storage Regulations (C.R.C., c. 1152) under the Railway Safety Act (for petroleum storage) could guide hydrogen regulations.

- Regulators may also want to ensure that hydrogen use in rail applications is included as an option to generate compliance credits in ECCC's Clean Fuel Standard, Gaseous Stream. Separate standards/credit levels for green, blue and grey hydrogen should be developed. Relatedly, ECCC could consider incorporating hydrogen into the Greenhouse Gas Pollution Pricing Act with different rates for green, blue and grey hydrogen.

- Due to the combustion characteristics of hydrogen there will be a need for safety protection equipment and processes to safeguard against risks of ignition. Hydrogen gas can pose a significant hazard if it leaks or escapes, particularly in a confined space. If allowed to accumulate in a confined space, the atmosphere can become flammable or explosive. High pressure release may also lead to combustion, especially in the presence of sparks.

- First responder protocols and training will need to be developed and implemented for hydrogen locomotives and fueling sites.

- Risk assessments on crash worthiness are required for all rail applications.

- Early and ongoing engagement with communities adjacent to hydrail operations can mitigate safety concerns. Public perception of hydrogen could pose a significant barrier.

- It was noted that Europe is far ahead of North America on standards for hydrail. Canadian railways are working on demonstrations, however, with the expectation that regulators will put standards in place soon. CSA is also working to develop standards for hydrail.

- Industrial hydrogen producers such as Air Liquide are experts on hydrogen transportation and safety requirements, and can provide input into standards development.

Reference(s):

- Consultations: CP, SWRI, Wabtec, Ballard, Peter Eggleton
- Literature review:
    - Hydrogen Strategy for Canada, 2020 (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)
    - TELLIGENCE Group, 2020 (https://static1.squarespace.com/static/5b193e81cef372d012efda72/t/5f7b42e1a96b3a18f431f9f1/1601913574512/Hydrail+Prerequisites+-+2020+Final+Revision-converted.pdf)
    - Transport Canada Innovation Centre, 2019 (https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-belluz.pdf)