3

ENGINEERING CONSULTING SERVICES

VOLUME 6 - APPENDIX

SECTION 6.18 – RAILWAY BATTERY ELECTRIC PROPULSION

Feasibility Study Final Report Phase I

Consultant Reference: LGA-1-GN-F-FRN-RT-0006_00_LGA Final Technical Report

2023-03-10

with subconsultant

Transportation Infrastructure Program

Feasibility Study, Phase I

Battery and Electric Train Propulsion Technologies for Phase I of the Billy Diamond Highway Railway

Client Reference: 2020-01

Consultant Reference: LGA-1-BD-T-RRS-RT-0001_01

2023-02-10

Stantec ▮ DESFOR ▮ SYSTRA

with subconsultant WSP

Document History and Status

Revision	00	01
Date	2023-01-18	2023-02-10
Prepared by	MD/EA	MD/EA
Reviewed by	CL	CL
Approved by	AC/PT	AC/PT
Comments	Draft for revision and comments	Final Draft

Approvals

Prepared by:

Ercan AFACAN
Deputy Director, Rolling Stock
SYSTRA Canada

Maya DIMITROVA, Eng.
Railway Operations Specialist
SYSTRA Canada

Reviewed by:

Catherine LAPLANTE, M.Sc.
VEI Transport Economist
SYSTRA Canada

Approved by:

Alessandro CIRELLA, P.Eng.
VEI Project Director
Stantec

Document Identification

Transportation Infrastructure Feasibility Study, Phase I

BATTERY AND ELECTRIC TRAIN PROPULSION TECHNOLOGIES

Consultant Reference:
LGA-1-BD-T-RRS-RT-0001_01

2023-02-10

Table *of* Contents

List *of* Tables

List *of* Figures

1. LIST OF ABBREVIATIONS

Acronyms	Abbreviation
BDH	Billy Diamond Highway
CAPEX	Capital Expenditure
EPA	U.S. Environmental Protection Agency
EU	European Union
ft	Feet
GCR	Grevet and Chapais Railway
GHG	Greenhouse gases
HP	Horsepower
HQ	Hydro Quebec
in	Inches
Km	Kilometer
KP	Kilometer point
kV	Kilovolt
kWh	Kilowatt-hour
L	Liters
OLE	Overhead line equipment (catenary)
OPEX	Operating Expenses
m	Meters
mm	Millimetres
MPH	Miles per hour
MTPA	Million tonnes per annum
MW	Megawatt
MWh	Megawatt-hour
PR	Progress Rail
REM	Réseau Express Métropolitain
ROW	Right-of-way
tCO_2eq/km	Tonnes of CO_2-equivalent per kilometer
TPC	Train Performance Calculator
US	United States

2. INTRODUCTION

2.1 CONTEXT

The Grande Alliance is an innovative Memorandum of Understanding between the Cree Nation and the Quebec government, focused on the economic development of the Nation's territory and its specific cultural and ancestral rights on the land. To ensure a true long-term collaboration, the basis of this alliance is focused on three main points – Connect, Develop, and Protect.

A logical continuation of the Paix des Braves Treaty (2002) established in the context of the James Bay and Northern Quebec Agreement (1975), this alliance mobilizes the participation of all Cree Nation communities ("Connect") to involve Cree actors in contributing to a common vision of socio-economic development of the territory ("Develop"), while protecting the ways of doing things and the heritage assets ("Protect").

The Grande Alliance is therefore proceeding with the Feasibility Study of Phase 1 of the development of the territory, which includes a road and rail network in the southern part of the territory, with the primary goal to be a respectful socio-economic development of the communities.

This is an important first step that will serve as a cornerstone for the future of both the Cree Nation and for the relationship with the Quebec Government.

The Grande Alliance program is categorized as described below (Figure 2-1~~Figure 2-1~~):

- Phase I includes the extension of the railway between Matagami and Rupert River (KM 257 of the Billy Diamond Highway (BDH)), the rehabilitation of the railway between Grevet and Chapais (GCR), the implementation of transshipment centers along these two railway lines (especially one near km 257 of the BDH) and the upgrading/paving of local road connections to four Cree communities.
- Phase II includes the extension of the Billy Diamond Highway between Radisson and Whapmagoostui/Kuujjuarapik, the extension of Route 167 northbound up to the Transtaiga Road, and the extension of the railway between Rupert River and Radisson.
- Phase III is comprised of the extension of the railway from Radisson to Whapmagoostui/Kuujjuarapik and the construction of a deep-sea port on James Bay at Whapmagoostui/Kuujjuarapik. The extension of the Transtaiga Road eastbound up to Schefferville was first considered, but the Client withdrew it from the scope of the study.

Figure 2-1: Transportation Infrastructure Components of La Grande Alliance Program

2.2 Study Objective

It is difficult to ignore the impacts of climate change around the world today – impacts on crop yields and the risk of food shortages, the increasing frequency of extreme natural events (such as flooding, hurricanes and wildfires) affecting housing as well as people's safety, the disruption of natural cycles resulting in a significant decrease of the animal population worldwide, among many others. Furthermore, it is important to also consider that climate change has a significant financial cost as well.[1] It has also been well established that human activity and the release of greenhouses gases (GHG) in the atmosphere is one of the main drivers of climate change.[2]

In response to the risks posed by climate change, countries and organisations around the world are adopting greenhouse emission reduction goals with the aim of limiting the extent of global warming, and consequently the impacts of climate change. Canada's own *2030 Emissions Reduction Plan* was adopted in 2020, with the objective

[1] https://www.ucdavis.edu/climate/news/cost-climate-change
[2] https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/

of reducing GHG emissions by 40-45% as compared to the emissions produced in 2005, and the ultimate goal of reaching net-zero emissions by 2050.[3]

To meet their own carbon reduction goals, major mining companies such as Rio Tinto and Vale are now considering using alternative propulsion modes with conventional electrification and battery-powered locomotives as the primary two options to reduce GHG emissions.

The purpose of this study is to provide a discussion and validate the feasibility of using alternative train propulsion modes for Phase 1 of the Billy Diamond Highway railway, with the aim of reducing the lifecycle GHG emissions of the project. This will include the study of:

- battery-powered trains;
- electric trains powered by overhead catenary;
- hybrid trains, which will include a combination of battery and diesel propulsion.

[3] https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview.html

3. ROLLING STOCK

The following sections will present the various train propulsion modes in existence, as well as their global maturity, market status, practicality, and environmental impact. The propulsion modes discussed are diesel, catenary, battery-electric, hydrogen and hybrid trains.

3.1 OVERVIEW OF THE AVAILABLE TECHNOLOGIES

Recent developments in railway rolling stock have shown numerous applications of so-called “zero or low emission trains” relying on innovative technologies. While so far these have been mainly limited to urban transit, the alternative propulsion modes are starting to emerge as a promising way to sustain growth in conventional rail transportation as well.

Rail transport accounts for about 1% of the total transportation emissions in the world.[4] In the European Union (EU), the rail network is mostly electrified, especially over the major transportation corridors and within urban areas. At the current time, around 60 % of the EU network is electrified, and carries approximately 80 % of all railway traffic in this region. Railways elsewhere – such as in North America, in the Middle East and in Africa – are rarely electrified.

Although there are not a lot of technical obstacles for electrifying a railway line, the cost of building the necessary infrastructure can be significant. It is also important to consider how the energy is supplied as methods for electricity production can vary considerably from one country to the next, or even within the same country.

It’s important to note that today all railway freight operations in North America are using diesel-based propulsion. However, in recent developments, Some Class 1 railways have begun testing alternative technologies with the aim of minimizing or eliminating diesel-based propulsion all together within their fleet.

3.1.1 Diesel Trains

3.1.1.1 Technology

Diesel-based propulsion is a mature technology. Diesel has long been the technology of choice for moving people and goods by rail thanks to its efficiency, durability, and reliability. U.S. freight railroads can, on average, move one ton of freight more than 470 miles with a single gallon of diesel fuel, thanks to the low rolling resistance of steel wheels coupled together with the energy efficiency of diesel locomotives.[5]

There are two categories of diesel trains: “pure” diesel train (with mechanical transmission) and “diesel-electric” where diesel engines are used to generate power for electric traction motors, thus improving energy efficiency and performances at low speed.

Diesel is the most energy-efficient internal combustion engine type and it is the prime mover for key sectors of the global economy. The latest diesel engines can achieve near-zero emissions with ever increasing fuel efficiency and relatively low CO_2 emissions, with further improvements on the horizon. In addition, both new and existing engines can utilize low-carbon renewable biofuels. Taken together, these elements make diesel technology part of the solution to reducing GHG emissions.

[4] https://ourworldindata.org/co2-emissions-from-transport
[5] globenewswire.com

Code de champ modifié

3.1.1.2 Current Market Situation

In North America, diesel is the predominant propulsion mode in railway operations. Despite some alternative traction modes being currently tested, notably with Liquid Natural Gas and Compressed Natural Gas, Class 1 railways continue to operate diesel trains over vast distances. At the end of 2018 just over 26,000 diesel-powered freight locomotives[6] were in operation in the U.S. These trains are very long with lots of cargo. There are few of them per line and they tend to run very long distances. Likewise, Australia is diesel-dependent for its railway industry, as is the case in Brazil. Great swathes of Russia's network rely on diesel traction as do networks in Asia, Latin America and Africa.

Currently, there are ongoing efforts to make diesel near-zero pollutant emissions. This transformation in locomotive engines is ongoing with new engines now able to meet U.S. EPA Tier 4 Emissions regulations for both particulate matter and oxides of nitrogen, utilizing ultra-low sulfur diesel fuel. Additives can also be added to diesel to limit its environmental impact.

3.1.1.3 Environmental Impacts

Carbon footprint: The production, distribution and combustion of diesel all generate GHG emissions. About 2.68 kg of CO_2 are produced by burning a liter of diesel fuel.[7] In France, according to the energy agency ADEME, the Well-to-Wheel emissions factor of Diesel is 3.25kgCO_2eq/L.[8]

Air pollution: Tier 4 locomotive technology enables a reduction of particulate emissions from diesel locomotives by as much as 90% and nitrogen oxide emissions by as much as 80%.[9] Currently, all new locomotives sold in the USA must meet Tier 4 standards. However, older diesel locomotive on the used market would be a cheaper alternative to Tier 4 locomotives but would produce significantly higher emissions.

To accelerate the movement to zero- or near-zero emission locomotives, the California Air Resources Board (ARB) has petitioned the U.S. EPA to take action in adopting more stringent emission standards for locomotives. These new standards are to include standards for newly manufactured locomotives (which ARB refers to as "Tier 5"), and a new standard for Tier 4 locomotives upon remanufacture.[10]

[6] globenewswire.com
[7] US Energy Information Administration
[8] Documentation Base Carbone (ademe.fr)
[9] https://www.aar.org/article/freight-rail-moving-miles-ahead-on-sustainability/#!
[10] https://www.greencarcongress.com/2017/04/20170414-arb.html

Code de champ modifié
Code de champ modifié

Potential Amended Emission Standards for Newly Manufactured Locomotives and Locomotive Engines

Tier Level	Proposed Year of Manufacture	NOx		PM		GHG		HC		Proposed Effective Date
		Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[1]	Standard (g/bhp-hr)	Percent Control[2]	
5	2025	0.2	99+	<0.01	99	NA	10-25%	0.02	98	2025
		With capability for zero-emission operation in designated areas.								

1. ARB, Technology Assessment: Freight Locomotives, 2016.[3]
2. Compared with uncontrolled baseline, reflects percent control over line haul baseline for illustrative purposes; ARB staff assumed older pre-Tier 0 line haul and switch locomotives would be able to emit up to the Tier 0 PM emission standards, based on American Association of Railroads in-use emission testing (required to comply with U.S. EPA in-use emission testing requirements) for older switch locomotives with EMD 645 engines.

Figure 3-1: Potential amended emission standards Tier 5 [11]

Noise pollution: The dominant source of noise at medium speeds is the wheel-rail rolling friction, while at low speeds or when the train is stopped, it is noise from the engine and other power equipment the dominates. It is also important to note that rolling friction noise is much more important for freight rail[12] than for passenger trains.

Another important environmental consideration is fuel spills. Diesel fuel, like other hydrocarbon fuels, can lead to soil or groundwater contamination following spills.[13]

3.1.2 Catenary-Electric Powered Trains

3.1.2.1 Technology

Electrification is the most mature alternative propulsion option to diesel with the lowest technical risk. Catenary-electric propulsion is the dominant propulsion mode for long-distance passenger and freight trains on railway networks in the EU. This is due to its practicality, fewer safety risks for users, and the use of higher voltages which makes it possible to limit losses in electricity transmission over long distances. Furthermore, electric locomotives have the benefits of being much quieter, have no direct emissions, and are generally assessed as being more reliable than diesel locomotives.

Electricity is generally cheaper per unit of freight moved when compared to diesel. The International Union of Railways estimates electricity costs for train propulsion are only 50-60 percent of diesel-based propulsion costs when compared directly[14]. This cost difference is even more substantial in Quebec as the price of electricity is very low by international standards.[15] The maintenance of an electric locomotive is also cheaper than that of its diesel equivalent since the former has fewer moving parts.

A significant drawback related to railway electrification is the high capital cost related to overhead line equipment (OLE). Investment costs for electrifying a railway line often amount to several million dollars per kilometer, including

---

11 greencarcongress.com
12 https://www.europarl.europa.eu/RegData/etudes/etudes/join/2012/474533/IPOL-TRAN_ET(2012)474533_EN.pdf
13 https://railroads.dot.gov/sites/fra.dot.gov/files/2021-06/Study%20of%20Hydrogen%20Fuel%20Cell%20Tech.pdf
14 oliverwyman.com
15 0.05227 CAD$/kWh at the time of writing of this report.

Code de champ modifié
Code de champ modifié
Code de champ modifié

costs related to power generation equipment, transformers, transmission lines and OLE as well as the service disruption caused by the overhead wire installation. This major investment in infrastructure usually has a long payback period, which may offset the advantages of cheaper energy and maintenance.[16] In the case of transnational freight lines, fully electrifying freight lines may also present interoperability issues.

In addition, it is important to consider that the construction of an overhead line system must be compatible with height requirements related to bridges and tunnels along the route.

Several catenary-electric locomotives are currently in use for freight operations throughout the world. However, there are only a handful of cases in the United States where catenary-electric freight locomotives have been in use, all of which were built 25 or more years ago. Neither of the two major locomotive manufacturers, General Electric and EMD (now part of Progress Rail), has produced catenary electric locomotives in over 25 years.

There are several modern catenary-electric heavy-haul locomotives in use around the world today. However, importing locomotives from outside of North America poses significant challenges relating to North American locomotive standards.

3.1.2.2 Current Market Situation

Only about one-quarter of rail lines worldwide are electrified with OLE. The rate of OLE electrification varies among countries, from Switzerland's 99% to the EU's 62%, to Asia's 47% to North America's less than 1%.[17] Currently there aren't any electrified freight locomotives being sold nor in operation in North America. Table 3-1~~Table 3-1~~ provides a comparison of the cost of diesel versus the cost of electricity in various regions around the world.

Table 3-1: Comparison of the cost of fuel and electricity for different regions

Country	Switzerland	EU	Asia	USA	Canada
Price of Diesel ($US/L)	2.246 *(a)*	1.9396 *(b)*	1.1596 *(a)(c)*	1.411 *(a)*	1.672 *(a)*
Price of electricity ($US/kWh)	0.163 *(a)*	0.22 *(b)*	0.099 *(a)(c)*	0.128 *(a)*	0.094 *(a)* 0.040 *(QUEBEC)*

(a) https://www.globalpetrolprices.com/electricity_prices/
(b) https://selectra.info/energie/electricite/prix/europe,
(c) Mean value for China, Singapore, India, Malaysia & Indonesia

3.1.2.3 Environmental Impacts

Carbon footprint: Electric trains have always had no direct carbon emissions because they are powered entirely by electric motors. However, the means of generating the electricity to power these motors must be considered (Well-to-Tank emissions). Producing electricity by burning fossil fuels or coal is associated with large amounts of carbon emissions. Fortunately, approximately 96 % of the electricity produced in Quebec comes from hydroelectric power plants.

In all cases, railway electrification can play an important role in decreasing local emissions in densely populated urban areas where intermodal rail yards are often located.

---

[16] Institute of Transport Economics
[17] https://journals.sagepub.com/doi/full/10.1177/0954409719867495

Code de champ modifié
Code de champ modifié

The website Electricity Maps[18] provides the emissions factors associated with electricity for various geographical regions.

Regarding the carbon footprint related to catenary infrastructure and equipment, an average emissions ratio of 73 tCO_2eq/km was estimated based on data provided by the French railway operator SNCF. This analysis was carried out for the renewal of catenary infrastructure based on the life cycles for 1500 V and 25 kV OLE.[19]

Air Pollution: Catenary-electric locomotives have the advantage of zero air pollutant direct emissions.

The land required for the construction of catenary infrastructure must also be taken into consideration. This can be a significant challenge in urban areas, as well as due to various constraints related to sustainability and the protection of biodiversity along the right-of-way (ROW).

3.1.3 Battery-Powered Trains

3.1.3.1 Technology

Battery-powered trains are the latest evolution of electric trains: an onboard energy storage allows them to run where there is no catenary. These rely on the same technologies related to rail traction efficiency which engineers have been optimizing for decades, from wheel-rail contact to energy recovery.[20] In terms of energy conversion, battery locomotives are extremely efficient compared to diesel locomotives, with an efficiency percentage of approximately 85% compared to about 30% for diesel locomotives.

The Current State of the Technology: Much effort has been made to develop batteries that are lightweight, have small volume, and are robust over many discharge cycles. Lithium titanate is a leading battery type currently being used in electric vehicles due to its high-power capability, long lifecycle, and chemical stability. It is expected to be a good candidate for powering electric trains. Other key types are lithium nickel cobalt aluminum oxide, lithium iron phosphate and lithium nickel manganese cobalt oxide batteries.

The choice of battery cell technology is dependent on the operational requirements of the train. This means that careful modelling is required to define the operational pattern, based on the train's speed profile or duty cycle. Battery characteristics and sizing are then defined accordingly, as well as its life expectation under operational conditions.

An advantage of this set up is that braking energy – the energy dissipated during braking of the train – can be harnessed by an energy storage and management system. However, a battery can often not accept all the regenerated braking energy, so it is necessary to dissipate the surplus energy in resistors (as with rheostatic braking). Infrastructure for recharging the trains must also be considered – the train may be recharged at the terminals, as well as at charging stations along its route.

An important disadvantage of batteries is that their energy density is much lower than that of diesel fuel. An analysis carried out by the Rail Safety and Standards Board has demonstrated that storage requirements related to batteries are 10-20 times when compared to diesel fuel.[21] Freight trains are much heavier and typically need significantly more power than passenger trains.[22] This means that battery capacity and range are important factors for this use

---

[18] electricitymaps.com/map
[19] https://journals.sagepub.com/doi/full/10.1177/0954409719867495
[20] https://www.systra.com/en/expert_insights/zero-emission-trains-energy-transition-or-green-washing/
[21] https://ehr.mydigitalpublication.co.uk/july-2021
[22] Institute of Transport Economics

case, and recharging batteries at small intervals may be impractical. Furthermore, some commercial space on the train may need to be given up due to battery requirements, which could have a financial impact.

A technical challenge associated with batteries is that their performance and autonomy can vary significantly depending on the operational conditions (temperature/climate, track geometry, etc.). In addition, an important limitation of batteries is their power intensity – the rate at which they can be recharged.

Future Developments: Although the current industry is focused on lithium-ion technologies, a shift into solid-state battery design is expected in the future as demands related to lifespan and energy/power density continue to increase. Other concerns are related to overcoming safety issues and limiting the risks of fire, explosion, and the release of toxic gases. Hence, there is a continuous need to further improve lithium-ion batteries and develop new battery technologies.

In solid-state batteries, the highly reactive liquid electrolyte is replaced with a solid-state electrolyte, which is inherently safer and more rigid and promises to increase the battery's energy density without compromising safety. The development of solid-state batteries and their commercialization would represent a real technological disruption. However, further research is needed to ensure the stability of the electrode/electrolyte interfaces. The use of solid electrolytes would also have a big impact on manufacturing processes.

Regarding the required investments to move from the pilot project phase to commercial production, it is likely that the first applications of solid-state batteries would only cover certain market segments, such as consumer electronics. Once it is possible to take advantage of consumer feedback and economies of scale, it will expand to larger applications including electric vehicles and trains. Companies like SAFT are already developing "solid" Li-ion batteries. They believe that it will emerge as a mature technology in about 8 to 10 years.[23]

3.1.3.2 Current Market Situation

Currently, all railway battery projects have been focused on passenger trains. However, in recent years, testing has begun for battery electric solutions for freight trains.[24]

In April 2021, Burlington Northern Santa Fe Corporation (BNSF)[25] and Wabtec (formerly General Electric) completed a test on a 350-mile route between Barstow and Stockton California.[26] For this test a battery-powered locomotive named the "FLXdrive" was paired with diesel trains in a hybrid consist – between two Tier 4 locomotives. The tested battery-electric freight locomotive had a 2,400 kWh of onboard energy storage which can deliver a continuous power of 4,400 HP for a period of 30-40 minutes. It features an energy management system and a top speed of approximately 75 mph. The test results showed an average reduction of 11% in fuel consumption and GHG emissions for the train, which is the equivalent of over 6,200 gallons of diesel fuel saved and around 62 tonnes of CO_2 emissions reduced.[27]

[23] saftbatteries.com
[24] Institute of Transport Economics
[25] BNSF.com
[26] Wabtec: Read this page for further technical details
[27] https://www.wabteccorp.com

Code de champ modifié
Code de champ modifié
Code de champ modifié
Code de champ modifié
Code de champ modifié

Canadian National Railway recently announced having also placed an order for a Wabtec FLXdrive locomotive. It is expected to be delivered in 2023.[28] In addition to this, Wabtec announced a collaboration with General Motors to develop and implement GM's Ultium battery technology for use in its locomotives.

Wabtec has also announced that the development of the next-generation FLXdrive is already in the works. It will have a similar power delivery but will feature a significantly larger battery capacity of 7 MWh. According to Wabtec, this level of energy can reduce locomotive fuel consumption and carbon emissions by up to 30% on certain routes.

Like the original generation of the FLXdrive, the 7 MWh version will be integrated into multiple-unit consists with the overall train energy management under the control of Wabtec's Trip Optimizer train control software. This will allow an optimal recharging and discharging of the battery to maximize train fuel savings and battery life. Second-generation FLXdrives are planned for commercial use and could enter supply chain routes in the next few years.

In July of 2020, Vale received its first 100% electric battery-powered switchyard locomotive produced by Progress Rail and named the "EMD Joule", as part of its Power Shift Program. The switcher's batteries will feature a 1.9 MWh storage capacity expandable to 2.4 MWh, enabling it to operate up to 24 hours without needing to recharge.[29]

Currently, Progress Rail is offering the EMD Joule Battery-Electric Locomotive series available as a new build or as a rehaul of an existing diesel locomotive by converting it to a battery propulsion. These locomotives support a wide range of railway operations with battery capacities of up to 14.5 MWh. Applications include switching/shunting yards, regional service, and in-consist operation in tandem with diesel-electric locomotives.

As of 2022, the Wabtec's FLXdrive is further along in its development than its competitors in the freight sector and has received the most orders so far - Roy Hill, Canadian National, Rio Tinto, BHP and Union Pacific, which is North America's largest railroad. Progress Rail's Joule has orders from Vale, FMG, BHP and Union Pacific.

As for battery technologies, developments from the automotive industry are likely to result in increased battery capacity and lifespan while decreasing cost, with these benefits expected to trickle into the rail industry as well. At the same time, large oil & gas companies are staking out their part of the market by acquiring smaller battery suppliers, which only further supports the potential of the technology.[30]

3.1.3.3 Environmental Impacts

Carbon footprint: As with catenary-electric trains, battery-electric trains have no direct carbon emissions. However, any pollution associated with generating the electricity for recharging their batteries must be considered. The higher the share of renewable energies in the traction power grid, the lower the CO_2 emissions of a battery-powered locomotive. In addition, it is important to consider the carbon footprint of battery production. According to the French Energy Agency -ADEME-, producing a Li-Ion battery emits 125 $KgCO_2$/kWh.[31]

Air Pollution: Electrification can play an important role in decreasing local air pollutant emissions in densely populated urban areas as battery-electric locomotives have the advantage of not emitting air pollutants locally.

Second life and Recycling: Manufacturing and dismantling are the most important stages of a battery's lifecycle when it comes to environmental impact. At the end of its first life, a battery still has 75 to 80% of its original capacity.

[28] electrek.co
[29] https://www.mining.com/vale-develops-first-100-electric-locomotive-in-brazil/
[30] https://www.systra.com/en/expert_insights/zero-emission-trains-energy-transition-or-green-washing/
[31] ecologie.gouv.fr

Code de champ modifié
Code de champ modifié
Code de champ modifié
Code de champ modifié

The principle of a "second life" relates to optimizing the use of a product to reduce its environmental footprint and increase its economic value. The recycling process of Li-ion batteries is still relatively under-developed due to the low demand, and the difficulties related to providing cost-effective industry-scale solutions. The recycling process is also complicated by the structure of large battery packs. However, recycled materials have a significantly lower carbon footprint. For example, the use of recycled aluminum creates approximately 95%[32] less GHG emissions when compared to producing aluminum from natural sources. The net reduction in emissions is estimated to be in the range of 1–2.5 kg CO_2 per kg of battery recycled.[33]

End-of-life management for batteries – including second-life applications of automotive batteries and standards for the management of battery waste – is crucial to reduce the volumes of raw materials needed for batteries and to limit the risk of shortages. However, the more batteries are used to power vehicles, the faster the developments in this technology will advance. There is at least one company in North America specializing in the recycling of lithium batteries which is now ensuring a closed loop lithium-ion battery resource recovery with a recovery reaching 95% of all lithium-ion battery materials – extracting high-grade materials for battery production at a cost lower than mined and refined material.

3.1.4 Hybrid Trains

3.1.4.1 Technology

Hybrid trains incorporate a combination of locomotives with different means of converting energy to power the traction motors. Some of the combinations currently being tested on the market are:

- Hydrogen-Battery Locomotive / Diesel-Electric Locomotive
- Battery Locomotive / Diesel-Electric Locomotive
- Battery Locomotive / Catenary Electric Locomotive

Hybrid trains can also be comprised of dual-mode locomotives, which can switch between different power sources. A hybrid locomotive can also take the form of a diesel-electric locomotive combined with a battery tender. Traction power would be provided to the electric traction motors of the locomotive by the batteries of the battery tender car and, upon reaching a defined minimum state of battery charge, the diesel engine is activated.

Hybrid trains and dual-mode propulsion systems, involving batteries located between the power source and the traction system connected to the wheels, can be used to reduce air emissions and increase efficiency. Surplus energy, or energy derived from regenerative braking, can be used to recharge the energy storage system to further improve energy efficiencies. The power source in dual-mode hybrid trains can also be dynamically changed, to allow zero emission (and low noise) operation at stations or at locations where it is most suitable.

Another type of hybrid locomotive is the catenary-electric/diesel hybrid locomotive. An alternative to the catenary electric locomotive, its main prime mover is a diesel engine, but it is equipped with a pantograph allowing it to run in electric mode with an electrified catenary system.

There are already multiple cases where dual-mode hybrid locomotives are being used. The ALP45-DP from Bombardier/Alstom is operated by both New Jersey Transit and EXO Montreal. The locomotives used to run in

[32] theicct.org
[33] theicct.org

Code de champ modifié
Code de champ modifié

electric mode throughout the entirety of the Deux-Montagnes line and along the Mascouche line between Montreal Central Station and Ahuntsic station. However, with the recent conversion of the Deux-Montagnes line into the main line of the Réseau Express Métropolitain (REM) light metro system, and the permanent truncation of the Mascouche line to Ahuntsic station, the locomotives have been running exclusively in diesel mode since January of 2020.

Another notable case is the catenary/battery-electric train which is currently being operated in Japan called the Series EV-E301.[34] This passenger train operates in catenary-electric mode between Utsunomiya and Hoshakuji, an 11.7-km section of electrified track, and in battery-electric mode between Hoshakuji Station and the terminal Karasuyama Station, a 22.4-km long section of track which is not electrified. The train is also able to recharge its batteries during operation in catenary-electric mode.

3.1.4.2 Current Market Situation

While Wabtec's FLXdrive is currently being tested in between diesel locomotives in North America, DB Cargo is partnering with Toshiba to convert 300 older shunting locomotives to diesel-battery hybrids.[35]

A quick hybridization option could be to add battery tenders (specialized cars) behind existing locomotives, enabling fast swapping and off-train recharging. This could drastically lower fuel needs and maximize regenerative braking potential. These battery boxes on wheels could then be recharged at designated locations.

3.1.4.3 Environmental Impacts

The use of hybrid propulsion technologies in rail traffic has a high potential in reducing the environmental impacts of diesel propulsion on non-electrified lines. Hybrid-electric diesel trains allow for a better energy efficiency with a reduced need for diesel fuel, thus reducing GHG emissions and air pollution. The EcoTrain project lead by DB RegioNetz Verkehrs GmbH has the aim of finding new approaches for energy-efficient mass transit vehicles operated in non-electrified territories. A lifecycle impact assessment of a hybrid locomotive (battery-diesel) which was carried out as part of this project showed a reduction in emissions of 1.04×10^6 kgCO2eq (15% less) compared to a diesel train and a reduction of 16% in the overall fuel consumed.[36]

3.2 DISCUSSION

Considering the early development stage of battery-electric locomotives, it's important to note that there are still many limitations related to the use of these in the railway industry.

The environmental impact associated with the production of lithium-ion batteries is a major concern. The process of mining lithium is extremely inefficient, and the mining process is very detrimental to the environment due to the resulting contamination of local water supplies with harmful chemicals.

Furthermore, electric-rail technologies cannot be considered as being zero-emissions unless the energy produced at the source is zero emissions as well. Still, it is generally accepted that battery-electric rail equipment is better for the environment than its diesel-based alternative, despite the negative environmental impacts associated with battery manufacturing.

[34] Battery-Electric Cars in Japan: https://www.jreast.co.jp/e/development/tech/pdf_31/tec-31-27-32eng.pdf
[35] oliverwyman.com
[36] Life Cycle Assessment of a Hybrid Train – Comparison of Different Propulsion Systems: pdf.sciencedirectassets.com

Code de champ modifié
Code de champ modifié
Code de champ modifié

Since the present report focuses on alternative propulsion modes, the alternative of hydrogen fuel cell locomotives must be mentioned, despite not being part of the scope of the current study.

Hydrogen fuel cell-powered locomotives have the advantage of only generating water as a by-product of their operation. However, that certainly does not mean that the technology is without drawbacks. With an efficiency of approximately 60%, hydrogen-based traction power is not as efficient as battery-electric-based power. Furthermore, electrolysis, the process of creating the hydrogen gas used to fuel cell trains, is only about 80% effective, bringing the overall efficiency of hydrogen fuel cells down to about 50%. In addition, the cost of building the facilities needed to generate hydrogen gas can be quite high.

Overall, both battery-powered and hydrogen-powered trains are better alternatives to diesel propulsion with respect to their overall environmental impact, and both are less expensive than catenary-electric trains, but they both have their downsides. However, a clear winner has not yet been established, with major railroads such as Canadian National and Union Pacific investing into battery-electric trains, and Canadian Pacific and BNSF investing into the hydrogen alternative.

Still, neither of these alternative propulsion modes is yet ready to fully replace diesel trains in North America. Thus, for the time being, railway operators should avoid having a full reliance on battery-based propulsion. However, when used as part of a hybrid operation, battery-electric propulsion can already provide a significant increase in fuel efficiency and a reduction in GHG emissions.

3.3 Rolling Stock Maintenance

While there is still limited experience in the industry with respect to battery-powered trains, maintenance costs are expected to be significantly lower than for its diesel-electric counterpart – as much as 75% less. The most-significant maintenance items for a locomotive are the wheels, brakes, and traction motors. The batteries have a life expectancy of about 10 years; however, this value depends on the operating conditions and the number of charging/discharging cycles accumulated over time.

Battery locomotives have also a battery maintenance system which includes blowers to maintain the batteries at their optimum operating temperature. These blowers will require regular maintenance as well.

Vision Eeyou Istchee

4. THE BILLY DIAMOND HIGHWAY RAILWAY

4.1 GENERAL CHARACTERISTICS

The following table provides the general characteristics of the Billy Diamond Highway railway:

Table 4-1: Characteristics of the Billy Diamond Highway railway

Item	Characteristics	Comments
Railway Network	Class 3 track	Right Hand Running
Gauge	Standard Gauge	1,435 mm (4ft. 8-1/2 in)
Operating Days	340 days (trains can run at night)	
Axle Loading	30.0 metric tonnes	
Annual Net Product Transported	1.5 Million Tonnes (anticipated)	
Traction Mode	Diesel-Electric	
Siding Length	Clearance length (train length w/fouling point distance) +10%	With minimum 200 m long back tracks

The Billy Diamond Highway railway alignment extends between the Waskaganish, located at KP 236, and Matagami, located at KP 0. Figure 4-1~~Figure 4-1~~ below provides an overview of the railway's alignment.

Commenté [MH1]: Wrong conversion

a mis en forme : Surlignage

a mis en forme : Surlignage

Figure 4-1: The approximate alignment of the Billy Diamond Highway railway

As for the vertical profile, the maximum grades in the southbound direction (descending KPs) is 1.50 %, while the maximum grade in the northbound direction is 1.47%.

4.2 Operations

As the railway will be maintained and operated at Class 3 standards, the following maximum operating speeds will be applicable on the line as per Transport Canada:

Table 4-2: Class 3 applicable speed limits

Train Type	Speed Limit
Freight Trains	40 MPH / 64 KM/H
Passenger Trains	60 MPH / 96 KM/H

4.2.1 Freight Trains

Freight traffic on the line is expected to be about 1 train per direction per day. Thus, the train will travel southbound towards Matagami on one day, where it will be loaded/unloaded overnight. It will travel back north on the next day and will remain at Waskaganish overnight, before repeating this cycle.

Freight trains will be serving various industrial clients and the train consists will be mixed. Table 4-3~~Table 4-3~~ provides the type of freight cars considered for freight operations, as well as the specifications assumed. There will be a client siding located at KP 60, where the train will stop to couple and decouple flat cars loaded with lumber.

Table 4-3: Freight car specifications

Client/Merchandise	Wagon Type	Payload (tonnes)	Tare Weight (tonnes)	Total weight (tonnes)	Length (m)
Critical/Alcam	Lithium Hopper	79.2	24	103.2	9.2
Nemaska	Lithium Flat Car	79.3	40.7	120	21.1
Hydro Quebec	Freight Flat Car	90.1	29.9	120	21.1
N/A	Lumber Flat Car	82.1	37.9	120	22.4

The following table provides the anticipated train compositions at the writing of this report:

Table 4-4: Freight train make-up

Route	Train Make-Up	Total Weight Hauled
Southbound Start KP 236 (Waskaganish) End KP 60 (Lumber Siding)	38 Loaded Lithium Hoppers 19 Loaded Lithium Flat Cars 6 Empty Freight Flat Cars	6,381 tonnes
Southbound Start KP 60 (Lumber Siding) End KP 0 (Matagami)	38 Loaded Lithium Hoppers 19 Loaded Lithium Flat Cars 8 Loaded Lumber Flat Cars 6 Empty Freight Flat Cars	7,341 tonnes
Northbound End KP 0 (Matagami) Start KP 60 (Lumber Siding)	38 Empty Lithium Hoppers 19 Empty Lithium Flat Cars 8 Empty Lumber Flat Cars 6 Loaded Freight Flat Cars	2,709 tonnes
Northbound End KP 60 (Lumber Siding) Start KP 236 (Waskaganish)	38 Empty Lithium Hoppers 19 Empty Lithium Flat Cars 6 Loaded Freight Flat Cars	2,405 tonnes

As for diesel train traction, which is currently the main propulsion mode considered, it is currently assumed that it will be provided by two EMD SD70 locomotives. This locomotive model has been in operation around the world for decades and is a proven choice for freight train operations. Furthermore, these locomotives are readily available on the used market, which can provide additional savings in the project's capital cost. Table 4-5~~Table 4-5~~ provides the specifications for the EMD SD70 locomotives.

Table 4-5: EMD SD70 locomotive specifications

Item	Specification
Model	SD70
Weight (tonnes)	194.4
Number of axles	6
Axle load (tonnes)	32.4
Length (m)	22.04
Power (hp)	4,300
Max adhesion (%)	26

4.2.2 Passenger Trains

There will be two passenger trains per week operating on the Billy Diamond Highway railway. Table 4-6~~Table 4-6~~ provides a summary of the planned passenger train service on the railway.

Table 4-6: Passenger train service on the Billy Diamond Highway railway

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Route	Travel southbound (Waskaganish to Matagami)	No service	No service	Travel northbound (Matagami to Waskaganish)	Travel southbound (Waskaganish to Matagami)	No service	Travel northbound (Matagami to Waskaganish)

Passenger trains will be composed of one locomotive, three passenger coaches and one genset car. A freight locomotive will be used to pull the passenger coaches, which makes it possible to simplify the railway fleet management and maintenance by only having a single type of locomotive to maintain. The genset car will generate the necessary power as required for the passenger coaches. The rolling stock specifications are provided in Table 4-7~~Table 4-7~~ below.

Table 4-7: Passenger coach and genset specifications assumed

Item	Specifications
Model	Passenger coach/genset
Weight (tonnes)	56.15
Number of axles	4
Axle load (tonnes)	14.04
Length (m)	20

5. ASSUMPTIONS

Please note some of the project characteristics may change after the completion of the present report. The following section provides the assumptions on which this study is based on.

5.1 EQUIPMENT AVAILABILITY

As mentioned in Section 3.1.2, supplying catenary-electric freight locomotives for the Grande Alliance project would pose significant challenges. At the same time, there are multiple battery-electric locomotives currently being developed and tested for North American use. However, while the technology is still in early development, it will be assumed that by the time operations on the Billy Diamond Highway railway begin, there will be battery-electric locomotives available for purchase with the specifications provided in Table 5-1~~Table 5-1~~ or better:

Table 5-1: Battery locomotive specifications assumed for the purpose of the present study

Item	Specifications[37]		
Model	Wabtec FLXdrive[38]	Progress Rail Battery Loco Type 1	Progress Rail Battery Loco Type 2
Weight (tonnes)	195	195	260
Number of axles	6 (Co-Co)	6 (Co-Co)	8 (BB-BB)
Axle load (tonnes)	32.5	32.5	32.5
Length (m)	23.32	23.3	24
Power (hp)	4291	6034	8716
Max adhesion used (%)	31	31	31
Battery capacity (MWh)	7.0	8.0	14.5

[37] Specifications for the battery locomotives Type 1 and 2 were provided by Progress Rail. However, these locomotives are still in development and the specifications may change in the future.

[38] https://www.wabteccorp.com/newsroom/press-releases/roy-hill-sets-new-course-with-purchase-of-flxdrive-battery-locomotive

Code de champ modifié

5.2 Energy Requirements

Energy requirements for this study were calculated using the Railsim Train Performance Calculator (TPC) software developed by SYSTRA. This software is able to simulate the performance of the train while considering:

- The track geometry, including both the horizontal alignment and the vertical profile;
- The speed limits on the line;
- The rolling stock details, including the locomotive tractive effort, the weight of the various equipment, and other specifications.

TPC makes it possible to the determine tractive requirements of the trains, as well as the energy consumed, be it in terms of electricity or diesel fuel. Table 5-1~~Table 5-1~~ below provides an example of some of the results obtained using the Railsim TPC software.

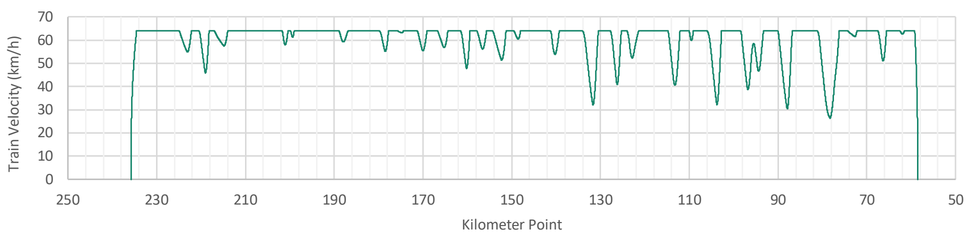

Figure 5-1: Train velocity for a freight train hauled by two Progress Rail Type 1 Battery Locomotives travelling south from Waskaganish (KP 236) to the lumber siding (KP 60)

Simulations were carried out for each scenario studied in order to calculate the energy required for each trip. This value was then increased by 5% in order to consider that the actual power consumed by a locomotive may be variable depending on specific conditions and the particularity of operations on a given day, as well as energy consumed during train movements within the yards.

The total energy required per trip is provided in Table 5-2~~Table 5-2~~. In order to reduce the energy required for a given trip, battery locomotives will be able to use some of the energy released during braking to recharge their batteries. It is estimated that regeneration will be able to reduce energy requirements by approximately 15-18%. Since the batteries will not be able to accept all the regenerated energy (as it may exceed their maximum charging rate), it was assumed that the recharging efficiency during braking will be about 60%.

Table 5-2: Energy required for traction per trip using a train hauled by two battery locomotives

Route	Progress Rail Battery Loco Type 1 (2 locomotives in train consist)		Progress Rail Battery Loco Type 2 (2 locomotives in train consist)	
	Without energy regeneration	With energy regeneration	Without energy regeneration	With energy regeneration
Southbound (KP 236 – 0)	25.07 MWh	21.42 MWh	26.19 MWh	22.38 MWh
Northbound (KP 0 – 236)	13.80 MWh	11.46 MWh	13.68 MWh	11.33 MWh

Energy requirements for catenary-electric locomotives will be essentially the same as for battery-powered locomotives. However, while these can regenerate energy during braking as well, there will not be enough traffic on the line for this energy to be recaptured, and thus all of it will be lost. Catenary-electric locomotives do not have a way of storing regenerated energy and the only way for it to be effectively used is for another train to be in close enough proximity to be able to use the transmitted energy at the same time it is being regenerated.

5.3 Challenges Related to Battery-Powered Locomotives

Battery technologies still have many limitations which makes their use in railway operations challenging. The suitability of this propulsion mode will vary depending on the specific operational conditions, with some of the main factors being:

- the length of the trips;
- the local climate;
- the tonnage hauled;
- the track geometry and track gradients;
- the availability of electrical infrastructure to recharge the batteries;
- the flexibility of operations to allow for the time it takes to recharge the batteries.

The following challenges related to using battery-powered locomotives have been considered in this analysis and should be taken into consideration when implementing battery traction:

- The local climate of the Grande Alliance project involves harsh winter months, when the low temperatures will have a significant negative impact on the ability of the batteries to provide the necessary tractive energy. While it is difficult to estimate the exact impact, based on experience from the automotive industry it was estimated that the battery charge available for locomotive traction during the winter months will be reduced by approximately 35%.
- Due to the significant distance that trains cover between the terminals of Matagami and Waskaganish, battery tenders will be required to supplement the onboard batteries of the locomotives and provide sufficient energy for the trip.
- In order to limit battery wear and the impact on the available battery capacity, battery-powered locomotives may need to be parked inside the maintenance shops during the cold winter nights. However, there may not

be sufficient space to store all battery tenders. Thus, additional heating may need to preserve the condition of the batteries.

- Fast charging the batteries will increase the rate of wear and reduce their lifespan, and thus should be kept to a minimum. Furthermore, if fast charging is used, the batteries cannot be charged above 95%.
- To limit battery wear and ensure that batteries reach their full lifespan, these should not be discharged below 20%. This reduces the usable battery charge of the trains.
- It is well understood with the current state of technology that battery capacity will reduce over time due to wear. This effect is estimated to amount to about a 25% loss of charge over a period of 10 years. This loss was considered in the present analysis to ensure that, even with only 75% of its charge available, trains will be able to complete their trip.
- The rate of charge of the batteries provided by Progress Rail was 1.2 MW for fast charging up to a charge of 80%. Considering the significant battery capacity required for the trains, this may result in the need of multiple charging stations at each terminal to recharge the locomotives in parallel order to reduce the overall time required.

5.4 Power Supplied to the Railway

One of the challenges related to electric trains, be it using catenary-electric locomotives or battery-powered ones, is ensuring that sufficient electric energy will be provided to support railway operations. For the current project, it was assumed that the appropriate contract will be established with Hydro-Quebec (HQ) to supply the necessary power. HQ already owns infrastructure in proximity of the Grand Alliance project, as shown in Figure 5-2~~Figure 5-2~~.

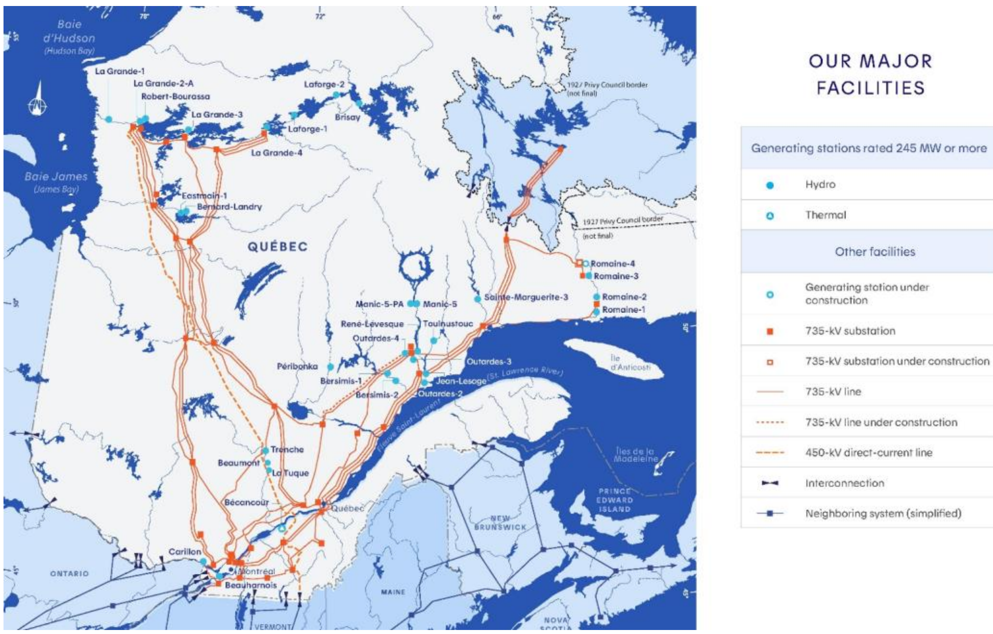

Figure 5-2: Hydro Quebec map of facilities[39]

[39] Hydro Quebec Annual Report 2021

6. DESCRIPTION OF SCENARIOS

The following scenarios will be studied in the present report:

- Alternative A: Full railway electrification with catenary-electric locomotives
- Alternative B: Battery-powered trains
    - Scenario B1: Charging the locomotives at Waskaganish and Matagami.
    - Scenario B2: Charging the locomotives at Waskaganish, Matagami and recharging at a boost station at the midway point (KP 118)
    - Scenario B3: Charging the locomotives at Waskaganish and Matagami, and swapping the battery tenders at the midway point (KP 118)
    - Scenario B4: Running a hybrid train with two diesel and one battery locomotive, and recharging the locomotive at Waskaganish and Matagami

6.1 ALTERNATIVE A: CATENARY ELECTRIC LOCOMOTIVES

Using catenary-electric locomotives would require the full electrification of the railway, which includes the construction of catenary poles along the line using a 2x25 kV system. Figure 6-1~~Figure 6-1~~ below provides a schematic illustrating the global architecture of the electrification network from the Hydro Quebec grid to the train.

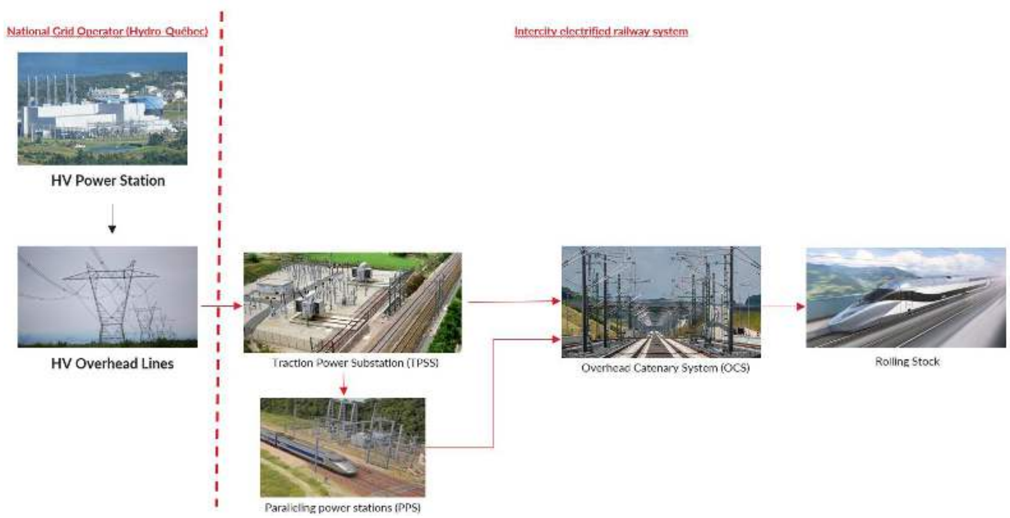

Figure 6-1: Schematic of the electrification infrastructure required

The substation transforms power from the high-voltage network to 25kV to supply the catenary. An additional power cable, called feeder, which is in opposite phase to the catenary is also at a potential of 25 kV in relation to the rail. The potential difference between the catenary and the feeder is 50 kV.

The result of this assembly is that the electrical power is then transported over a large distance under a voltage of 50 kV (between the feeder and the catenary) to reduces losses, while the autotransformer delivers power to the train at 25 kV (between the catenary and the rail).

In addition, the current feeding the train comes from the two autotransformers which surround it (in front and behind it), lowering the current in a section of catenary.

This type of electrification has many advantages:

- A smaller number of substations is required (spaced at around 80 km);
- The drop in voltage is eliminated;
- EMC and stray current impacts are limited;
- The ability to meet the necessary power demand required for high frequency train and/or high-speed operations;
- Generally suitable for long distance railway operations.

6.2 Alternative B: Battery Electric Locomotives

6.2.1 Scenario B1: Charging at the Terminals

This scenario would use two battery-electric locomotives to provide motive power for the train. An additional battery system with enough capacity to last the journey between terminals (~236 km) would supplement the internal batteries of the battery-electric locomotives. Locomotives will be able to recharge at each terminal (Waskaganish and Matagami) overnight and will be ready to carry out a full trip on the following day.

Due to the combination of long travel distances, the tonnage hauled, the cold weather and the railway grades, this scenario results in significant requirements in terms of the battery capacity needed for each train.

The main advantage of this scenario is that infrastructure requirements are kept to a minimum. However, until the reliability and performance of the batteries can be proven in harsh winter operating conditions like the ones currently in Quebec, this scenario involves the risk of a stranded train with fully discharged batteries. Recovering a stranded train would involve significant challenges, due lack of charging infrastructure along the line.

6.2.2 Scenario B2: Charging at a Boost Station Located Midway (KP 118)

In this scenario, the train would recharge at each terminal (Matagami and Waskaganish), in addition to a boost station located at the halfway point of the Billy Diamond Highway railway, approximately at KP 118. This scenario addresses the challenge related to the high battery capacity required for trains in Scenario 1B by allowing the trains to stop at the halfway point of the trip and recharge their batteries. This results in a reduction of the battery capacity required per train by about 50% and significantly reduces the risk related to stranded trains. However, the additional charging infrastructure requires additional capital costs, support staff at the charging facility and will increase the overall travel time of the trains.

While ultra-fast-charging technologies are currently in development with promises of being able to recharge batteries in only minutes, this would result in very high requirements in terms of power delivery to the boost station. Furthermore, the technology is not yet advanced enough to enable this rate of charging for batteries of the size and the capacity required for train operations. A representative of Progress Rail provided an estimate that, with the current state of battery technologies, a locomotive equipped with an 8 MWh battery can be fast charged from a

20% charge to an 80% charge in about 4 hours. Thus, it is expected that the time required for recharging the train at the boost station will be in the order of hours in the best of scenarios.

6.2.3 Scenario B3: Battery Tender Swapping at the Halfway Point (KP118)

This scenario is like the charging midway scenario, but instead of fast charging at the stops, the discharged batteries would be swapped with fully charged ones at designated battery swap facilities. The swapping process will be much faster than the required time to fully recharge a depleted battery, resulting in a significant time saving advantage to the midway charging scenario.

It is important to note that swapping the on-board batteries of the locomotives would be complicated and is not currently possible. It would require overhead cranes and manipulation equipment suitable for the handling of batteries, as well as additional safety measures to mitigate the risks of chemical fire and explosion.

On the other hand, swapping entire discharged battery tender wagons with a set of fully charged ones would be as easy as uncoupling and switching the wagons. The time required for this operation would be in the order of minutes. The downside of this option is that additional tracks would be required to store the spare battery tender wagons while these are being recharged. In addition, it requires the purchase of additional battery tenders.

6.2.4 Scenario B4: Diesel/Battery Hybrid Approach

By combining both diesel-powered and battery powered locomotives, this scenario makes it possible to reduce the risk related to the early stage of development of battery-powered locomotives, while providing an opportunity to test this technology and still obtain certain benefits in terms of reduced diesel fuel requirements and GHG emissions. Furthermore, as technologies improve over time, additional equipment and infrastructure can gradually be added such that zero emission operations can be attained at some point in the future.

In the present case, this scenario considered that train traction will be provided by two diesel locomotives and one battery locomotive. No battery tenders were considered, but the addition of such wagons can further improve fuel consumption and GHG emissions.

The battery locomotive will be placed between the two diesel locomotives, similar to the approach taken by Roy Hill with the Wabtec FLXdrive[40], and will benefit from being able to recharge its batteries during braking. However, the battery locomotive will not have enough energy on its own to fully replace a diesel locomotive, hence why two diesel locomotives are required instead of just one.

[40] https://www.wabteccorp.com/newsroom/press-releases/roy-hill-sets-new-course-with-purchase-of-flxdrive-battery-locomotive

Code de champ modifié

7. STATIC ENERGY MODELLING

Energy modelling was carried out using static calculations to determine the battery capacity requirements and the impact of the time required for recharging battery locomotives. These calculations were based on the results from the TPC simulations and the assumptions described in the previous sections.

At the core of this analysis is estimating the energy required for traction versus the energy capacity of the batteries.

To provide robustness to the results provided, energy calculations were carried out for the worst-case scenario, which considers a reduced battery capacity due the cold weather conditions and battery wear.

7.1 AVAILABLE BATTERY CAPACITY

The first step of the static energy modelling is to calculate the available battery capacity of each locomotive and the battery tenders. The following table shows the available capacity for each type of locomotive and the battery tenders.

Table 7-1: Available battery capacity of the locomotives and battery tenders

Model	Wabtec FLXdrive[41]	Progress Rail Battery Loco Type 1	Progress Rail Battery Loco Type 2	Battery Tender
Total battery capacity (MWh)	7.0	8.0	17.7	5.0
Available battery capacity (MWh)	2.7	3.1	6.9	1.9

As shown in Table 7-1 above, the available battery capacity for traction of the trains is much lower than the total capacity of the batteries, due to the capacity lost in cold weather, the fact that batteries should not be discharged below 20% and because a worst-case scenario is considered where the batteries have lost 25% of their charge due to wear.

7.2 SCENARIO ANALYSIS

7.2.1 Scenario B1: Charging at the Terminals

In this scenario, the train should have sufficient battery capacity to do a full trip going south, as well as a full trip going north on the Billy Diamond Highway railway. Batteries will be recharged at the terminals overnight. The available time for recharging at the terminals is about 12 hours.

As per the energy requirements shown in Table 5-2~~Table 5-2~~, the energy required for a southbound trip is almost double that required for a northbound trip. Thus, the southbound energy requirements will govern the train consist makeup in terms of the battery capacity required. Furthermore, when we compare the available capacity of two

[41] https://www.wabteccorp.com/newsroom/press-releases/roy-hill-sets-new-course-with-purchase-of-flxdrive-battery-locomotive

Code de champ modifié

Progress Rail Type 1 battery locomotives of 6.2 MWh to the tractive energy required for a southbound trip of 21.4 MWh (for freight trains), it becomes evident that several battery tender cars will be required:

Table 7-2: Calculation of battery tender requirements for Scenario B1 (freight trains)

Item	Train Consist	Progress Rail Battery Loco Type 1	Progress Rail Battery Loco Type 2
Traction energy required	Southbound	21.4 MWh	22.4 MWh
Available battery capacity (locomotives)	2 x battery locomotives	6.2 MWh	11.3 MWh
Available battery capacity (battery tenders)	Loco Type 1: 8 x battery tenders Loco Type 2: 6 x battery tenders	15.6 MWh	11.7 MWh
Total available battery capacity for the train	-	21.8 MWh	23.0 MWh

Thus, 8 battery tenders will be required for the freight train (with 2 x Progress Rail Battery Locomotives Type 1) to have sufficient available battery capacity, in addition to the 71 freight cars hauled. Using Type 2 locomotives would reduce this requirement to 6 battery tenders, due to their larger battery capacity. The additional load of hauling the battery tenders was also considered in the tractive energy requirements and an iterative process was used to determine the optimal configuration.

A charging rate of 1.2 MW was assumed for all locomotives and battery tenders. At this charging rate, it would take:

- 4 hours to recharge the Progress Rail Battery Loco Type 1;
- 7.3 hours to recharge the Progress Rail Battery Loco Type 2;
- 2.5 hours to recharge a 5 MWh battery tender.

For this scenario, considering the significant battery capacity required for one freight trip on the Billy Diamond Highway railway, it would take 28 hours to fully recharge two Progress Rail Battery Loco Type 1 locomotives and 8 battery tenders. Since only 12 hours are available for train recharging, charging infrastructure must allow 3 vehicles to be recharged in parallel, which can reduce the total charging time to about 10 hours. Refer to Figure 7-1 for a diagram describing the train cycle for this scenario.

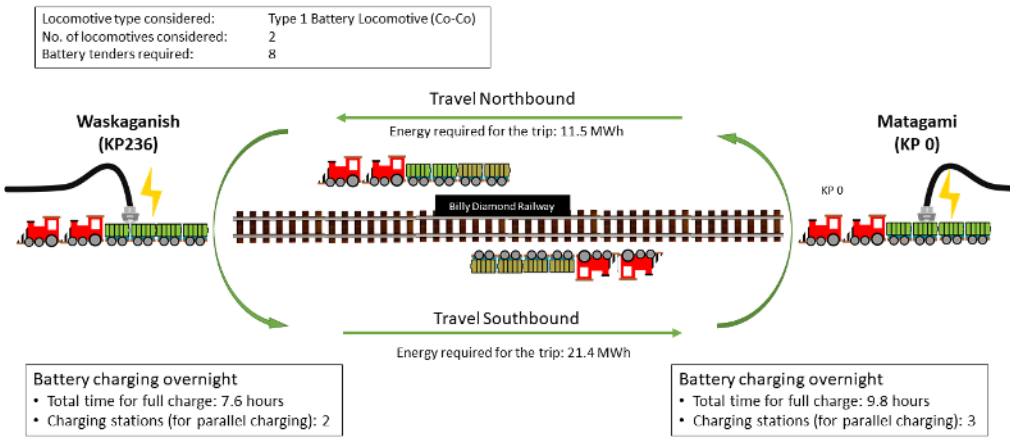

Figure 7-1: Train cycle diagram for Scenario B1

7.2.2 Scenario B2: Charging at a Boost Station Located Midway (KP 118)

The main advantage for this scenario is that, since the train can be recharged halfway through the trip, a smaller battery capacity will be required, thus reducing the number of battery tenders which need to be hauled. The boost station was placed at the halfway point (KP 118) and the energy requirements are as follows:

Table 7-3: Traction energy requirements for Scenario B2

Direction	Route	Progress Rail Battery Loco Type 1	Progress Rail Battery Loco Type 2
Southbound	KP 236 – 118	9.7 MWh	9.9 MWh
	KP 118 – 0	10.8 MWh	11.4 MWh
Northbound	KP 0 – 236	9.5 MWh	9.2 MWh

As shown in Table 7-3, the trip southbound is now divided into two almost equal portions with very similar energy requirements. Furthermore, the trip northbound has the same energy requirements as one of these portions, which makes it possible to optimize the train battery tender configuration.

Table 7-4 below provides a summary of the energy calculations for this scenario.

Table 7-4: Calculation of battery tender requirements for Scenario B2

Item	Train Consist	Progress Rail Battery Loco Type 1	Progress Rail Battery Loco Type 2
Traction energy required	Southbound	10.8 MWh	11.4 MWh
Available battery capacity (locomotives)	2 x battery locomotives	6.2 MWh	11.3 MWh
Available battery capacity (battery tenders)	Loco Type 1: 3 x battery tenders Loco Type 2: 1 x battery tenders	5.9 MWh	1.9 MWh
Total available battery capacity for the train	-	12.1 MWh	13.3 MWh

As shown in the table above, 3 battery tenders will be required for the Progress Rail Battery Locomotive Type 1, and only 1 battery will be required for trains equipped with Type 2 locomotives. It must be noted here that Type 2 locomotives will have sufficient battery capacity to make the trip without battery tenders, however this would result in significantly higher charging time at the boost station.

Considering the significant time required to recharge the locomotives or battery tenders, it would be imperative to keep the time the train will spend at the boost station to a minimum to limit the impact on operations. The time required to recharge the train's batteries at the boost station was estimated to be approximately 5 hours. This can only be achieved if the charging infrastructure allows 3 vehicles to be recharged at the same time. This time would be doubled if only two vehicles can be recharged in parallel.

Figure 7-2 illustrates the train cycle for Scenario B2.

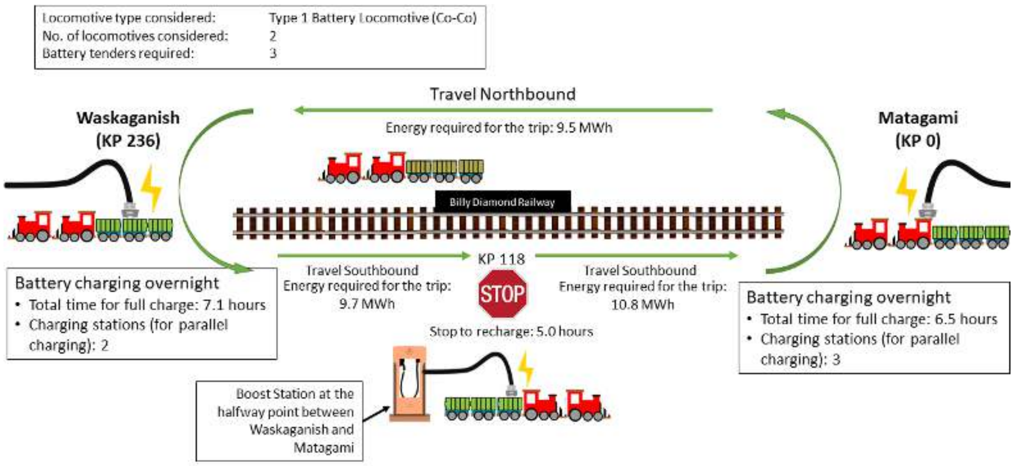

Figure 7-2: Train cycle diagram for Scenario B2

7.2.3 Scenario B3: Battery Tender Swapping at the Halfway Point (KP118)

This scenario considers that fully charged battery tenders will be available at the Boost Station at KP 118. This way, the train travelling southbound would be able to stop and uncouple the discharged battery tenders, while coupling the fully charged ones. Subsequently, the train could do the second part of the trip without needing to wait for batteries to be recharged at the Boost Station.

In terms of the battery requirements, 4 battery tenders will be required for trains with Type 1 locomotives, and 3 battery tenders will be needed for trains with Type 2 locomotives. Figure 7-3 illustrates the train cycle for Scenario B3.

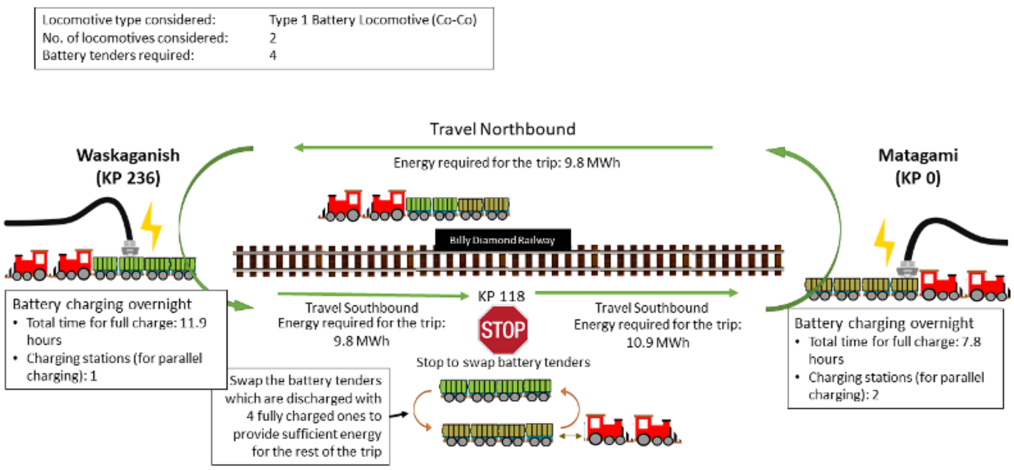

Figure 7-3: Train cycle diagram for Scenario B3

This scenario makes it possible for the train to haul only 4 battery tenders, and there is no time lost for charging at the Boost Station, however, additional battery tenders must be purchased when compared to Scenario B2, and additional infrastructure is required for recharging when compared to Scenario B1.

7.2.4 Scenario B4: Diesel/Battery Hybrid Approach

This approach combines two diesel locomotives with one battery locomotive. While this scenario will not result in zero emissions, it will allow a significant reduction in emissions and fuel consumption with minimal impact on operations and a smaller initial investment.

For this scenario, it was considered that no battery tenders will be hauled with the train. The battery locomotive will be recharged overnight at the terminals, as well as using regenerative braking and will pick up a portion of the tractive load. However, it may run out of charge at a certain point, after which the diesel locomotives will pick up 100% of the traction.

The estimated fuel savings are provided in Table 7-5.

Table 7-5: Summary of fuel savings for Scenario B4

Item	Direction	2 Diesel Locomotives only	2 Diesel Locos + 1 FLXdrive Battery Locomotive	2 Diesel Locos + 1 Progress Rail Battery Loco Type 1	2 Diesel Locos + 1 Progress Rail Battery Loco Type 2
Diesel Fuel Consumption (L)	Northbound	2,257	1,809	1,625	1,121
	Southbound	4,745	4,278	4,126	3,460
	N+S	7,002	6,088	5,751	4,581
Reduction in Fuel Consumption	Northbound	-	20%	28%	50%
	Southbound	-	10%	13%	27%
	N+S	-	13%	18%	34%

7.2.5 Passenger train

The passenger train has much smaller requirements in terms of traction energy when compared to the freight trains. This makes it much better suited for the use of battery locomotives. In fact, calculations show that passenger trains will be able to complete a full trip either northbound or southbound without the need of battery tenders, even if the train is hauled by only one battery locomotive. See the estimated energy requirements in Table 7-6 below.

Thus, the only scenario applicable for a battery-powered passenger train would be Scenario B1 – where the train is only recharged at the terminals.

Table 7-6: Traction energy requirements for the passenger train

Item	Train Consist	Progress Rail Battery Loco Type 1	Progress Rail Battery Loco Type 2
Traction energy required	Southbound	2.5 MWh	2.9 MWh
	Northbound	2.4 MWh	2.8 MWh
Available battery capacity (locomotives)	1 x battery locomotive	3.1 MWh	6.9 MWh
Total available battery capacity for the train	-	3.1 MWh	6.9 MWh

As for the hybrid scenario, the optimal configuration would be composed of 1 diesel locomotive and 1 battery locomotive. However, this configuration would be contingent on the possibility of linking control between the two locomotives such a way that the train driver can be in either locomotive and be able to control the train – regardless of the traction mode (be it in battery mode or diesel mode). In this case, the battery locomotive will still have sufficient capacity to the full trip and the hybrid scenario will also be able to provide a 100% reduction in fuel consumption.

Table 7-7: Diesel fuel consumption for the hybrid passenger scenario

Item	Direction	2 Diesel Locomotives only	1 Diesel Loco + 1 FLXdrive Battery Locomotive[42]	1 Diesel Loco + 1 Progress Rail Battery Loco Type 1	1 Diesel Loco + 1 Progress Rail Battery Loco Type 2
Diesel Fuel Consumption (L)	Northbound	463	0	0	0
	Southbound	469	0	0	0
	N+S	932	0	0	0
Reduction in Fuel Consumption	Northbound	-	100%	100%	100%
	Southbound	-	100%	100%	100%
	N+S	-	100%	100%	100%

Since the battery locomotive alone can meet 100% of the traction requirements of the train, the main purpose of the diesel locomotive will be to provide redundancy in case of breakdown. Thus, during normal operations the diesel locomotive can be switched off completely, allowing for zero fuel consumption and zero emissions during travel.

It must be noted that the diesel locomotive will need to be started on a regular basis, as keeping the engine off for extended periods of time would result in premature deterioration of its condition. As such, the overall emissions for operating the passenger train would not be quite zero, however these would be minimal when compared to purely diesel-based operations.

[42] It is assumed that the FLXdrive can function in tandem with a diesel locomotive while providing 100% of the traction.

7.2.6 Summary of the Energy Modelling Results

Table 7-8 below provides a summary of rolling stock requirements for all battery scenarios.

Table 7-8: Summary of the rolling stock requirements for each scenario

Scenario	Type	SD70 / Passenger loco (Diesel locomotive)	Option 1 Wabtec FLXdrive		Option 2 Progress Rail Battery Loco Type 1		Option 3 Progress Rail Battery Loco Type 2	
			Locomotives	Battery tenders	Locomotives	Battery tenders	Locomotives	Battery tenders
B1 (Charging at terminals)	In-operation	0	Not applicable, as the Wabtec FLXdrive was not designed to operate without the assistance of diesel locomotives.		2	8	2	6
	Spare	0			1	1	1	1
	Total	0			3	9	3	7
B2 (Charge at Boost Station)	In-operation	0			2	3	2	1
	Spare	0			1	1	1	1
	Total	0			3	4	3	2
B3 (Swap battery tenders)	In-operation	0			2	8	2	6
	Spare	0			1	1	1	1
	Total	0			3	9	3	7
B4 (Hybrid)	In-operation	2	1	0	1	0	1	0
	Spare	1	0	0	0	0	0	0
	Total	3	1	0	1	0	1	0
B1 (Passenger)	In-operation	0	Not applicable, as the Wabtec FLXdrive was not designed to operate without the assistance of diesel locomotives.		1	0	1	0
	Spare	0			0	0	0	0
	Total	0			1	0	1	0
B4 (Passenger)	In-operation	1	1	0	1	0	1	0
	Spare	0	0	0	0	0	0	0
	Total	1	1	0	1	0	1	0

Table 7-9 provides a summary of the energy consumed for each scenario. A charging-to-traction efficiency of 55% was estimated during the winter months of operations, and a corresponding efficiency of 85% was estimated for the summer months. The charging efficiency changes since batteries take about the same energy to recharge, however they have a reduced capacity due to the cold temperatures during the winter months.

Table 7-9: Summary of the energy consumption for each scenario

Scenario	Locomotive Configuration	Season	Energy consumed for charging (MWh)		Fuel Consumed (L)	
			Southbound	Northbound	Southbound	Northbound
Diesel	2 x SD70	Any	0	0	4745	2257
A (Catenary-electric)	2 x Catenary-electric Locomotives	Any	25.1	13.8		
B1 (Charging at terminals)	2 x Progress Rail Battery Loco Type 1	Winter	38.8	20.7	No diesel fuel consumed.	
		Summer	25.2	13.5		
	2 x Progress Rail Battery Loco Type 2	Winter	40.5	20.5		
		Summer	26.3	13.3		
B2 (Charge at Boost Station)	2 x Progress Rail Battery Loco Type 1	Winter	37.0	17.2		
		Summer	24.1	11.2		
	2 x Progress Rail Battery Loco Type 2	Winter	38.5	16.7		
		Summer	25.0	10.8		
B3 (Swap battery tenders)	2 x Progress Rail Battery Loco Type 1	Winter	37.5	17.8		
		Summer	24.3	11.6		
	2 x Progress Rail Battery Loco Type 2	Winter	39.5	17.9		
		Summer	25.6	11.6		
B4 (Hybrid)	2 x SD70 1 x Wabtec FLXdrive	Winter	4.9	4.9	4278	1809
		Summer	3.2	3.2		
	2 x SD70 1 x Progress Rail Battery Loco Type 1	Winter	5.6	5.6	4126	1625
		Summer	3.7	3.7		
	2 x SD70 1 x Progress Rail Battery Loco Type 2	Winter	10.2	8.6	3460	1121
		Summer	6.7	5.6		
Diesel (Passenger)	1 x Diesel Passenger Locomotive	Any	0	0	469	463
B1 (Passenger)	1 x Progress Rail Battery Loco Type 1	Winter	4.4	4.4	No diesel fuel consumed.	
		Summer	2.9	2.9		
	1 x Progress Rail Battery Loco Type 2	Winter	5.2	5.1		
		Summer	3.4	3.3		
B4 (Passenger)	1 x Passenger Loco (Diesel) 1 x Wabtec FLXdrive	Winter	4.4	4.4		
		Summer	2.9	2.9		
	1 x Passenger Loco (Diesel) 1 x Progress Rail Battery Loco Type 1	Winter	4.4	4.4		
		Summer	2.9	2.9		
	1 x Passenger Loco (Diesel) 1 x Progress Rail Battery Loco Type 2	Winter	5.2	5.1		
		Summer	3.4	3.3		

7.3 Infrastructure and Other Requirements

For the detailed infrastructure requirements for propulsion alternative A, which includes using catenary-electric trains and the full electrification of the Billy Diamond Highway railway, please refer to the Full Electrification Study report (reference number: LGA-1-BD-T-REL-RT-0001).

The following table provides a comparison of the infrastructure and other requirements for each scenario:

Table 7-10: Comparison of the infrastructure and other requirements for each scenario, as well as the impact on operations

	Alternative A: Full electrification	**Scenario B1:** Charging at the terminals	**Scenario B2:** Charging at terminals and at the midway boost station	**Scenario B3:** Battery tender swapping	**Scenario B4:** Hybrid trains
Infrastructure	Requires the full electrification of the railway with catenary infrastructure, as well as the necessary electric equipment (such as substations) to deliver electric power along the line.	A battery charging station at Waskaganish (2 x 1.2 MW charging stations) A battery charging station at Matagami (3 x 1.2 MW charging stations)	A battery charging station at Waskaganish (2 x 1.2 MW charging stations) A battery charging station at Matagami (3 x 1.2 MW charging stations) A battery charging station at the halfway point (KP 118) which also includes a siding track such that the mainline can remain unobstructed during charging (3 x 1.2 MW charging stations)	A battery charging station at Waskaganish (1 x 1.2 MW charging stations) A battery charging station at Matagami (2 x 1.2 MW charging stations) A battery charging station at the halfway point (KP 118) which also includes a siding track such that the mainline can remain unobstructed during charging, as well as a backtrack to store the spare battery tender wagons. (1 x 1.2 MW charging stations)	A battery charging station at Waskaganish (1 x 1.2 MW charging stations) A battery charging station at Matagami (1 x 1.2 MW charging stations)
Rolling stock	4 catenary electric locomotives instead of the diesel locomotives	4 battery-electric locomotives instead of the diesel locomotives 9 battery tender wagons	4 battery-electric locomotives instead of the diesel locomotives 4 battery tender wagons	4 battery-electric locomotives instead of the diesel locomotives 9 battery tender wagons	2 battery-electric locomotives in addition to 4 SD70 locomotives (diesel)
Impact on operations	No impact is anticipated with the current assumptions	No impact is anticipated with the current assumptions	Will increase travel time in the southbound direction by approximately 5 hours Will require an additional crew due to the additional time required for charging before arrival at Matagami	No impact is anticipated with the current assumptions	No impact is anticipated with the current assumptions

8. CAPEX

The capital cost estimates for all scenarios have been developed for comparative purposes. Please note only the direct construction cost was estimated. Some items were omitted from the cost estimate due to being irrelevant to the cost comparison. Table 8-1 below provides a summary of the costs. All costs are in 2023 US dollars.

Table 8-1: Comparative Capital Cost Estimate[43]

Scenario		A	B1	B2	B3	B4	Ref.
Description		Full railway electrification	Charging at terminals	Charge at Boost Station	Swap battery tenders	Hybrid	Reference costs (diesel-only)
CAPEX ($M)	**Infrastructure Total**	**328.3**	**19.4**	**34.9**	**35.1**	**20.8**	**-**
	Power Supply Infrastructure	30.6	20.4	30.6	30.6	20.4	-
	Overhead Catenary Structures	299.7	0.0	0.0	0.0	0.0	-
	Recharging Infrastructure	0.0	0.9	1.5	0.8	0.4	-
	Additional Siding (Boost Station)	0.0	0.0	4.8	5.7	0.0	-
	Maintenance Shop Comparative[44]	-2.0	-2.0	-2.0	-2.0	0.0	-
	Rolling Stock Total	**11.2**	**59.8**	**44.8**	**59.8**	**22.7**	**9.4**
	Locomotives	11.2	32.8	32.8	32.8	22.7	9.4
	Battery Tenders	0.0	27.0	12.0	27.0	0.0	0.0
	Total CAPEX	**339.5**	**79.2**	**79.7**	**94.9**	**43.5**	**9.4**
	Increase from Diesel Base Case	330.1	69.7	70.3	85.5	34.1	-

As shown above, the hybrid scenario B4 is the one requiring the least additional investment. However, the scenarios B2 and B3 require the highest capital investment of all battery options, mainly due to the requirement of constructing a Boost Station, which requires additional track and recharging infrastructure.

With respect to full railway catenary electrification (scenario A), the initial capital investments are significantly higher, due to the cost of construction of catenary infrastructure over the full length of the railway. For the detailed CAPEX of each scenario, please refer to Appendix 5A.

[43] An SD70 equivalent catenary-electric locomotive was considered for scenario A. For scenarios B1, B2 and B3, the estimates provided are based on the use of a Progress Rail Type 1 battery locomotives. For scenario B4, the use of a Wabtec FLXdrive locomotive was assumed.

[44] This represents the difference in the cost of construction of the rolling stock maintenance shops for catenary-electric and battery-powered trains. Since these types of locomotives do not have a diesel engine, some of the equipment in the shop will not be required. The additional equipment needed at the maintenance shop to service battery and catenary-electric locomotives would be insignificant.

9. OPEX AND SUSTANING CAPITAL

The operating cost estimate was developed for the 50-year project horizon to provide a comparison with respect to the energy consumption, rolling stock maintenance and infrastructure maintenance. These items are responsible for the largest cost difference between the propulsion modes compared. The sustaining capital cost estimate for rolling stock and infrastructure maintenance was developed for the same project horizon. An annualized average cost was calculated for easier comparison. All costs are in 2023 US dollars.

Table 9-1 OPEX and Sustaining Capital for all scenarios[45]

Scenario		A	B1	B2[46]	B3	B4	Ref.
Description		Full railway electrification	Charging at terminals	Charge at Boost Station	Swap battery tenders	Hybrid	Reference costs (diesel-only)
OPEX - Annual ($M)	**OPEX Total**	**3.894**	**0.764**	**0.863**	**0.882**	**2.334**	**2.486**
	Energy	0.263	0.337	0.310	0.315	1.669	1.988
	Rolling Stock Maintenance	0.083	0.128	0.103	0.128	0.374	0.498
	Infrastructure Maintenance (EL/BATT)	3.548	0.299	0.450	0.439	0.291	-
	Increase from Diesel Base Case	1.408	-1.723	-1.624	-1.604	-0.153	-
Rolling Stock Sustaining Capital - Annualized ($M)	**Rolling Stock Total**	**0.270**	**4.781**	**3.306**	**4.781**	**1.431**	**0.552**
	Increase from Diesel Base Case	-0.282	4.229	2.754	4.229	0.879	-

The full catenary electrification scenario (A) results in an actual increase in annual operating costs when compared to the diesel-only scenario. The reason for this is that at a level of transportation of about 1.5 MTPA, the line does not have enough traffic such that electrical energy's lower cost can compensate for the increased infrastructure maintenance cost.

With respect to the battery-powered train scenarios, there are significant savings when it comes to energy and rolling stock maintenance cost when compared to the diesel-only reference scenario.

Regarding Sustaining Capital, we see that the catenary electrification scenario provides a cost advantage when compared to the battery scenarios, and even when compared to the diesel-only scenario. The reason for this is that the battery packs on the battery locomotives and battery tenders have an estimated lifespan of about 10 years, after which these will need to be replaced. For the Progress Rail Type 1 locomotive, this was estimated to cost about

[45] An SD70 equivalent catenary-electric locomotive was considered for scenario A. For scenarios B1, B2 and B3, the estimates provided are based on the use of a Progress Rail Type 1 battery locomotives. For scenario B4, the use of a Wabtec FLXdrive locomotive was assumed.

[46] This scenario may require an additional crew at the Matagami yard to support unloading due to the delayed arrival of the train. The exact impact on staffing and the railway's annual cost may need to be considered at future stages.

$ 4.7 million USD, and a cost of $ 2.9 million USD was estimated for a single battery tender. The detailed OPEX and Sustaining Capital estimates are provided in Appendix 5B.

10. INVESTMENT COMPARISON AND DISCUSSION

In terms of capital investment requirements, the catenary electrification scenario is the least desirable by a significant margin (see Figure 10-1 below).

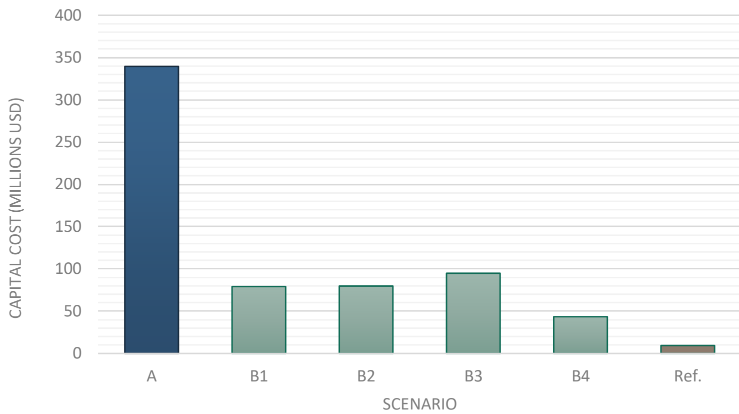

Figure 10-1: Comparison of the total capital cost of all scenarios

When we consider the operating cost and the annualized average sustaining capital cost together, scenario B4 results in the smallest combined annual cost of all alternative propulsion modes.

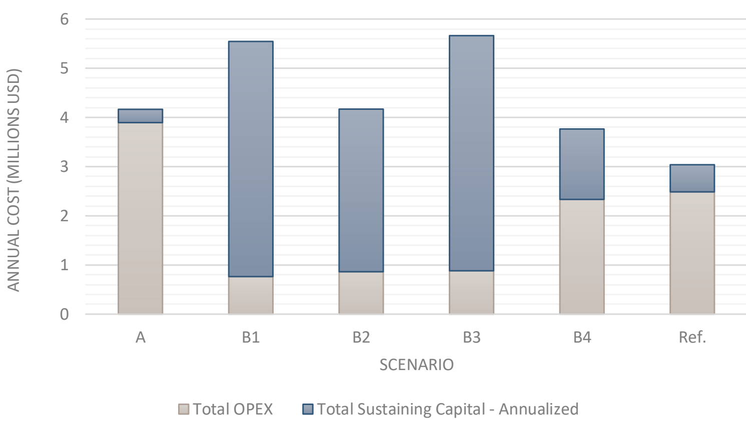

Figure 10-2: OPEX and Sustaining Capital comparison for the different scenarios

As shown in Figure 10-2, all scenarios have a higher combined annual cost when compared to the reference diesel-locomotive scenario. The reason for this is that the estimated annual traffic is not at a level where the reduced energy costs can compensate for the increased maintenance costs (more specifically, the power supply infrastructure maintenance and battery replacement costs).

It must be noted that the cost of batteries is expected to improve in the coming decades, as well as some battery characteristics, such as energy density and lifespan. In addition, the cost of carbon-based fuels is likely to increase. With time, these changes are likely to tip the cost comparison more in favour of the battery-powered train scenarios. However, the rates of such changes are difficult to predict and thus the related cost considerations were excluded from this analysis.

It's important to consider that GHG emissions, as well as the emission of other harmful by-products by the diesel combustion engines, will be reduced significantly for all scenarios when compared to the diesel-only reference case. The table below provides a summary of the annual emission reduction for train operations for each scenario.

Table 10-1: Summary of the annual fuel and emission reduction

Scenario	A	B1	B2	B3	B4	Ref. Diesel
Annual diesel fuel consumption (L)	0	0	0	0	949,653	1,189,240
Annual electricity consumption (MWh)	6,576	8,418	7,740	7,872	2,030	0
Reduction in fuel consumption and emissions	100%	100%	100%	100%	20%[47]	-

It is important to consider that battery-powered locomotives are still in early development and testing has not yet been carried out over a long enough period such that conclusions can be drawn with respect to the reliability and suitability of this technology for railway operations. Furthermore, the exact performance and behaviour of the technology under extremely low temperatures is still unknown. There might be potential impacts on the batteries' lifespan, the power output, the charging efficiency, and other characteristics which differ from those assumed in the present study. These risks cannot be ignored and thus a full dependence on battery locomotives for the railway operations cannot be recommended at the current time. This includes scenarios B1, B2 and B3.

Looking at the catenary-electric scenario, since there are no freight catenary-electric locomotives currently being manufactured and used in North America, there may be supply risks to consider. These risks can amount to higher supply costs than what was estimated, as well as delays in the supply of the locomotives. There is also the risk of the reliability of these locomotives being lower than anticipated.

Considering all the challenges and risks mentioned above, the recommended approach is a staged one – where only the battery hybrid scenario B4 is implemented at an initial stage. This will make it possible to test the battery technology without having a full reliance on it. Risks will be greatly mitigated due to the redundance provided by diesel locomotives. In addition, the battery-powered locomotives will still provide a significant reduction in GHG emissions. This scenario also has the advantage of having the smallest capital cost and the lowest combined OPEX and Sustaining Capital annual costs of all alternative propulsion mode scenarios.

[47] The use of a Wabtec FLXdrive locomotive was considered. The emission reduction increases to 25% if the Progress Rail Type 1 battery locomotive is used instead.

A feasible approach for the staged implementation can be as follows:

- **Stage 1:** Implementation of battery-hybrid operations for passenger trains only (B4 passenger + diesel freight)
- **Stage 2:** Hybrid operations for both freight and passenger operations (B4 passenger and freight)
- **Stage 3:** Incremental replacement of the diesel locomotives with battery locomotives over time
- **Stage 4:** Full transition to battery-powered trains

The emission reduction potential for railway operations increases with each subsequent stage, and capital costs can be distributed over a longer period. This approach would provide a reduction of the risks related to battery trains, as well as the capital cost investments at the beginning of the project, while still harnessing the potential of the technology in terms of reduced environmental impacts. Furthermore, there may be significant technological advancements by the time Stage 4 is reached, which can be taken advantage of.

11. CONCLUSION

This study aims to provide a discussion and validate the feasibility of using alternative train propulsion modes for Phase 1 of the Billy Diamond Highway railway, with the goal of reducing the lifespan GHG emissions of the project. This includes the consideration of three propulsion alternatives:

- battery-powered trains;
- fully electric trains powered by overhead catenary infrastructure;
- hybrid trains, which combine battery and diesel propulsion.

Railway catenary electrification is not a new technology. It has been widely used in Europe and other continents for both freight and passenger operations for decades. However, currently there are no freight operations in North America where electric locomotives are being used. Furthermore, there are no electric freight locomotives being manufactured and sold in North America and importing locomotives from outside the continent would pose significant challenges due to the mismatch in locomotive standards. In addition, this approach would require significant capital investments for the catenary infrastructure.

Regarding battery-powered trains, the technology is still in development and there has not yet been any extensive real-world testing done in the context of freight operations. However, developments from the automotive industry are likely to result in continuous improvements to aspects like battery capacity, lifespan, and decreased cost. The benefits are expected to trickle into the rail industry too, gradually making the technology more viable over time.

Considering the significant challenges and cost related to full catenary railway electrification and the state of battery train propulsion technologies today, the recommended approach would be to initially implement a hybrid scenario – where battery locomotives can be used in combination with diesel locomotives. This can still provide a significant reduction of the GHG emissions for this project, while enabling operators to gain experience and test the robustness and viability of battery-powered locomotives. As the technology matures, it will be possible to gradually increase the number of battery locomotives in the fleet using a staged approach. Over time, it will be possible to transition to fully battery-powered operations.

CREE DEVELOPMENT CORPORATION

Respect · Collaboration · Strength

ᒥᔅᑕᒦᐧᑫᐦᒡ