Winnipeg | Transit Transports

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Transition to Zero-Emission Technical Evaluation Report

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LIST OF ABBREVIATIONS

Abbreviation	Term/Phrase/Name
A	Ampere
AC	Alternating current
ADL	Alexander Dennis Limited
AMO	Asset Management Office
APC	Automated Passenger Counter
APTA	American Public Transportation Association
ART	Arterial Duty Cycle
AVL	Automatic Vehicle Location
B2	2% Biodiesel
Bar	Bar
BEB	Battery-Electric Bus
BEB-LR	Long-range Battery-Electric Bus
BEB-RC	Rapid-charge Battery-Electric Bus
BOL	Beginning-of-Life
BRT	Bus Rapid Transit
BYD	Build Your Dreams Company
C	Celsius
CAD	Canadian Dollar
CARB	California Air Resources Board
CBD	Central Business District Duty Cycle
CCS	Combined Charging System
CFCP	California Fuel Cell Partnership
CHBC	California Hydrogen Business Council
CIB	Canada Infrastructure Bank
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COM	Commuter Duty Cycle
CMVSS	Canadian Motor Vehicle Safety Standards
CNG	Compressed Natural Gas
CNL	Canadian Nuclear Labs
CPR	Cardiopulmonary Resuscitation
CTE	Center for Transportation and the Environment
CUTRIC	Canadian Urban Transit Research & Innovation Consortium
CUTA	Canadian Urban Transit Association
CW	Curb Weight
DC	Direct Current
DGE	Diesel Gallon Equivalent
DOD	Depth of Discharge
DOE	U.S. Department of Energy
DRC	Democratic Republic of Congo
EMI	Electromagnetic Interference
EMS	Energy Management Systems
ENC	Eldorado National of California

EOL	End-of-Life
ESAL	Equivalent Single Axle Load
ESS	Energy Storage System
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FC-BEB	Fuel Cell Battery-Electric Bus
FCM	Federation of Canadian Municipalities
FMEA	Failure Mode and Effects Analysis
FTA	Federal Transit Administration
GHG	Greenhouse Gas
GIS	Green Infrastructure Stream
GIC-CCM	Green Infrastructure Stream - Climate Change Mitigation Sub-Stream
GTL	Green Transportation Leasing
GVWR	Gross Vehicle Weight Rating
H_2	Hydrogen
HA	Hazard Analysis
HPC	High-Power Charger
HV	High Voltage
ICIP	Investing in Canada Infrastructure Program
ICIP-PTIS	Investing in Canada Infrastructure Program - Public Transit Infrastructure Stream
ICIP-GIS	Investing in Canada Infrastructure Program – Green Infrastructure Steam
LCA	Life-Cycle Analysis
LCC	Life Cycle Cost
LFP	Lithium Iron Phosphate
LTO	Lithium Titanate Oxide
HVAC	Heating Ventilation, and Air Conditioning
KBRC	Kilometers Between Road Calls
kg	Kilograms
km	Kilometer
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt Hour
LV	Low Voltage
MKBF	Mean Kilometers Between Failures
MW	Megawatt
NABI	North American Bus Industries
NCA	Nickel Cobalt Aluminum Oxide
NF	New Flyer
NFI	New Flyer Industries
NFPA	National Fire Protection Agency
NIR	National Inventory Report
NMC	Nickel Manganese Cobalt
NPV	Net Present Value
NRCAN	Natural Resources Canada

NREL	National Renewable Energy Laboratory
O&M	Operation & Maintenance
OEM	Original Equipment Manufacturer
PEM	Polymer Electrolyte Membrane
PM	Preventative Maintenance
PPA	Power Purchase Agreement
PPE	Personal Protective Equipment
PTIS	Public Transit Infrastructure Stream
PV	Photovoltaic
PVR	Peak Vehicle Requirement
RFI	Request for Information
RNG	Renewable Natural Gas
ROI	Return on Investment
RPS	Renewable Portfolio Standard
SAE	Society of automotive engineers
SAM	System advisor model
SMR	Steam Methane Reforming
SOC	State-of-Charge
SOH	State-of-Health
SSM	Safety Services Manitoba
TPRD	Thermally-Activate Pressure Relief Device
TOU	Time-of-Use
TTC	Toronto Transit Commission
UL	Underwriters Laboratory
USD	US Dollar
V	Volt
VW	Volkswagen
Wh	Watt Hour
WTMP	Winnipeg Transit Master Plan
ZEB	Zero-Emission Bus
ZEV	Zero-Emission Vehicle

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- Manitoba Hydro
- Manitoba Trucking Association
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- Village of Dunnottar
- Zen and the Art of Clean Energy
- Zero Emission Bus Resource Alliance

EXECUTIVE SUMMARY

The Standing Policy Committee on Infrastructure Renewal and Public Works approved Winnipeg Transit's recommendation for the creation of a detailed study into the costs associated with purchasing and deploying a fleet of 12-20 battery-electric buses and associated infrastructure.

This report is one of three deliverables associated with the Electric Bus Study and will be used to support decisions on transit electrification, including bus technology fleet mix; zero-emission fleet ramp-up rate; route planning / dispatching strategy; fueling / charging infrastructure planning; facilities upgrades; maintenance planning; human resources / training requirements; charging locations; funding availability; and an economic benefits analysis.

Zero-Emission Bus (ZEB) is the common industry term for all buses that produce no tailpipe emissions. This definition currently includes various forms of buses with electrical propulsion systems, including standard battery-electric buses (BEB), fuel cell battery-electric buses (FC-BEB), fuel cell-electric buses (FCEB), and trolleybuses.

Fuel cell-electric buses and trolleybuses rely predominantly on alternative energy sources as the main power supply and include only a very small battery pack as secondary power. Due to technology limitations, high purchase price, and a limited number of manufacturers producing these types of buses it was determined that both were outside the scope of this study. Only the three remaining types of zero-emission buses, including long-range battery-electric, on-route rapid-charge battery-electric, and fuel cell battery-electric (battery-dominant), were considered in scope for this study.

The report includes an overview all of in-scope zero-emission buses and associated fueling / charging infrastructure; establishes guidelines for comparing technologies; evaluates greenhouse gas emissions and environmental and social impact of zero-emission buses; provides a comparison of heavy-duty zero-emission buses to Transit's current diesel buses; reviews the financial implications associated with transitioning to a zero-emission fleet; reviews funding and financing models available to support this transition; and provides an implementation strategy for beginning the transition to zero-emission. The report was developed through extensive research and engagement with transit agencies, industry, non-profit organizations, post secondary institutions, as well as work across Winnipeg Transit and other City departments.

The data used in support of this evaluation was based on the current state of Winnipeg Transit's fleet and operations in the fall of 2019. The COVID-19 pandemic has had a significant impact on Transit's overall operations in 2020, with public health orders and reduced ridership levels necessitating reductions to service, and changes to operations. Operational data from pre-COVID levels of service is used throughout the report nonetheless, as it is expected that transit service will return to these levels in the future, and that using levels of service from during the COVID-19 pandemic would result in incorrect assumptions and an underestimation of necessary resources.

The main body of the report is predominantly divided into 3 sections, with Parts 2 through 7 constituting the majority of the technical evaluation, Parts 8 and 9 focusing on the financial implications of transitioning to zero-emission buses, and Part 10 discussing recommendations on a potential test fleet mix and future considerations for broader expansion of zero-emission transit beyond the first 12-20 buses.

Under the technical evaluation section, a review of all available zero-emission buses, including heavy-duty, medium-duty, double decker, and bi-articulated buses was completed, but the detailed technology evaluation was restricted to just heavy-duty zero-emission buses. Each type of in-scope zero-emission bus and their associated fueling strategies was then reviewed in detail with the pros and cons of each summarized. Beyond the larger decisions on buses and refueling infrastructure there are a number of other items that should be considered when comparing technologies. Topics, including battery characteristics, range and performance limitations, energy management requirements, and safety are discussed in detail. Broader discussions on the global impact that each type of zero-emission bus has on greenhouse gas emissions and secondary toxicity factors are also included. The technical portion of the report concludes with a comparison of each manufacturer's available zero-emission battery bus technology compared to Transit's current Xcelsior diesel buses based on physical dimensions, weight, performance, noise, and safety.

The financial implications of transitioning Winnipeg Transit's diesel fleet to zero-emission buses constitutes a significant portion of the report. Fleet costs were estimated based on expected capital, operational, and indirect costs, such as training and public engagement costs associated with each type of zero-emission bus using various refueling strategies. Analyses for each propulsion system were completed both for a small test fleet comprised of eight 40-foot and eight 60-foot buses, as well as for the large-scale deployment of zero-emission buses with a fleet mix of 92% 40-foot and 8% 60-foot buses, which closely aligns to Transit's current fleet mix. The total fleet size of each technology used in the large-scale evaluation was adjusted based on technology limitations, such as range and charging or fueling time.

When evaluated based on a small-scale deployment, battery-electric buses have clear economic advantages over fuel-cell battery-electric buses. However, when evaluated based on a large-scale deployment and considering the technology constraints of both the buses and the refueling infrastructure, strictly from a cost perspective there is no one technology that had a clear advantage over the others. With economies of scale, the purchase price of both battery-electric and fuel cell battery-electric buses are expected to be similar, so performance, infrastructure, and operational advantages will be the main drivers to separate the two technologies.

Battery-electric buses have the advantage of lower maintenance and predictable fueling cost; however, complexities associated with scaling charging infrastructure, including power management, energy storage, back-up generation, equipment maintenance, and charger management will drive significant operational changes which may necessitate significant additional investment.

Fuel cell battery-electric buses have superior range, predictable mid-life overhaul cost, low large-scale infrastructure cost, and would drive no significant operational changes; however, the cost of hydrogen could be a barrier to unlocking maximum savings. If low-cost delivered hydrogen could be sourced, the potential lifetime savings from fuel cell battery-electric buses could be on par with, or better than, battery-electric buses. If Transit is restricted to producing hydrogen fuel on-site, operational savings are likely to be only moderately better than diesel buses.

In the conclusions section, many items are considered beyond just the buses themselves. Operational considerations, including garage layout, depot management software limitations, and available hydro electrical service, influenced decisions on the zero-emission bus fleet. As it is not immediately clear which technology is the best solution for large-scale electrification, and more than one technology may need to be deployed, it is recommended that Transit include more than one technology in the next phase of electrification. This should include both a mix of propulsion systems as well as a mix of vehicle lengths.

Establishing a test fleet which includes a mix of propulsion systems as well as a mix of vehicle lengths will provide Transit with the ability to collect data to assist with planning and decisions before determining the following step in electrification. This direction will require a higher initial investment and does not produce the highest operational savings for the test fleet, but as the intent of the program is to study and collect data for long-term decision making rather than to maximize short-term savings, taking a mixed fleet approach best fits this requirement. Focusing on short-term savings with the test fleet would result in a missed opportunity to achieve significant savings when fleet-wide electrification is pursued.

As Winnipeg Transit previously collected significant amounts of data on the performance and operation of on-route rapid-charge battery-electric buses during its four-year battery-electric bus demonstration, there is no need to further evaluate this technology. Additional information on the performance of long-range battery-electric buses, fuel cell battery-electric buses and 60-foot zero-emission buses is still necessary to fully evaluate the systemic changes required to transform Transit from a diesel bus operator to a zero-emission bus operator. Including the following mix of buses would support this evaluation:

- Four 40-foot long-range BEBs with approximately 440 kWh of Capacity
- Four 60-foot long-range BEBs with approximately 466 kWh of Capacity
- Four 40-foot FC-BEBs
- Four 60-foot FC-BEBs

While both Brandon Garage and Fort Rouge Garage have the potential to support a small-scale deployment of zero-emission buses, Brandon Garage is the preferred location to support a small-scale deployment of zero-emission buses because it is the newest facility, and has the greater ability to expand electric grid capacity up to the levels necessary for supporting a zero-emission test fleet. Without significant time and investment, selecting Brandon Garage as a zero-emission garage will restrict future expansion of the zero-emission fleet at Fort Rouge Garage due to electrical service limitations imposed by Manitoba Hydro's existing local area infrastructure.

A Class 3 estimate of the proposed mixed test fleet of 16 buses operated out of Brandon Garage concluded that the total cost of the Transition Fleet Project is expected to be approximately $38.3 million. There are, however, many programs available that can help offset some of the capital costs associated with zero-emission buses and infrastructure. The Investing in Canada Infrastructure Program (ICIP) - Public Transit Infrastructure Stream (PTIS) appears to be the program that offers the greatest potential assistance with capital costs. Under ICIP-PTIS the maximum federal contribution would be 40% of eligible expenses and the provincial contribution would be 33.3% of eligible expenses. This would reduce the City's contribution towards the project to approximately $11.4 million.

Transit currently intends to utilize the zero-emission test fleet to offset mileage that would have otherwise been completed by the same number of diesel buses. Any additional infrastructure maintenance costs associated with maintaining a combination of depot plug-in charging and fueling using on-site produced hydrogen will likely be offset by zero-emission bus maintenance and fueling savings. As such, there is no anticipated impact to the operating budget with the introduction of the test fleet. Operating costs are expected to fluctuate yearly based on actual electricity pricing; maintenance requirements of buses, chargers, and refueling infrastructure; and repair and overhaul needs. It is likely that any potential cumulative savings from fueling or maintenance will be negated by costs associated with mid-life overhaul such as battery replacement and fuel cell refurbishment. These costs may not be incurred until years 9 to 12. The true operating costs of zero-emission buses will need to be evaluated as the buses are operated in regular service over several years, as small fluctuations in cost of diesel fuel or electricity could either improve or negate any potential savings. There may be opportunities for Transit to refine energy management strategies and improve savings as it becomes more familiar with the performance and operation of the buses and refueling infrastructure.

Manitoba's energy mix is 99% renewable which creates a unique opportunity for Transit to potentially operate both battery-electric and fuel-cell battery-electric buses from renewable sources at costs significantly lower than other cities in North America. The decision on which technology best suits Winnipeg will be highly dependent on the results of Transit's zero-emission bus trial.

The test fleet should operate for a minimum of 18-24 months to allow Transit sufficient time to collect and review data to understand the true costs and challenges of each technology. The results of this trial, combined with the results from the earlier battery-electric bus demonstration, would be used to consider the systemic changes required to transform Transit from a diesel bus operator to a zero-emission bus operator, and to provide insight on fleet mix for future bus procurements.

After testing is complete, Winnipeg Transit will be well positioned to begin purchasing zero-emission buses as part of its Transit Bus Replacement Program. Transit would gradually retire diesel buses from service, initially procuring 18 zero-emission buses and associated refueling infrastructure each year, and eventually transitioning to full replacement with 30-35 zero-emission buses annually once transit operations are fully aligned to support the new technology. Based on the current status of fleet electrification at Winnipeg Transit, a 40% zero-emission fleet can be achieved by 2032, just two years behind the 2030 target, but the transition to a 100% zero-emission fleet would be completed several years ahead of the 2050 target. Purchasing any diesel buses after 2030, or accelerating the transition to zero-emission buses, could result in the early retirement of diesel buses that have not yet reached the end of their estimated 18-20 year normal service life.

Transitioning Winnipeg Transit from a diesel bus operator to a zero-emission bus operator will not be as easy as replacing a diesel bus with a zero-emission bus. It will require a systemic change to operations throughout the entire organization, and will require significant amounts of planning over the course of several years to implement. It is recommended that Transit launch a Transition to Zero-Emission Bus Program for the purpose of planning and managing the various projects and sub-projects that will be created by the transition to zero-emission, with the Transition Fleet Project being the first project delivered under this program. The goal of the program would be to set the direction for establishing a zero-emission fleet and following through on initiatives subject to securing funding sources and Council approval.

Electrical service constraints at the Brandon Garage and Fort Rouge Garage will require Transit to make a decision regarding fleet mix for future zero-emission bus procurements, but the transition to zero-emission is purposely planned to be gradual to allow Transit sufficient time to plan and adjust its zero-emission roll-out strategy based on data collected from the test fleet. A targeted fleet mix of approximately 70% long-range BEBs and 30% FC-BEBs is initially recommended, but there are options available for accommodating a different fleet mixture of zero-emission buses, if the results of the zero-emission bus trial produces a strong preference for one technology over the other.

Regardless of which mix is ultimately selected, transitioning from diesel to zero-emission buses will occur as diesel buses reach the end of their useful lives. Charging or refueling infrastructure purchases will also need to be aligned with bus procurements. The current diesel bus fleet will need to be replaced with a combination of both diesel and zero-emission buses to allow operations to transition more smoothly. Replacing the existing Transit Bus Replacement Program with the proposed Transition to Zero-Emission Bus Program will help to ensure a smooth transition to a zero-emission fleet. Including the initial 16 zero-emission buses, Transit can reach its goal of purchasing 100 to 110 zero-emission buses by the end of 2027 with a budget of $280.4 million, based on a completed Class 4 estimate. There may be some flexibility within this budget to adjust the quantity and length of buses, the propulsion mix, or the refuelling infrastructure based on the outcome of the trial or the evolution of ZEB technology.

The existing Transit Bus Replacement Program has a projected 7-year cost of $161 million (2021 Adopted Budget plus 6-year forecast). This program is funded through a combination of Federal, Provincial, and City financing, with the City's contribution being approximately 55% or $88.4 million. If Winnipeg's application to the Investing in Canada Program (ICIP) is successful, the City's expected contribution towards the new $280.4 million Transition to Zero-Emission Bus Program would be approximately 28% or $78.4 million, and the Federal and Provincial Governments would finance the remaining 72% or $202.0 million. This would result in an incremental savings of $10.0 million, while at the same time freeing Federal Gas Tax contributions for other transit projects.

Construction of a replacement for North Garage as a purpose-built zero-emission facility is needed to support future zero-emission bus fleet purchases by the time the first 100-110 buses are delivered. If this new zero-emission garage is not completed by 2027, electrical service constraints at Brandon Garage or Fort Rouge Garage would restrict any future expansion of the zero-emission bus fleet. This may have long-term operational and cost implications. Transit's North Garage replacement has been identified as a priority infrastructure project by Transit. There are potentially significant savings from designing a transit garage with future consideration for zero-emission bus charging and hydrogen fueling infrastructure, rather than retro-fitting a garage designed for diesel buses, both from a capital and operations perspective, as well as a planning and project management perspective. Based on a previously completed Class 4 estimate, this project is estimated to cost $210.9 million, excluding any future costs associated with purchasing and installing charging or fueling equipment.

Based on projected rate of transition, if fleet replacement with zero-emission buses begins in 2024 as planned, by 2030 Transit's fleet would be 30% zero-emission (210 of 700 buses), which is under the current target of 40% (280 of 700 buses). However, the entire fleet would be zero-emission by 2047, more than three years ahead of schedule.

The Winnipeg Transit Master Plan is proposing significant route network changes that could affect fleet size and fleet mix going forward. Efficiency improvements may not require Transit to expand its fleet at the same rate as it does today. Replacing 40-foot buses with 60-foot buses is one such way that service could be improved without directly increasing fleet size. As such, it may be possible for Transit to reach the target of 100% zero-emission sooner than shown without the early retirement of diesel buses. Much of this will be determined by the actual efficiency gains and ridership increases realized under the Winnipeg Transit Master Plan.

1 INTRODUCTION

The Standing Policy Committee on Infrastructure Renewal and Public Works approved Winnipeg Transit's recommendation for the creation of a detailed study to evaluate the costs associated with purchasing and deploying a fleet of 12-20 battery-electric buses and associated infrastructure.

The Transition to Zero-Emission: Technical Evaluation Report is one of three deliverables associated with the Electric Bus Study. It is intended to provide a framework for Winnipeg Transit to evaluate currently available zero-emission technology and support future decisions on transit electrification, including bus technology fleet mix; electric fleet ramp-up rate; route planning / dispatching strategy; fueling / charging station infrastructure planning; facilities upgrades; maintenance planning; human resources / training requirements; charging locations; funding availability; and an economic benefits analysis.

Zero-Emission Bus (ZEB) is the common industry term for all buses that produce no tailpipe emissions. This definition currently includes various forms of buses with electrical propulsion systems, including standard battery-electric buses (BEB), fuel cell battery-electric buses (FC-BEB), fuel cell-electric buses (FCEB), and trolleybuses.

Fuel cell-electric buses and Trolleybuses rely predominantly on alternative energy sources as the main power supply and include only a very small battery pack as secondary power. Due to technology limitations, high purchase price, and a limited number of manufacturers producing these types of buses it was determined that both were outside the scope of this study. Only the three remaining types of zero-emission buses, including long-range battery-electric, on-route rapid-charge battery-electric, and fuel cell battery-electric (battery-dominant), were considered in scope for this study. Each of these technologies has been reviewed in detail along with options for refueling infrastructure.

The report includes an overview of all in-scope zero-emission buses and associated fueling / charging infrastructure, establishes guidelines for comparing technologies, evaluates greenhouse gas emissions and environmental and social impact of zero-emission buses, provides a comparison of heavy-duty zero-emission buses to Transit's current diesel buses, reviews the financial implications associated with transitioning to a zero-emission fleet, reviews funding and financing models available to support this transition, and provides an implementation strategy for beginning the transition to zero-emission. The report was developed through extensive research and engagement with transit agencies, industry, non-profit organizations, post secondary institutions, as well as work across Winnipeg Transit and other City departments.

The data used in support of this evaluation was based on the state of Winnipeg Transit's fleet and operations in the Fall of 2019. The COVID-19 pandemic has had a significant impact on Transit's overall operations in 2020, with public health orders and reduced ridership levels necessitating reductions to service, and changes to operations. Operational data from pre-COVID levels of service is used throughout the report nonetheless, as it is expected that transit service will return to these levels in the future, and that using levels of service from during the COVID-19 pandemic would result in incorrect assumptions, and an underestimation of necessary resources in the long term.

1.1 Report Structure

The Transition to Zero-Emission: Technology Evaluation Report is organized into 11 sections

	Topic	Purpose
Part 1	Introduction	Introduces the report and provides an outline guide to the document.
Part 2	Background and Context	Highlights the context of this report, including a history and profile of the City of Winnipeg, a brief overview of the local impacts the City can expect as a result of introducing zero-emission buses, as well as a brief overview of Winnipeg Transit operations.
Part 3	Overview of Zero-emission Bus Technology	Provides insights into the types of zero-emission buses available in the North American market, and summarizes the pros and cons of long-range battery-electric, on-route rapid-charge battery-electric, and fuel cell battery-electric buses.
Part 4	Overview of Charging Infrastructure	Summarizes the pros and cons of various refueling models available for zero-emission bus charging, including on-route conductive charging, on-route inductive charging, plug-in depot charging, overhead depot charging, and on-board hydrogen charging.
Part 5	Considerations for integrating zero-emission buses	Outlines items to consider when comparing technologies, such as battery characteristics, range and performance limitations, energy management requirements, and safety.
Part 6	Greenhouse Gas Emissions and Environmental Impact	Evaluates the upstream and downstream impact of zero-emission buses on global greenhouse gas emissions, as well as the environmental and social implications associated with their supply chain.
Part 7	Comparison of Zero-emission Bus Technologies by Manufacturer	Compares heavy-duty zero-emission buses to Transit's current Xcelsior diesel buses based on physical dimensions, weight, performance, noise, energy consumption, and safety.
Part 8	Financial Implications of Fleet Electrification	Outlines the expected capital, operational and indirect costs associated with launching a fleet of 12-20 zero-emission buses. Costs associated with full fleet adoption of zero-emission buses are also included for consideration.
Part 9	Funding Zero-emission Buses and Charging Infrastructure	Outlines of the various financing models and funding programs available that target zero-emission buses and refueling infrastructure.
Part 10	Conclusions	Provides recommendations and costing for establishing a test fleet of sixteen zero-emission buses and discusses options for further expansion of Transit's zero-emission fleet.
Part 11	Reference	A list of references cited in the report

2 TRANSITION TO ZERO-EMISSION: BACKGROUND AND CONTEXT

The City of Winnipeg is a vibrant and growing community in the heart of the Canadian prairies. With its location around the confluence of the Red and Assiniboine Rivers, the area has served as a meeting place for Indigenous peoples for thousands of years. The broader region falls within Treaty #1 and is recognized as the traditional territory of the Anishinaabe, Cree and Dakota people, as well as the birthplace of the Métis Nation and the Heart of the Métis Homeland.

As the largest city in Manitoba, the 749,500 residents who currently call Winnipeg home represent 60% of Manitoba's total population. Incorporated in 1873, the City of Winnipeg's growth and development patterns were originally shaped by the railway, which supported the farming and agricultural industry of the region. Situated in the fertile Red River floodplain, the highly productive agricultural lands of the area have long defined the local character and economic life of Winnipeg. As such, farmland has historically influenced the settlement pattern and growth of the community.

Winnipeg has a number of natural and economic assets that attract many people to live in and visit the City, and to enjoy its services, amenities and distinct culture. Winnipeg experiences a continental climate with a vast temperature range from hot summers to very cold winters. Its flat topography and location on a floodplain make the city prone to flooding, though the city's Red River Floodway (built in 1969; expanded in 2009) provides some protection.

The city is a multi-cultural municipality and regional centre with a diverse economy based on manufacturing, service, government and trade. After relatively flat growth in the 1980s and 1990s, Winnipeg has been experiencing rapid population growth since 2011. This growth is largely driven by immigration. This growth is forecast to continue at a rate of about 9,000 to 10,000 new residents per year over the next 20 years.

The data used in support of this evaluation was based on the current state of Winnipeg Transit's fleet and operations in the Fall of 2019. The COVID-19 pandemic has had a significant impact on Transit's overall operations in 2020, with public health orders and reduced ridership levels necessitating reductions to service, and changes to operations. Operational data from pre-COVID levels of service is used throughout the report nonetheless, as it is expected that transit service will return to these levels in the future, and that using levels of service from during the COVID-19 pandemic would result in incorrect assumptions, and an underestimation of necessary resources

2.1 Project Need & Benefits

In 2019 Canada declared a national climate emergency, stating that, "C*anada is in a national climate emergency which requires, as a response, that Canada commit to meeting its national emission target under the Paris Agreement and to making deeper reductions in line with the agreement's objective of holding global warming below two degrees Celsius and pursuing efforts to keep global warming below 1.5 degrees Celsius."* [1].

Prior to this announcement, the City of Winnipeg had previously made several independent commitments to reducing GHG emissions, culminating in the 2018 release of *Winnipeg's Climate Action Plan: Planning for Climate Change. Acting for People* [2].

The City of Winnipeg worked with Golder Associates to provide an updated community energy and greenhouse gas inventory, and to forecast energy and emission reductions under various climate reduction scenarios [3]. This report identified transportation as accounting for over 50% of the City's total emissions, with Transit's share at less than 1%, or 43,495 tonnes of GHG's per year. Transitioning transit away from diesel fuel, however, was identified as one key step in a strategy which maximizes GHG reduction.

Table 1: Summary of Vehicle Emissions [3]

Activity	Annual Emission Rate (tonne CO_2e/year)				GHG Intensity (tonne CO_2e per capita)	Percent of Total
	CO_2	CH_4	N_2O	Total GHGs		
Transit	43,044	57	395	43,495	0.06	0.8%
Vehicles - Residential	1,689,442	2,434	33,241	1,725,116	2.49	32.1
Vehicles - Commercial	938,779	338	6,525	945,642	1.37	17.6

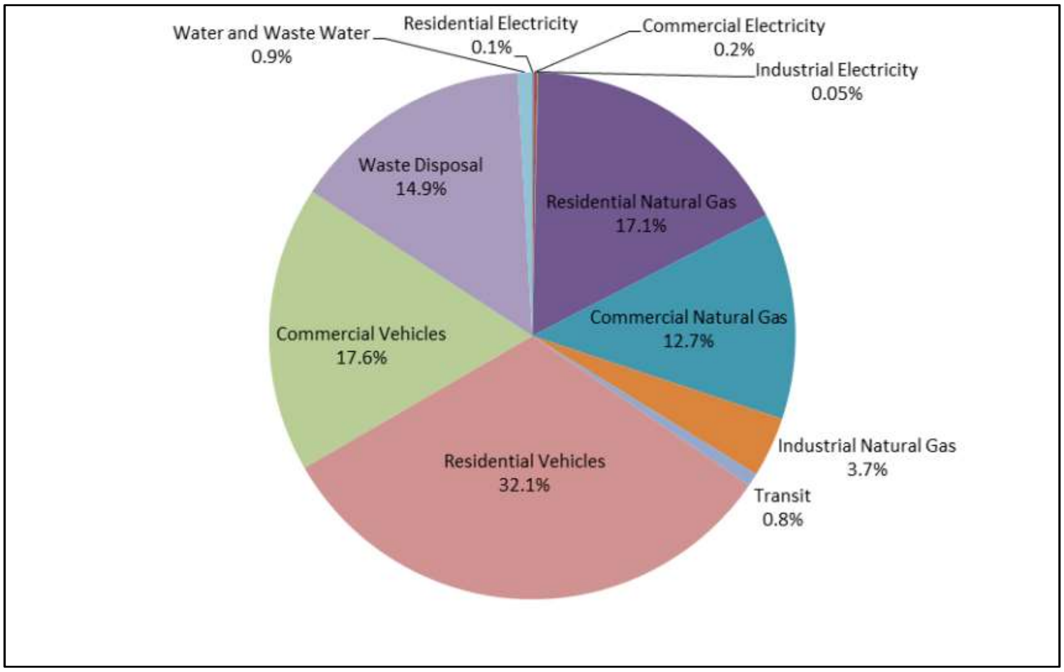


Figure 1: Summary of Total Community GHG Emissions in 2011. Source: [2]

Winnipeg's Climate Action Plan further solidified bus electrification as a City of Winnipeg priority by identifying the utilization of Zero-emission buses (ZEB) as a key strategic opportunity for Winnipeg meeting its 2050 GHG target of 80% reduction relative to 2011 levels [2]. More recent modeling completed by the City of Winnipeg's Office of Sustainability is projecting that by percentage of kilometres travelled, Transit's fleet needs to be 40% electric by 2030 and 100% by 2050 in order for the City to meet its GHG reduction targets [3].

2.2 Electric Bus Demonstration

As early as 2009, the Transit Department was asked to evaluate electric propulsion as a way of managing operating costs against the rising cost of diesel fuel, and to actively lower greenhouse gas (GHG) emissions. At that time on-wire trolleybuses were the only commercially available electric propulsion system. It was concluded that converting the fleet to trolleybuses was cost prohibitive, not only with respect to the purchase of the buses themselves, but also the need to install and maintain the network of overhead wires. The limits imposed by the trolley electrical infrastructure on the design of the transit route network and on the flexibility to interline buses, would introduce inefficiencies resulting in a larger overall transit fleet, increase operating costs, and decrease service reliability [4].

Off-wire electric bus technology began to accelerate shortly after this time, and in 2014 Winnipeg had the opportunity to join a larger consortium in a demonstration project to evaluate the viability of battery-electric bus technology. As Winnipeg Transit's contribution to the project, four leased New Flyer Xcelsior battery-electric buses were operated over a 4-year period on Route 20 Watt-Academy, and charged at the Winnipeg Richardson International Airport. The project allowed all of the partners involved to learn key lessons about the construction, operation, and maintenance of battery-electric buses. Unfortunately, the prototype technology used on these buses was not adequate for long term operation in Transit's fleet, and at the conclusion of the demonstration in 2018, the buses were retired and returned to the manufacturer, who owned them throughout the project.

While the demonstration project was ongoing, the Manitoba Government and the City of Winnipeg established a joint task force to examine the potential for broadly implementing electric buses beyond the initial demonstration project. Their 2016 report concluded that in addition to reduction in GHG and other pollutants, that electric buses have also proven to be quieter and cheaper to operate than their diesel counterparts [5]. While the capital costs for purchasing electric buses are still significantly higher than that of diesel, it is expected that decreased maintenance and low energy rates in Manitoba will result in the lifecycle cost reaching near parity over a 12 to 18-year period. The expectation of significant lifecycle cost savings has not yet been proven by full-life validation.

Concerns were raised by the task force regarding the lack of information on costs, and the complexity associated with large-scale integration of electric buses and infrastructure into existing transit operations. Based on these concerns, it was recommended that electrification be pursued in a staged approach; first deploying 12 to 20 electric buses, increasing to 120 to 200 buses, then full fleet electrification.

At the conclusion of the demonstration project a significant number of barriers to large scale transit electrification still remained [5]. Uncertainty with regard to the systemic changes needed to transform Transit from a diesel bus operator to a zero-emission bus operator remains, as implementing new technology would require fundamental changes to route planning, scheduling, fuelling, parking, dispatching, service, and maintenance.

With a target of working towards a larger deployment of electric buses, Transit recommended first purchasing and operating a small fleet of 12-20 zero-emission buses. A Bus Electrification Study was launched to evaluate the current state of zero-emission buses and assess the lifecycle cost, performance, and safety of both the buses and their associated refueling infrastructure.

2.3 Overview of Winnipeg Transit's Operations

2.3.1 Fleet

Winnipeg Transit currently operates a fleet of approximately 640 buses carrying an average of 200,000 passengers each weekday. The fleet is a mix of New Flyer diesel Low Floor, and diesel Xcelsior buses in 30, 40 and 60-foot lengths. Individual buses travel between 50,000 to 70,000 km/year and are on an 18 to 22-year replacement cycle, with a typical bus accumulating 1,060,000 km by retirement.

The fleet is expected to grow by 12-15 buses per year in order to improve service while also supporting a growing population.

2.3.2 Facilities

Buses currently deploy from three locations, Fort Rouge Garage, Brandon Garage and North Garage. Approximately 70% of buses are deployed from Fort Rouge Garage, with the remaining 30% equally divided between the Brandon Garage and North Garage. Brandon Garage is the newest facility having been completed in 2014. Originally designed as a facility for street cars, North Garage is over 80-years old, and its replacement has been identified as one of Transit's highest-priority capital projects. It is not being considered as a location for storing a zero-emission test fleet as this would require significant investment in an obsolete facility that is due to be replaced.

Manitoba Hydro reviewed the electrical loads and capacity at both Brandon Garage and Fort Rouge Garage. They have indicated that Fort Rouge Garage has been expanded to its maximum capacity, but their current infrastructure could support expanding service at Brandon Garage up to 2,500 kVA. It may be possible to expand service beyond these limits, but doing would require system upgrades, which would require significant time and investment to implement.

The results of their review are as follows:

Table 2: Electrification capabilities of Winnipeg Transit Garages based available grid power

Garage	Current Service [kVA]	Unused Service [kVA]	Current Site Capacity [kVA]	Available Service for Electrification [kVA]
Fort Rouge	3,000	1,200	3,000	1,200
Brandon	750	400	2,500	2,150
North	N/A	N/A	N/A	N/A
Total	3,750	1,400	5,500	3,350

A maintenance garage extension was recently competed at Fort Rouge Garage. The projected new load for this facility was 2,700 kVA, therefore Transit purchased the necessary transformation equipment to increase service capacity to 3,000 kVA. Based this investment, Fort Rouge Garage qualified for lower energy rates under commercial electricity rate "General Service Large – exceeding 750 V but not exceeding 30 kV". Current loads at this facility have been lower than estimated, which potentially creates an opportunity to utilize some of the unused service for zero-emission bus refueling infrastructure. Some portion of the available capacity may have purposely allocated for future maintenance garage expansion, therefore the total load that could be utilized for transit electrification may be substantially lower than 1,200 kVA.

The transformation equipment servicing Brandon Garage is owned and operated by Manitoba Hydro, and as such, the facility only qualifies for the commercial electricity rate "General Service Medium". If capacity at Brandon Garage increases beyond what is currently supplied, Transit would be responsible for designing, purchasing, and installing the transformation equipment necessary to do so. With this additional investment, Brandon Garage would also have access to the same lower cost large service rates they are receiving at Fort Rouge Garage. There are currently no plans to expand capacity at Brandon Garage, as such it is likely that the entire 2,150 kVA potentially available at this site could be used to support zero-emission bus refueling infrastructure.

While both Brandon Garage and Fort Rouge Garage have the potential to support a small deployment of zero-emission buses with available grid power, Brandon Garage is the preferred location because it is the newest facility, and has the greater ability to expand grid capacity up to the levels necessary supporting a zero-emission test fleet.

2.3.3 Diesel Buses

Winnipeg Transit currently utilizes only diesel buses. All operations have been optimized based on the range, performance, and refueling time of diesel buses.

Table 3: Pros and Cons of diesel buses

Pros	Cons
Range >550 km	GHG & other emissions
Quick fueling	Fluctuating fuel cost
No restriction to route planning	High fuel consumption
Well established operational strategy	Noisy
Proven reliability	Smell
Predictable maintenance	Frequent particulate filter replacement
Lowest purchase price	Limited external funding partnerships from other levels of government for future purchases
Established fueling infrastructure	
Good cold weather performance	

2.3.4 Dispatch Schedule

Interlining (combining two or more routes) is used to maximize operational efficiencies. On weekdays, Transit's 87 routes are combined into 832 interlined runs. Weekend service is operated with fewer and longer runs. Individual runs range in length from 20 to 600 kilometers and in duration from 2 to 23.5 hours. All runs start and end at the same garage.

The number of buses dispatched varies throughout the day based on peak service demand. Peak morning and afternoon service currently requires 524 buses including:

47 – 60-foot articulated buses
452 – 40-foot buses
25 – 30-foot buses

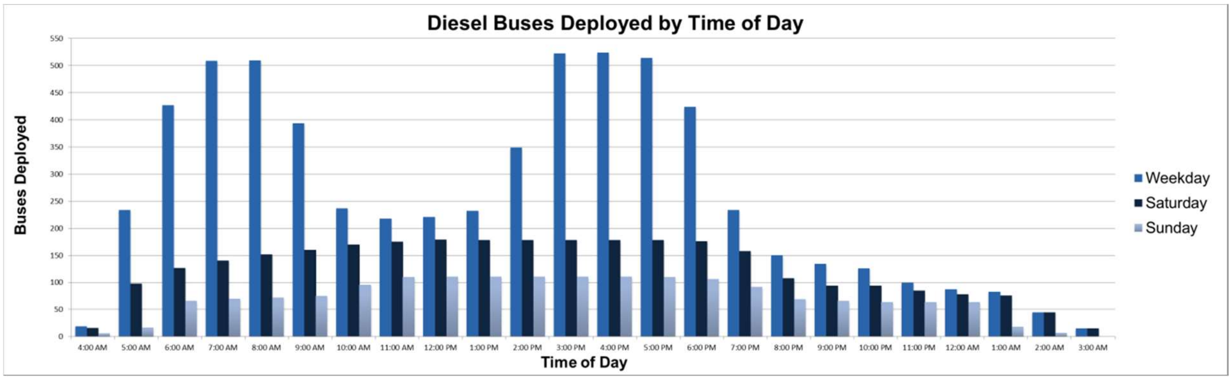


Figure 2 Time of Day Deployment of Buses by Run Length

The remaining buses in the fleet are designated spares. Transit maintains a spares ratio of between 15-20%. Transit's fleet currently only has 51 articulated 60-foot buses, so 40-foot buses are sometimes used on runs designated for 60-foot buses as required.

2.3.5 **Duty Cycle**

Winnipeg Transit's drive cycle rarely changes, but the duty cycle of a bus varies seasonally due to variable use of heating and air-conditioning.

2.3.5.1 Drive Cycle

Buses travel an average speed of 22 km/h and stop approximately 4 times per kilometer. On a weekday, a typical bus travels 130 km transporting an average of 58 passengers per hour. On a typical weekend, a typical bus travels over 300 km transporting an average of 38 passengers per hour.

Table 4: Winnipeg Transit average and maximum run length, Fall 2019.

	Range [km]	
	40-Foot	60-Foot
Average Run Length	177.05	134.95
Max Run Length	600.71	447.22

2.3.5.2 Climate

Winnipeg has a cold continental climate with average daytime highs of 25.9°C in the summer and -11.3° C in the winter, with daily average temperatures of +19.7°C and -16.4°C respectively. Thirteen days each summer and winter are considered extreme with temperatures exceeding either +/-30°C. Winters are long and cold with an average of 193 days dropping below freezing, 52 of which the temperature drops below -20°C. On average there are 113 days when the temperature never rises above freezing [6].

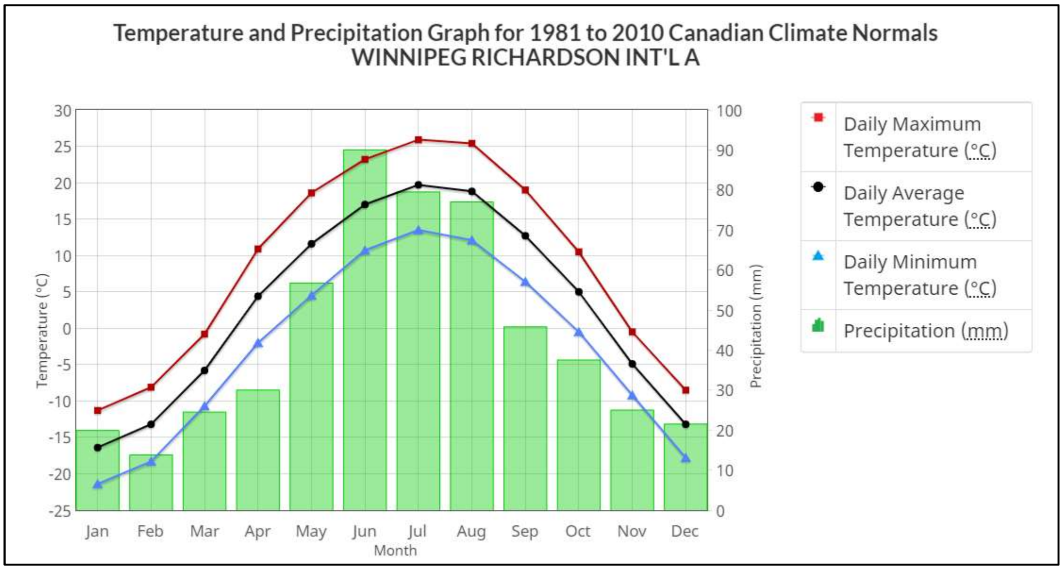


Figure 3: Winnipeg climate normals. Source: [6]

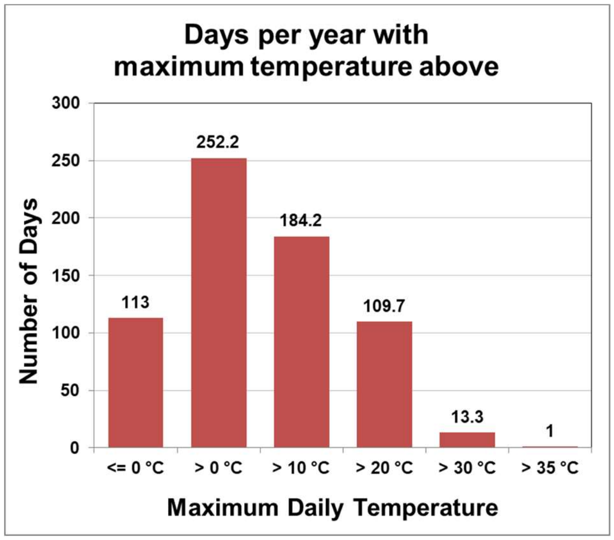


Figure 4: Days per year with maximum temperatures below stated [6]

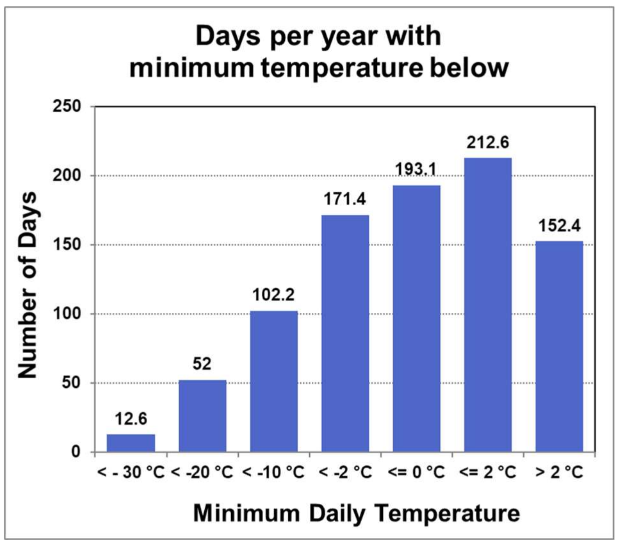


Figure 5: Number of days with minimum temperature below stated [6]

2.3.6 Transit Master Plan Impact

Winnipeg is growing and its transit system needs to grow also. By 2035 over one million people are expected to be living in or commuting to work Winnipeg [7]. The City needs to invest in important services and infrastructure like public transit to support a growing, thriving, modern city, now and into the future. The Winnipeg Transit Master Plan (WTMP) is being developed to ensure that transit can connect people and communities as the city grows.

The Winnipeg Transit Master Plan shapes a 25-year vision for our transit system. It will give Winnipeggers better transit options for getting around, make it easier for people to choose and access transit, help reduce existing and future road congestion, and position transit as an important part of a transportation system that can serve future generations.

To make service more efficient, frequent and reliable, Transit is proposing a network realignment emphasizing frequent, reliable transit on major streets throughout the city. The backbone of the network will be bus rapid transit (BRT) corridors; BRT routes will be designed with longer distances between stops, and will be operated on dedicated transit-only lanes enabling buses to operate at higher speeds. Frequent and Direct lines make up the remainder of the Primary Network offering all-day, high-frequency service on major streets to and from downtown. The Feeder Network will consist of Connector and Community routes which connect to the Primary Network and help people move around their neighbourhoods.

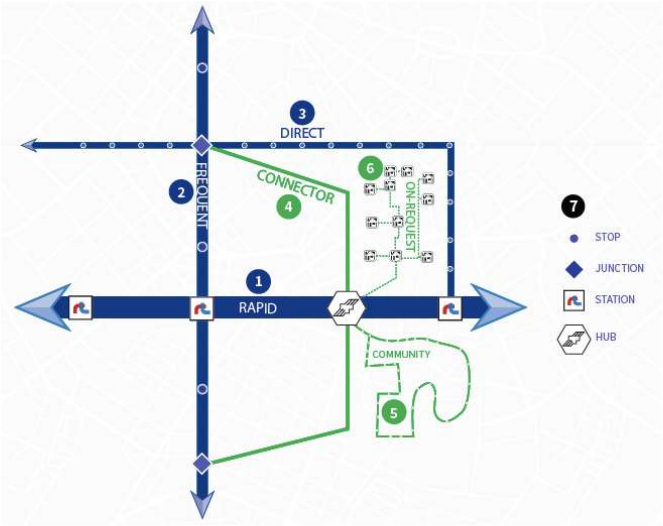


Figure 6: Winnipeg Transit proposed network realignment. Source: [8]

To improve passenger service and reduce pass-ups, Transit plans to operate BRT routes with 60-foot articulated buses as much as possible. Over a period of time, there will be a need to replace retiring 40-foot buses with 60-foot buses, as well as outright purchasing new 60-foot buses in order to adopt this strategy. Today by range, 60-foot buses make up less than 8% of the fleet. It is expected that after the network realignment as much as 20% of the fleet may need to be 60-foot buses.

While Transit's typical duty cycle is similar to the Federal Transit Administration (FTA) Central Business District (CBD) duty cycle, the new BRT duty cycle is more aligned with the Arterial (ART) duty cycle. The buses will operate with a top speed of 80 km/h, an average speed of 35 km/h, and with an average of one stop per kilometer. Ridership is expected to increase to an average of 80 passengers per hour per bus on these lines, with lower ridership expected on the other Primary Network routes (Frequent, Direct), and Feeder Network routes (Connector, Community, On-Request).

The impact of network realignment with regard to duty cycle and fleet mix will need to be considered while evaluating zero-emission propulsion systems.

The WTMP is expected to be brought to Winnipeg's City Council for approval in March 2021. If approved, implementation of the route network, rapid transit infrastructure, and other infrastructure, would take place over the following several years.

3 OVERVIEW OF ZERO-EMISSION PROPULSION SYSTEMS

North American transit bus manufacturers currently supply three main types of zero-emission buses as well as several sub types within each group, including long-range battery-electric, on-route rapid-charge battery-electric, fuel cell battery-electric (battery-dominant), fuel cell-electric (fuel cell-dominant), and Trolley electric.

Both fuel cell-electric buses (fuel cell-dominant) and Trolleybuses rely predominantly on alternative energy sources as the main power supply and include only a very small battery pack as secondary power. Fuel cell-electric buses are currently only produced by one manufacturer in the USA and are available only in 35 or 40-foot lengths, thus they could not be used to replace 60-foot diesel buses. They are also currently the most expensive, heaviest and least efficient zero-emission option available today. Trolleybuses were previously evaluated by Winnipeg Transit, with their 2009 study concluding that the financial and operational challenges associated with on-wire trolleybuses did not make them a viable alternative to diesel buses for Winnipeg. Since that time, no major changes have been made to the technology that would significantly alter the outcomes from that study [4]. It was determined that neither technology qualifies as a battery-electric bus and as such they are both outside the scope of this study.

Long-range battery-electric, on-route rapid-charge battery-electric buses, and fuel cell battery-electric (also known as battery-dominant fuel cell) buses all utilize large battery packs as their main energy source. They use the same propulsion system, with the only difference between battery-electric and fuel cell battery-electric buses being that on a fuel cell battery-electric bus, in addition to utilizing electricity stored in batteries, there is a fuel cell onboard which creates electricity from stored hydrogen for the purpose of maintaining battery charge. Battery-electric buses need to be charged directly while fuel cell battery-electric buses are fueled with hydrogen. It was determined that these three technologies qualify as battery-electric buses and are within the scope of this study.

Throughout this section of the report, mention is made of European manufacturers who do not sell buses in North America. It should be noted that due to the recent signing of the Canada-Europe Trade Agreement (CETA), it is expected than European buses may become more widely-available in Canada. At this time, it appears that only Van Hool of Belgium is actively pursuing entrance into the North American market.

3.1 Zero-Emission Bus Market Survey

There are three different types of zero-emission transit buses currently built in North America; heavy-duty, medium-duty and double decker buses.

Heavy-duty buses have a curb weight greater than 26,000 lbs (11,793 kg) and are expected to last at least 12 years or 800,000 km. Transit buses in this class are offered in 35-foot, 40-foot and 60-foot configurations, although actual length varies by manufacturer. These are the most common urban transit bus. Today, heavy-duty buses are utilized on 95% of Transit's service.

Medium-duty buses have a curb weight between 10,001 and 26,000 lbs (4,536-11,793 kg) and are expected to last at least 10 years or 565,000 km. Transit buses in this class vary in length from 20-feet to 30-feet, but are equipped with similar features to their heavy-duty counterparts. These buses are typically utilized on low frequency, low density community routes and for on-request service. Today medium-duty buses are utilized on 5% of Transit's service.

Double Decker zero-emission buses built for the North American market typically have three axles and a curb weight greater than 60,000 lbs. They are offered only in a 45-foot length. Double decker buses built for the European market are shorter, have only two axles, and have a lower gross vehicle weight rating. These buses are most commonly used on commuter routes which have long distances between stops, as the stairs can be a constraint on routes with frequent boarding and alightings. Transit does not currently operate any double decker buses.

Outside of North America, bi-articulated heavy-duty zero-emission buses, also known as trambuses, are also being produced. There does not appear to be a standard length in this class, but buses appear to be between 75 and 90 feet in length and have curb weights in excess of 53,000 lbs (24,250 kg). This technology is deployed on high frequency, high demand routes, with theoretical hourly capacities approaching that of light rail. Transit does not currently operate any bi-articulated buses.

3.1.1 Heavy-Duty Manufacturers

There are currently seven manufacturers selling heavy-duty zero-emission buses to the North American market. These include BYD, Eldorado National - California (ENC), Gillig, Green Power, Nova Bus, Proterra, and New Flyer.

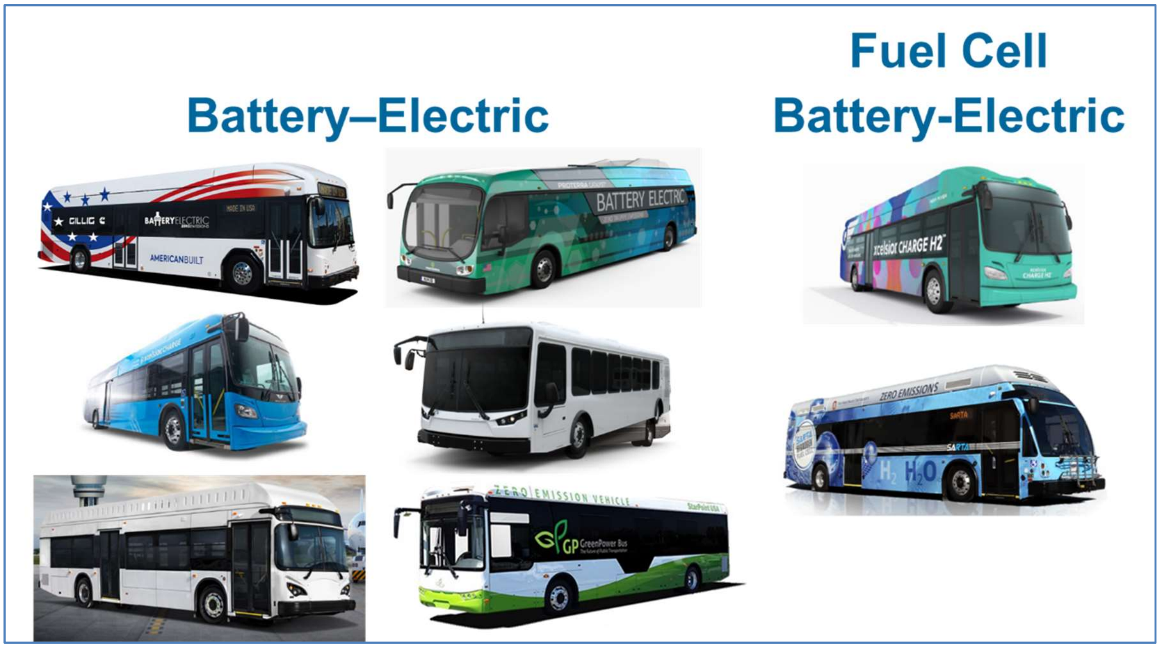


Figure 7: North American zero-emission heavy-duty Buses.
Source: Adapted from [9] [10] [11] [12] [13] [14] [15] [16]

Table 5: Heavy-Duty Transit market overview by propulsion system and length.

	Battery-Electric			Fuel Cell Battery-Electric		
	35-ft	40-ft	60-ft	35-ft	40-ft	60-ft
BYD	✓	✓	✓	x	x	x
ENC	x	x	x	✓	✓	x
Gillig	✓	✓	x	x	x	x
Green Power	✓	✓	x	x	x	x
New Flyer	✓	✓	✓	x	✓	✓
Nova Bus	x	✓	x	x	x	x
Proterra	✓	✓	x	x	x	x

As of October 2020, only BYD, ENC, New Flyer, Nova Bus, and Proterra have completed the Federal Transit Administration (FTA) Model Bus Testing Program, hereafter referred to as “Altoona testing”, for the referenced zero-emission bus models [17]. Altoona testing was developed to better regulate the safety and reliability of new transit buses [18]. All buses are tested to the same standards, so the reports generated provide a good frame of reference for comparing different makes and models of buses.

The Altoona test itself is divided into eight sections, including Maintainability and Accessibility, Reliability, Safety, Performance, Structural Integrity and Durability, Fuel/Energy Economy, Noise, and Emissions. The main component of the test is a ten-times accelerated life structural durability test. Heavy-duty buses are driven a minimum of 12,500 miles (20,117 km) on a durability test track with simulated passenger weight. The durability test track consists of several different stress-inducing elements that a bus may encounter during normal service, including bumpy roads, railroad crossings, pot holes, uneven surfaces, frame twisting, and hairpin turns. Unscheduled maintenance, breakdowns, and repairs times accumulated during this test are reported [19].

Altoona testing became a Pass/Fail test in August of 2016; however, most zero-emission buses sold today completed the test prior to this change. Under the pass/fail criteria a minimum standard has been established to create a high probability that a bus which passes this test will meet its expected service life. Buses are evaluated as follows:

Table 6: Altoona Pass/Fail Scoring System [20]

Test Category		Performance Standard	Base Points	Bonus Points	Range low	Range High	Score
Maintainability	Unscheduled Maintenance	<125 Hours	2	14	0	125	
Reliability	# Class 2 failures	< 2 Uncorrected	2	6	0	2	
Safety	Hazards	No uncorrected Class 1	10	0	P	F	
	Stability	Lane Change, 45 mph	2.5	0	P	F	
	Braking	<158 feet at 45 mph	0.5	2	80	158	
		Holds Lane, Split coefficient	2.5	0	P	F	
		Parking Brake, 20% Grade	2.5	0	P	F	
Performance	Acceleration 0-30 mph	less than 30 sec	1.5	0	P	F	
	Gradeability 2.5%	more than 40 mph	1.5	0	P	F	
	Gradeability 10%	more than 10 mph	2	0	P	F	
Structural Integrity	Distortion	exits are operational	1	0	P	F	
	Static Towing	no significant deformation	1	0	P	F	
	Dynamic Towing	Towable with std. wrecker	1	0	P	F	
	Jacking	liftable with std. jack	1	0	P	F	
	Hoisting	stable on jacks	1	0	P	F	
	Durability-Structural	no uncorrected failures	13	0	P	F	
	Durability-Powertrain	no uncorrected failures	12	0	P	F	
Fuel Economy	Liquid Fuels	1-13mpg	1	6	1	13	
	CNG	10-50 scf/mi			10	50	
	Hydrogen	15-98 cf/mi			15	98	
	Electric	1-3 kWh/mi			1	3	
Noise	Interior Noise (0-35mph)	less than 80 db	0.5	3	30	80	
	Exterior Noise (0-35mph)	less than 83 db	0.5	3	50	83	
Emissions	CO_2	0-4000 g/mi	1	4	0	4000	
	CO	0-20 g/mi		0.4	0	20	
	Total hydrocarbons	0-3 g/mi		0.4	0	3	
	NMHC	0-3 g/mi		0.4	0	3	
	Nitrogen oxides	0-3 g/mi		0.4	0	2	
	Particulates	0-0.1 g/mi		0.4	0	0.1	
Total			**60**	**40**			**/100**

In the U.S., completion of this test is mandatory for the receipt of federal funding. While buses are not required to have completed this test to receive federal funding in Canada it is highly recommended that Winnipeg Transit only consider buses that have passed, or are in the process of completing the Altoona test.

Most zero-emission buses that have been tested do not represent what is being sold today. Buses are now equipped with improved battery package, higher energy capacity and may have improved energy consumption through vehicle software optimizations. Manufacturers are required to request clarification from the FTA as to whether or not changes necessitate a retest. Often, the FTA only requires new models to complete partial testing to maintain eligibility for funding.

As heavy-duty transit buses make up almost the entirety of Transit's current fleet, it is recommended that a test fleet of ZEBs, used to evaluate the fundament changes to route planning, scheduling, parking, dispatching, service and maintenance required for transit electrification should be either primarily, or entirely, heavy-duty zero-emission buses.

3.1.2 Medium-Duty Manufacturers

While there are several manufacturers in this market segment selling cut-away style body on frame shuttle buses, there are currently six manufacturers selling the medium-duty unibody battery-electric buses, which Transit requires, to the North American market. Two heavy-duty manufacturers, Green Power and BYD, also produce a medium-duty bus, while Arboc, Lion Electric, Morgan Olson, and Grand West exclusively produce medium-duty buses. Globally there are several manufacturers producing medium-duty fuel cell battery-electric buses, but none are currently producing buses for the North American market.

Figure 8: North American zero-emission medium-duty buses.
Source: Adapted from [14] [21] [22] [23] [24] [25] [26]

Table 7: Medium-Duty Transit market overview by propulsion system and length.

	Battery-Electric			Fuel Cell Battery-Electric		
	20-ft	25-ft	30-ft	20-ft	25-ft	30-ft
Arboc	x	✓	✓	x	x	x
BYD	x	x	✓	x	x	x
Green Power	x	x	✓	x	x	x
Lion Electric	x	✓	x	x	x	x
Morgan Olson	✓	x	x	x	x	x
Grand West	x	x	✓	x	x	x

Even with unibody construction, buses in this market segment are more typically purchased by private transit and shuttle operators rather than public transit agencies. Since private operators are not eligible for US federal funding, Altoona testing is much less frequently attempted by manufacturers of medium-duty buses. Those that do seek Altoona certification typically test for 5, 7 or 10-year life rather than the more stringent 12-year test expected by public transit agencies.

As of October 2020, only BYD has completed Altoona's 12-year structural durability test. This has allowed them to pick up considerable market share in the zero-emission bus market. Arboc's Spirit of Equess structure has previously been validated for 10-year life with their diesel propulsion system. They have indicated that their electric propulsion system will be retested for 12-year life in the 2021 to 2022 timeframe. Lion Electric has indicated a similar time frame for completing 12-year life testing for their LionM bus. Green Power has previously tested their light duty EV Star body on frame bus, but does not currently have plans to test their medium-duty EV250 model. Morgan Olson's mini-bus is being develop in partnership with a Turkish bus manufacturer called Karsan. The Michigan built mini-bus will be an updated North American version of Karsan's Jest Electric [27]. Karsan's Jest Electric advertises a 10-year structural warranty, but no formal testing plans or release date for the mini-bus have been announced [24].

Technology is giving public transit agencies the opportunity to extend their service into lower demand areas that are traditionally under-serviced. Smaller, lower cost medium-duty battery-electric buses may fit well into this market as they more efficient, quieter, more maneuverable and lighter weight than a heavy-duty bus. With increased demand for these types of buses, more companies may enter this market in the future.

While this style of bus is likely to be part of Transit's long-term electrification strategy, because of the limited number of runs that currently require this size of bus, it is not recommended for Transit to include medium-duty transit buses in a test fleet of zero-emission buses.

3.1.3 Double Decker Manufacturers

There are currently three manufacturers in this market segment building buses in North America, and one additional European zero-emission bus manufacturer with non-electric buses operating in the US. Buses purposely built for the European market tend to be both shorter and taller than North American style buses. The North American style buses have a higher capacity and are easily distinguished from the European style buses by their dual rear axles.

Alexander Dennis Limited (ADL) produces both North American and European style double decker buses, while Green Power sells only North American style buses and Wright Bus sells only European style buses. BYD's recently announced North American battery-electric double decker is a coach rather than a transit bus, but it has been included in this discussion as they may offer a transit variation in the future.

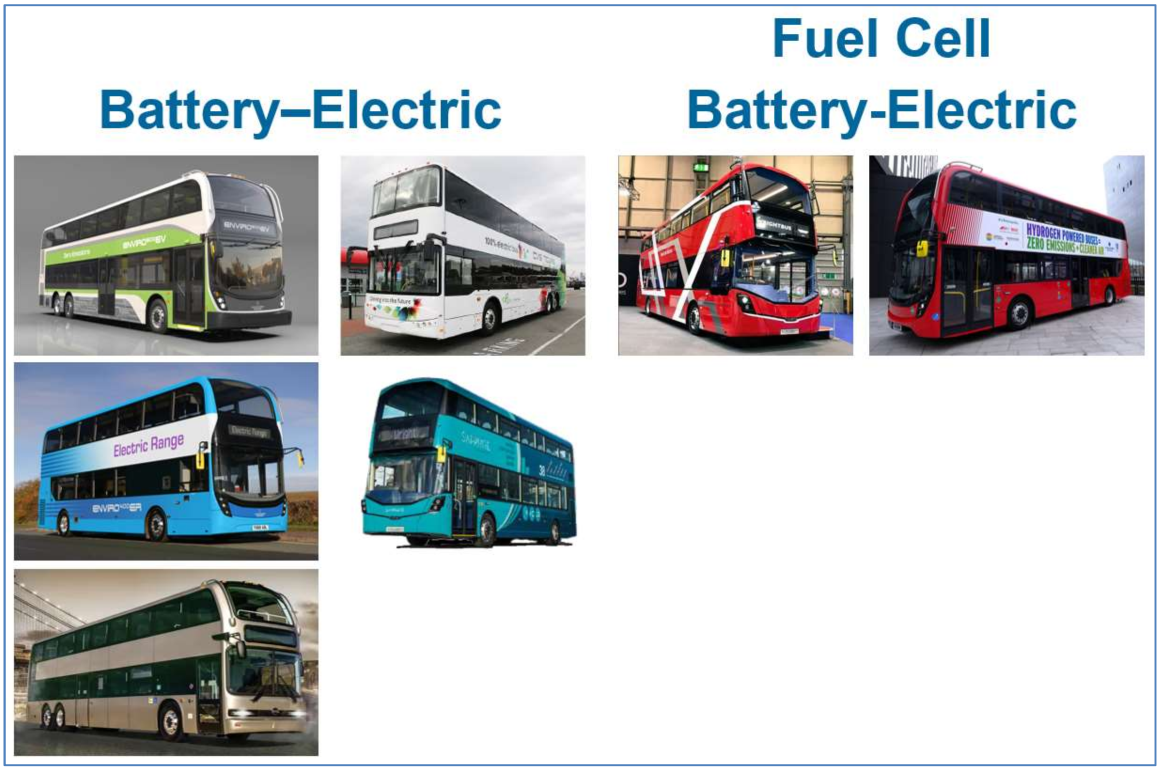


Figure 9: Manufacturers of double decker buses to the North American market. Source: Adapted from [28] [29] [30] [31] [32] [33] [34]

Table 8: Double decker market overview by style

	Battery-Electric		Fuel Cell Battery-Electric	
	NA	Euro	NA	Euro
ADL	✓	✓	x	✓
BYD	✓	x	x	x
Green Power	✓	x	x	x
Wright Bus	x	✓	x	✓

No manufacturer has Altoona-tested an electric propulsion system on a double-decker bus, but ADL has completed testing of their Enviro 500 platform with a diesel propulsion system. ADL was recently purchased by New Flyer; however, they currently utilize Proterra batteries and propulsion systems on their North American built double decker buses, and BYD batteries and propulsion systems on their European built double decker buses. ADL and Wright Bus additionally produce European style fuel cell battery-electric buses, but neither company has announced plans to offer this propulsion system on a heavier duty North American platform.

Double decker buses are common in Europe and are gaining in popularity in North America as they accommodate a similar number of passengers and have similar accessibilty as 60-foot heavy-duty buses, but tend to have fewer mechanical issues and a smoother ride as they do not have an articulated joint [35] [36] [37].

Transit does not currently operate any commuter style routes. With limited headroom and passengers encouraged to move up to the second level rather than stand, this design is not conducive to the shorter hop-on-hop-off trips more typically seen on Winnipeg Transit. The height of the buses exceeds current transit garage door limitations but would likely not have any more roadway restrictions than light rail. The ability to deploy these buses on the rapid transit service outlined in the Winnipeg Transit Master Plan would be limited, based on the fact that no manufacturer currently builds a double decker bus with both curb-side and street-side doors [35].

It is not recommended for Transit to include double decker buses in Transit's test fleet of zero-emission buses.

3.1.4 Bi-Articulated Bus (Trambus) Manufacturers

There are several manufacturers producing trolley buses in this class, but only two manufacturers are currently selling off-wire bi-articulated zero-emission buses. Both are located in Europe. Hess sells a 25-meter (80 feet) battery-electric buses, while Van Hool sells both a 24-meter (78 feet) battery-electric and fuel cell battery-electric bus.

Two Chinese manufacturers have also announced, but are not currently selling, bi-articulated buses. BYD advertised a 27-meter (89 feet) bus in 2019 but no specifications were released, and no pilot projects were announced [38]. Zhuzho CRRC Times Electric Co. Ltd (TEC) announced an autonomous variation they are calling Autonomous Rail Rapid Transit (ART) in 2017. The ART buses are currently undergoing testing, including hot weather and cold weather trials, and are expected to go into service in 2022 [39].

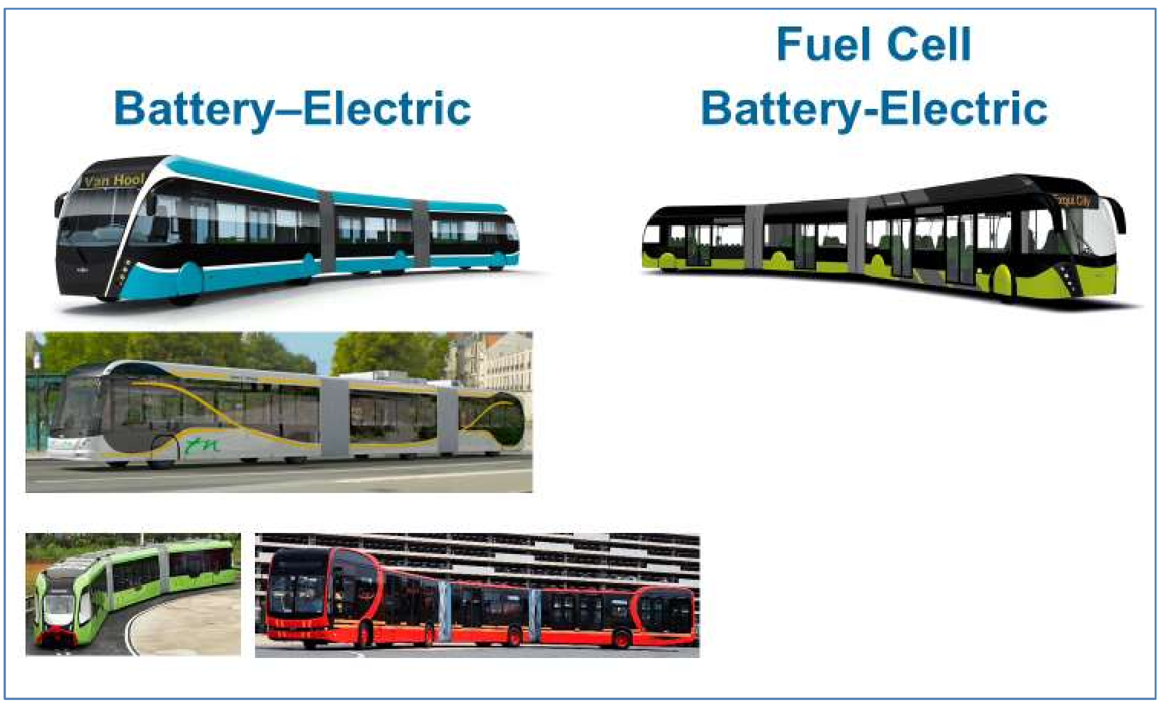


Figure 10: International double-articulated buses. Source: Adapted from [38] [40] [41] [42] [43]

Table 9: Bi-articulated trambus market overview by availability.

	Battery-Electric		Fuel Cell Battery-Electric	
	Production	Prototype	Production	Prototype
BYD	✓	✓	x	✓
Hess	✓	x	x	x
TEC	✓	x	x	x
Van Hool	x	✓	x	✓

As there are no North American manufacturers of this style of bus, therefore, there are also no Altoona tested buses in this class. As these buses are designed to run on smooth dedicated transit corridors rather than standard roads, Altoona testing may not be appropriate.

Bi-articulated buses offer the flexibility of a bus with the efficiency of light rail [44]. They offer similar passenger capacity to light rail with significantly lower infrastructure costs. These buses are heavy and consume more energy than a 60-foot zero-emission bus. Adding batteries to improve range restricts passenger capacity, therefore manufacturers are offering smaller battery capacities and range extending the buses with either on-route charging or on-board fuel cells.

The Winnipeg Transit Master Plan acknowledges that this technology is evolving, and provisions such as extended platforms at stations to accommodate bi-articulated buses are being included in designs for the rapid transit corridors [35].

It is unclear at this time whether or not this technology will be part of Transit's long-term electrification strategy, as ridership on each individual rapid transit line will dictate whether this technology or light rail will be more appropriate for future rapid transit lines. Because of this uncertainty, and the lack of available buses in the North American market, it is not recommended for bi-articulated buses to be included in Transit's test fleet of zero-emission buses.

At this time, only heavy-duty transit buses are appropriate for inclusion in Transit's test fleet of zero-emission buses, as such further technology evaluation will focus solely on bus and infrastructure offered for this market.

3.2 Long-Range Battery-Electric Buses

Long-range battery-electric buses (BEB-LR) are optimized to travel more than 300 km continuously between charges at Beginning of Life (BOL). They are supplied with high-energy batteries which typically have energy densities around 200 Wh/kg [45], allowing buses to be equipped with up to 660 kWh of energy [16]. This is the most commonly sold battery-electric bus in North America, and all heavy-duty battery-electric bus manufacturers offer a long-range battery-electric bus with high-energy batteries.

Figure 11: TTC's Proterra E2 long-range BEB. Source [46]

Batteries currently make up approximately 25% of a new bus purchase price [47]. Based on a cycle life of 4,000 charge and discharge cycles, long-range batteries should last 6-12 years depending on deployment strategy [48]. While the cost of heavy-duty commercial batteries continues to fall, any mid-life battery replacements will significantly impact budgets and must be accounted for in the lifecycle cost analysis.

The range of the buses is highly affected by battery capacity fade and is expected to decrease 20-30% over a period of 6-12 years. While manufacturers typically advertise maximum range based on 90% usable battery capacity at BOL, it is recommended that actual daily range be restricted to 70% of maximum range to limit capacity fade, and to ensure all buses have sufficient capacity to complete assigned runs regardless of the age of the fleet. If the expectation is to operate from full to empty each day, battery capacity may degrade at an accelerated rate, and the battery health of each bus will need to be monitored to ensure buses have enough range to complete their assigned run. Winnipeg Transit's Dispatch office would require new software and tools to effectively manage this task. It may take considerable time and effort to develop and integrate new tools with existing systems.

Long-range battery-electric buses are the most impacted by range loss in cold temperatures [49]. The addition of a diesel auxiliary heater is recommended to limit range loss in winter. Without a diesel auxiliary heater, maximum range could be reduced by as much as 60%, while adding the diesel heater limits performance losses to 20% or less. By comparison, Transit's diesel fleet utilizes on average only 10% more fuel in January than in June. The variation between winter performance of electric and diesel buses is amplified by reductions in regen energy from regenerative (regen) braking, either from reduced road traction caused by ice or snow, or operators turning off regen all together for improved handling [49].

The range gap between diesel and long-range battery-electric buses needs to be made up by either increasing the fleet size or charging buses mid-day and redeploying. Initial estimates are that even with operational changes to accommodate mid-day charging, Transit would need to replace their diesel fleet with more long-range battery-electric buses to maintain current service levels.

Another major trade-off for longer range is slower charge rates. These batteries can typically only charge between a C/4 and C/3 rate which limits charge power to 130 kW-220 kW depending on battery pack size. This lower charge rate limits the effectiveness of extending range using on-route opportunity charging unless extended layovers are scheduled [16] [12] [9]. As a result, long-range BEBs are primarily charged at a garage/depot for several hours before being deployed. This can be accomplished via a plug-in charger or with an overhead pantograph connecting to bus-mounted roof rails.

Weight is also a consideration with these buses, as excess battery weight results in an increased risk of overloading of axles and/or tires at full passenger loads [50]. The need for extra range must be balanced against efficiency losses and potentially higher maintenance costs caused by excess weight.

Table 10: Pros and Cons of long-range battery-electric buses

Pros	Cons
High Efficiency	End of life Operating Range between 220-330 km for 40-ft; 135-200 km for 60-ft
Range extended to 420+ km with mid-day charging	Not a 1:1 replacement for diesel; up to 6.5% more buses required
Does not need to be deployed on BEB-specific routes	Need to manage charge times in depot using software
Battery warranty available up to 12 years	Not zero-emission; Diesel Aux heater required in winter
Six manufacturers to choose from	Excess battery weight limits the number of passengers or risks overloading a full bus
	High replacement cost if batteries don't last 18 years
	Need a minimum 15-min layover at on-route charger to extend operation by 1 hour

3.3 On-Route Rapid-Charge Battery-Electric Buses

On-Route rapid-charge battery-electric buses (BEB-RC) are optimized to operate continuously by frequently charging for short periods of time throughout the day. They are supplied with high-power batteries which typically have energy densities around 100 Wh/kg, allowing buses to be equipped with up to 320 kWh of energy [45] [9]. This was the original type of battery-electric bus produced by most manufactures in North America. They are still common in Europe, but today only New Flyer and Nova Bus produce on-route battery-electric buses with high-power batteries, while Proterra has discontinued production of their rapid-charge buses.

Figure 12: TransLink's Nova bus LFSe rapid-charge BEB with ABB mast charger. Source: [51]

The amount of on-board energy limits continuous range to less than 100 km, but the trade-off is a charge rate between 3C and 5C which allows the buses to accept charge power in excess of 450 kW [52]. New Flyer and Nova bus currently only offer conductive charging via an overhead pantograph connection to bus mounted roof rails. Plug-in receptacles are supplied as a back-up charging method and to permit overnight and maintenance charging in a garage.

With the largest chargers currently available, buses would need to layover for two plus hours per day to recover the energy lost while driving; however, charging is spread out in 5 to 12-minute increments throughout the day rather than in one continuous charge session [53]. Total daily range is limited by charge time but less so than long-range BEBs, with a typical on-route charged bus capable of driving for 22 hours (484 km) with a combined 2 hours of charging interspersed throughout the day.

Despite having significantly less battery capacity than their long-range counter parts the difference in purchase price is only marginally cheaper due to the higher per/kWh costing of high-power batteries vs high-energy batteries. The high cycle count associated with on-route charging increases the rate of capacity fade, making it highly likely that battery packs will need to be replaced every 3-6 years, negating much of the initial savings over an 18-year period.

These buses tend to be lighter than long-range BEBs; however, they are still significantly heavier than diesel buses, and passenger loads may be affected with the largest available battery capacities.

Transit would need to ensure that the pack size selected matches expectations for bus charge time and range between charges. Battery packs have only a limited number of charge cycles before they need to be replaced, regardless of battery pack capacity. The distance a bus travels between charges should be adequately spaced based on battery capacity to ensure that buses are not being charged more frequently than necessary. Carrying more energy than required adds both unnecessary cost and weight to a bus, and frequent charging will result in shorter life and higher mid-life replacement costs.

Battery-electric bus specific runs which return a bus to a charger at least every 4 hours would need to be developed by the Schedulers in Service Development [53]. Interconnected or overlapping routes utilizing the same charger would need to be monitored to prevent charging backlogs and “double-booking”, which may be impossible in some cases given the lengths of overlapping routes relative to one-another. Charger availability and performance has a large impact on both service frequency and vehicle availability. Reductions in power output or a missed charge could result in a bus running out of energy in the middle of a route, between scheduled charges. A single on-route charger going down for service, or a service disruption blocking access to a charger, could result in multiple buses needing to be re-routed or replaced. Because of the short range of these buses, it would likely be preferable to replace these buses with long-range buses, rather than continue to replace them every 2-4 hours until the charger is repaired, or access is restored.

Although both very high and very low temperatures affect the range of on-route charged buses, the loss of range is less impactful due to the shorter distance between charges. It may be necessary to extend charge time during intense winter cold or summer heat, if buses are not able to meet the minimum distance required between charges.

If these buses are run, 24/7 rapid-charge BEBs theoretically have sufficient range to replace diesel buses. To prevent service losses from charging layovers, initial estimates are that Transit would need to replace their diesel fleet with more on-route charged battery-electric buses to maintain current service levels.

Table 11: Pros and Cons of rapid-charge battery-electric buses

Pros	Cons
High Efficiency	Range between charges <100 km
Daily range of 490+ km with frequent high-power charging	Only two manufacturers to choose from
Reduced range in extreme temperatures not as noticeable	Shorter range means unplanned service disruptions could result in vehicle tow
5 min charge extends operation by 1 hour; Fully charged in 20-45 minutes	Need a larger battery pack to take full advantage of maximum available charger rates
Smaller battery pack does not significantly reduce range daily	High battery replacement cost as battery life is only 3-6 years due to frequent charging
	Battery-bus specific runs required
	Not a 1:1 replacement for diesel - up to 10% more buses required
	Not capable of maintaining service levels during prolonged charger outages; must be replaced with a long-range bus (diesel, BEB-LR or FC-BEB)

3.4 Fuel Cell Battery-Electric Buses

Fuel cell battery-electric buses (FC-BEB), also known as battery-dominant fuel-cell buses, are a range extended battery-electric bus. They have identical propulsion systems to BEBs and are powered by high-energy batteries with capacities up to 150 kWh, but they also include an 85 kW or smaller fuel cell which charges the bus while driving by converting on-board stored hydrogen into electricity, with by-products of heat and water. [54] [55]. FC-BEBs are fully electric and produce zero tailpipe emissions. Utilizing hydrogen produced in Manitoba using renewable hydro-electricity results in these buses being fully zero-emission. FC-BEB have been optimized to travel more than 500 km on a typical transit duty cycle while also prolonging life of the batteries and fuel cell [10].

New Flyer is currently the only North American manufacturer producing this type of vehicle; however, ENC recently announced a new battery dominant fuel cell model called the Axess FCBD based on their current fuel cell-dominant Axess FC platform [11].

Figure 13: OCTA's New Flyer Xcelsior Charge H2 Fuel Cell Battery-Electric Bus. Source: [56]

A maintenance charger can be supplied to trickle charge the batteries, but otherwise these buses do not need to be charged. Instead, fuel-cell buses are fueled at a hydrogen fill station. Manual filling of buses can be as long as 20-30 minutes, but buses and dispensers can be equipped with compatible communication devices which monitor and control the temperature and flow rate of hydrogen to enable faster fill times. If the buses and dispensers are equipped for communication fill, a 40-foot bus can refuel as quickly as 6 minutes which is similar to diesel refueling, while a 60-foot bus requires at least 12 minutes due to the larger volume of on-board fuel. [10].

Because they are battery-dominant, the bus cannot operate if the batteries run out of energy even if there is reserve hydrogen available. A small fuel cell is optimal for maintaining battery state-of-charge during a typical transit duty cycle with low top speed and frequent braking, but does not provide sufficient power to sustain battery charge under continual operation at highway speeds or prolonged hill climbs. Under these conditions, the energy stored in the batteries combined with the additional energy generated by the fuel cell will enable the bus to operate for 30-60 minutes, but the battery will eventually drain to zero before the on-board hydrogen is fully consumed. When this happens, the bus will shut down. Transit does not currently intend to operate at speeds above 80 km/h for any extended period of time, nor are there significant grades in the city, so there should be no range anxiety when operating these vehicles in Winnipeg.

FC-BEBs can be driven without fuel on battery power only for approximately 30 kilometers. While it is not recommended to operate in this state on a regular basis as it would impact battery life, this feature does provide sufficient range for a bus to return the garage if it runs out fuel while in service, or to enable the bus to be moved if it were intentionally drained of hydrogen for service or repair.

With similarly-equipped options a fuel cell bus is lighter than an equivalent BEB; however, these buses are heavier than the lightest BEBs and are still significantly heavier than diesel buses, so there is risk of overloading axles with full passenger loads [54].

The addition of a fuel system results in higher predicted scheduled and unscheduled maintenance cost when compared to BEB, but maintenance costs are still expected to be lower than diesel buses [57]. Mid-life overhaul costs, however, are expected to be significantly lower than a BEB. The control strategy used on FC-BEBs greatly limits both the number of charge cycles and depth of discharge of the batteries, which means that the batteries are likely to last 12 years or more when driven on a normal transit duty cycle, while fuel cells are expected to last the entire life of the bus, with fuel cell stacks lasting 6-years or more. Fuel cell stacks can be refurbished to original capacity at a relatively low cost, while battery packs would require replacement.

Capacity fade of the batteries and fuel cell does not greatly affect performance, but fuel consumption will increase as the bus ages affecting range.

The process for converting hydrogen to electricity is only 50 percent efficient so FC-BEBs operate at a lower efficiency than BEBs, but they are still nearly twice as efficient as diesel buses [58]. If the source of power for both buses is commercially sold electricity, a FC-BEB will always be more expensive to refuel than a BEB due to efficiency differences. Grid electricity is easily accessible, but it may not be the most cost-effective method of refueling buses. With Manitoba’s grid-based electricity, an equivalent amount of hydrogen fuel can be produced at small-scale at cost parity to diesel. Large scale commercial hydrogen production has the potential to significantly reduce the cost of hydrogen to the point of cost parity with commercial electricity rates. As such, efficiency differences between BEBs and FC-BEBs do not necessarily directly relate to higher operating costs.

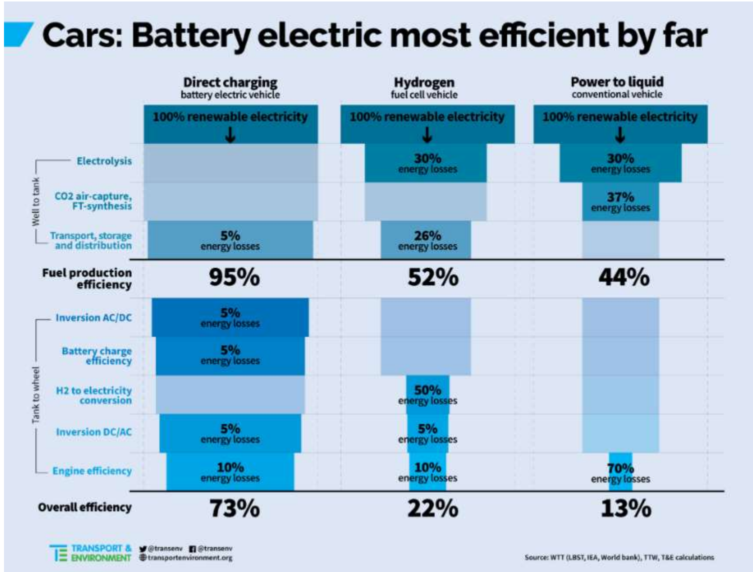


Figure 14: Well to Wheel efficiency of electricity vs green hydrogen vs diesel powered vehicles. Source: [58]

The side effect of lower efficiency is excess heat. Waste heat can be captured to supplement cabin heating in cold weather, resulting in lower range loss as compared to battery-electric buses with all electric heat [49]. Enough heat is captured to potentially eliminate the need for a diesel auxiliary heater.

Because of the range of these buses and the fast hydrogen refueling time, a fuel cell battery-electric bus can be a one-to-one replacement for a diesel bus at Winnipeg Transit. Some operational changes may be required to accommodate the longer refueling time associated with 60-foot buses, but on the whole the one-to-one replacement still holds true. This simplifies scheduling, as no significant changes would be required to run lengths or scheduling parameters.

Table 12: Pros and Cons of fuel cell battery-electric buses

Pros	Cons
500+km range on single fill	Lower efficiency than BEB
Filling/Redeployment easy to manage (6-10min Fueling)	Cost of hydrogen impacts operating cost
1:1 replacement for diesel buses	Increased maintenance vs BEB
Minimal range reduction in low temp	Only two manufacturers to choose from
Only zero-emission option for cold climate (i.e. no diesel aux heater required)	Limited range at high speeds (not a typical Winnipeg Transit duty cycle)
Batteries expected to last 12+ years	Filling/Redeployment somewhat more difficult to manage than diesel • 6-10 min for 40-foot FC-BEB • 12-20 min for 60-foot FC-BEB • 5 min for diesel bus
Low mid-life refurbishment cost	Not currently available in lengths under 40-feet
Short range on battery power alone if the bus runs out of fuel.	
Minimal impact to scheduling and dispatch	

4 OVERVIEW OF CHARGING INFRASTRUCTURE

4.1 Battery-Electric Charging Standards

Most North American bus manufacturers have signed onto CharIN to work together for the establishment of global standards for charging battery powered electric vehicles [59]. SAE International (SAE), formerly known as the Society of Automotive Engineers, is one of the main bodies responsible for developing and releasing vehicle standards. Through the cooperation of bus manufactures, standards, such as SAE J1772 for plug in charging, SAE J3105 for automated conductive charging, and SAE J2954 for automated inductive charging, have been released and are being updated, with the ultimate goal of full interoperability. More simplistically this means that any bus will be able to charge on any charger, regardless of the make of model of bus or charger.

The Canadian Urban Transit Research & Innovation Consortium's (CUTRIC) Pan-Canadian Electric bus demonstration is currently being utilized to test interoperability of conductive charging. There are currently no similar demonstrations under way for inductive charging; however, CharIN has released a guideline to encourage development of inductive interoperability [60].

Since Winnipeg Transit's battery-electric bus demonstration the following developments have occurred:

- Plug-in charging using SAE J1772 Combined Charging System (CCS) for both alternating current (AC) and direct current (DC) charging.
    - CCS1 combo connector defined as the standard plug for transit buses in North America
    - Standardized communication protocol between bus and charger
    - Multiple commercially available chargers (ABB, ChargePoint, Efacec, Heliox, Siemens, etc.)

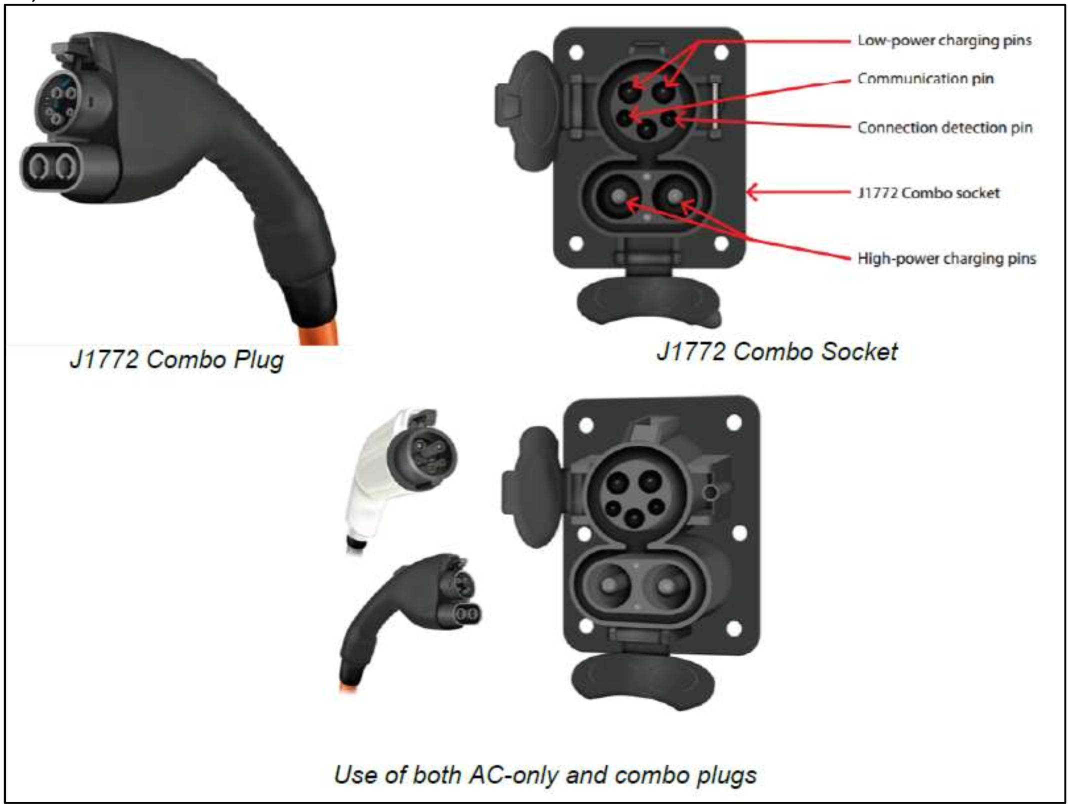


Figure 15: SAE J1772 Combined Charging Standard (CCS) receptacle and plug. Source: Adapted from [61]

- On-route conductive charging using SAE J3105-1 compliant fast charging equipment [62].
  - Infrastructure mounted pantograph connection established as the standard automated conductive charging method for transit buses in North America.
  - Standardized communication protocol between bus and charger.
  - Standardized charge rail position on buses.
  - Multiple commercially available chargers (ABB, Heliox, Siemens, etc.).

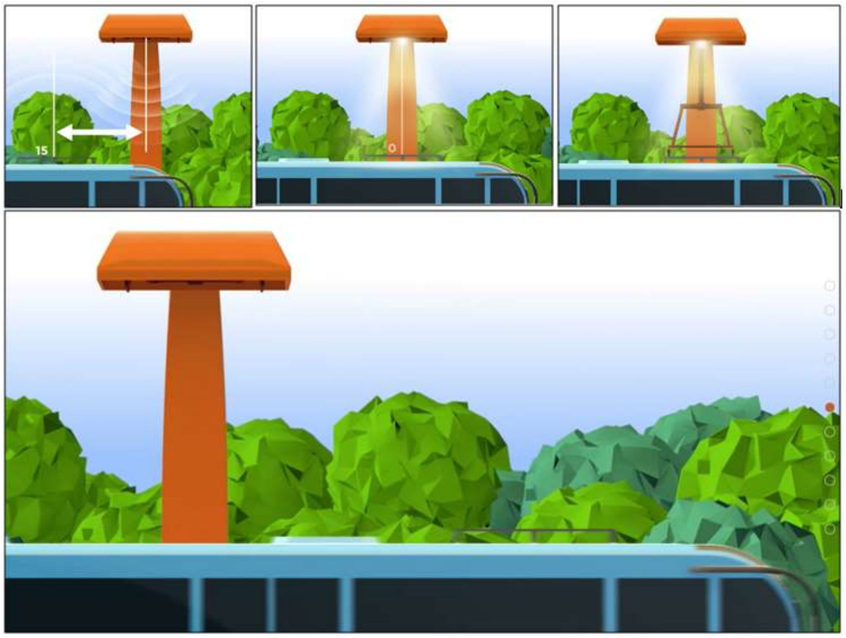


Figure 16: SAE J3105-1 overhead charging procedure. Source: Adapted from [63]

- On-route inductive charging using SAE J2954 (light duty inductive charging up to 11 kW)
  - Need to update standard to include heavy duty vehicles.
  - Need to establish safe upper charging limited above 11 kW (450 kW advertised).
  - Need to validate standard communication protocol between bus and charger through interoperability trial.

4.2 On-Route Overhead Conductive DC Fast Charging

Overhead charging is offered by all major North American battery-electric bus manufacturers with the exception of BYD. Battery-electric buses can be equipped with charge rails to enable overhead charging. An inverted pantograph attached to either a mast or an overhead gantry deploys and makes a physical connection with the bus mounted rails. The bus and charger must be properly aligned for charging to initiate.

Models are currently available up to 600 kW; however, actual charge rates are limited by battery technology and could be significantly lower than the rated power of the charger. See *Understanding Battery Charge/Discharge Limits* section for more information. While high-power chargers enable rapid-charge buses to drive an additional two hours with as little as six minutes of charging, long-range buses may require extended layovers of up to 30 minutes for similar range extension.

The high charge rate enables a larger number of buses to share the same charger. With 600A (450 kW) charging up to 17 buses per charger is possible, once time for bus alignment, charge initiation, and pantograph retraction is accounted for, although a more conservative number would be 13 buses to allow for some leeway between charging sessions. Lower charge power means longer charge times and fewer buses able to utilize the same charger. Operating fewer chargers works to reduce both monthly utility demand charges as well as initial infrastructure investment. Because of utility demand changes, a similarly-sized fleet of on-route conductively charged buses is expected to cost less per month than an equivalently sized fleet charged via plug-in chargers with a 3:1 ratio of buses to chargers [64].

The downside to this is that any charger going down will result in up to 17 buses needing to be rerouted or replaced every two hours with another bus from the depot. For large scale electrification there may be a need to install additional charges across the city to provide extra flexibility for re-routing.

It is estimated that the total energy required to electrify Winnipeg Transit's entire fleet today would exceed 25 MW. Currently, Transit is limited to no more than 2.5 MW at their two main garages without investing in transformation equipment. The ability to distribute load across the city is one potential way for Transit to avoid some of the costly garage updates.

There are, however, disadvantages to remotely locating chargers as well. Land purchases may need to factor into cost estimates as it will likely not be possible place all chargers on existing City-owned property. Cost to purchase and install mast style chargers is approximately $1,000,000 per location [65]. Selection of sites would need to include a review of power transmission in the surrounding area, as any potential power surges could result in a power de-rate which could ultimately reduce range. Running chargers from a microgrid with energy storage rather than directly from grid power is one method being utilized by transit agencies to improve resiliency and isolate chargers from grid variations; however, there can be significant costs associated with implementing this type of system [66] [67].

Location of chargers is critical. Charge cycles for these buses range from 5 to 15 minutes. To prevent passengers from experiencing travels delays while waiting for a bus to complete charging, chargers should be placed at terminal points rather than distributed along a route. Finding locations that enable serving of multiple routes would be critical to ensure maximum charger utilization. Unfortunately, this also compounds the risk of a single charger outage affecting multiple routes.

Another challenge with location is that the end terminus of a route can change as a route is extended or modified to service new developments, or changing ridership patterns. The installation of an on-route charger requires significant financial investment, and there is no guarantee that a charger will be required in a specific location for a period of time long enough to recoup the investment.

Construction and contracting are much more critical with distributed overhead charging as there is greater potential for construction delays as compared to plug-in chargers. Placement and alignment of the pantograph relative to the roadway are critical for successful charging. Road closures may be necessary during construction. Transit may also need to get design approval from the local community to ensure that the look of the charger aligns with other structures in the neighbourhood.

The outdoor installation also raises the risk of public safety. The public will need to be made aware of the presence of high voltage and kept safe from exposure. The equipment contains a high quantity of copper and other metals which could make the chargers a target for theft or vandalism. Additional surveillance or security may be required if this becomes a larger issue.

These chargers also require more maintenance than plug-in chargers due to the large number of moving parts and exposure to the elements from being located outdoors. The remote locations also add to this expense as a service crew will need to be dispatched to each charger site.

Figure 17: Metropolitan Transit Authority (MTA) on-route charger 12th Ave. New York, NY. Source: [68]

Table 13: Pros and Cons of on-route conductive charging

Pros	Cons
High utilization rate	High cost for charger purchase and installation ($1M+)
High ratio of buses to charger	Possible land purchase/expropriation required
Distributes power demand across the city	Charge rate limited by battery technology
High charging power (up to 600 kW)	Increased maintenance due to moving parts and outdoor storage
Can be placed at terminal points to service multiple routes	Charger related issues could result in service delays or disruptions
High efficiency	Susceptible to vandalism
	Need to protect the public from high-voltage equipment
	Potential for construction delays • Permitting • Design changes (blending with neighbourhood) • Road closures
	Maximum of 17 buses can use the same charger
	Multiple routes impacted if charger is not available
	Prolonged Service outages cannot be maintained with on-route charged buses and would require an alternative long-range replacement bus (diesel, BEB-LR or FC-BEB)

4.3 On-Route Inductive AC Fast Charging

Inductive charging is currently only offered by BYD and Gillig. While there may be other manufacturers globally, WAVE and Momentum Dynamics are the two companies with North American transit experience. Buses are equipped with a receiver pad and a transmitter pad is embedded into the roadway. Buses charge wirelessly when the receiver and transmitter are aligned. The supplied power is AC, and as such buses need to be equipped with an additional inverter in order charge the high-voltage batteries which require DC.

On-route inductive charging has many of the same advantages and disadvantages as conductive on-route charging, but there are a few differences between the two technologies.

The first difference is charging capacity. The largest capacity inductive charger installation to date is only 300 kW, although capacities up to 450 kW are advertised [69] [70]. Overall efficiency of an inductive charger to a similarly sized conductive charger will be lower, mostly due to losses caused by air gaps between the transmitter and receiver.

Due to the lower power outputs associated with this technology, longer layovers or more frequent charging will be required to extend range as compared to overhead charging. Layovers of at least 15 minutes will be necessary to extend the range of rapid-charge buses up to 2 hours. More frequent, shorter charging cycles could be used to extend range, but would do so at the expense of battery life.

The receiver plates installed on the vehicle are also significantly heavier than conductive charge rails. A 300 kW system could add as much as 120 kg of weight to the bus, close to the weight of two passengers [71].

Because the buses and chargers are not connected, regulating this technology falls to both the Underwriters Laboratories (UL) for the development of off-board equipment testing and certification, and SAE for the establishment of vehicle safety systems [72]. CharIN has recommended that SAE J2954 be expanded to cover heavy duty commercial charge rates above 11 kW. Until this updated, interoperability between buses equipped with different receiver pads is unlikely [60]. The lack of an established protocol for monitoring charge current, detecting foreign or live objects, or emergency shutdown guidelines are all items that could impact public safety [72]. The large magnetic fields generated by inductive charging produce electromagnetic Interference (EMI) which interferes with the performance of electronic equipment in close proximity to the charger. If the bus is not adequately shielded, EMI could pose an immediate danger to people with pacemakers and other implanted medical devices on or near the bus.

The charging interface for inductive charging is embedded into a roadway which eliminates moving parts and reduces maintenance costs, but any required repairs to the embedded equipped could result in road closures, rerouting of buses and significant construction costs.

There is also no information available on the long-term durability of installations in cold climates. The freeze-thaw cycles that Winnipeg regularly experiences could cause significant heaving of roads, resulting in holes and cracks. This process could potentially damage equipment embedded in the roadway. It is also unclear what impact snow, ice or general debris will have on charger efficiency.

Figure 18: WAVE inductive charging interface Source: Adapted from [65]

Figure 19: Momentum Dynamics inductive charging interface. Source: Adapted from [73]

Table 14: Pros and Cons of on-route inductive charging

Pros	Cons
High utilization rate	Expensive charger & installation (1M)
High ratio of buses to charger	Possible land purchase/expropriation required
Distributes power demand across the city	Charge rate limited by battery technology
Can be placed at terminal points to service multiple routes	Charger related issues could result in service delays or disruptions
No moving parts, or physical connection to be made between the bus and charger	Potential for constructions delays • Permitting • Road closures
	No Interoperability between suppliers
	Longer layover required due to low efficiency and max 300 kW power
	Efficiency impacted by snow/ice on roads
	Equipment could be damaged by freeze-thaw process
	Adds significant weight to the bus
	Unknown impact of EMI to public safety; i.e. pacemakers

4.4 Plug-In Depot Charging

Plug-in charging receptacles are standard equipment on all North American battery-electric buses. Buses charge when a male connector is physically plugged into the female receptacle on the bus. Generally plug-in chargers are located at a central depot, and buses charge continuously for several

hours at the end of a run. All battery-electric buses are equipped with a minimum of one charge receptacle, but some manufactures offer multiple charging receptacles. DC fast charging CCS1 sockets are available from all manufacturers and are built into the price of the bus, with the exception of BYD, who instead offers it as an upgrade from their proprietary AC socket.
[9] [16] [12].

The CCS1 connector for DC fast charging is rated up to a maximum of 200 A, 1,000 V, while BYD's proprietary AC connector is rated for 120 A, 528 V [74]. DC chargers with power ratings up to 150 kW, and AC chargers with ratings up to 100 kW, are available; however, actual charge rates are limited by battery technology and could be lower than the rated power of the charger.

Figure 20: Depot Plug-in charging. Source: [65]

This charging method is relatively mature and interoperability is common. There are a large number of charger manufacturers and the purchase cost for an individual unit is now around $100,000, with the installed cost of a single charger around $200,000 [65]. Some manufacturers also offer options which allow multiple buses to be plugged into the same charger and charge sequentially which simplifies operations with only minimal cost increase [75]. Up to four remote charge dispensers per charger is common. This technology is relatively low cost to implement for small test fleets, but costs scale almost linearly as the fleet grows, which means transit agencies should expect to pay an additional $75,000-$200,000 per bus for charging infrastructure as the fleet grows.

Figure 21: Sequential plug-in charging configuration with remote charger interface.
Source: Adapted from [75]

The chargers themselves have few moving parts and are expected to require little maintenance, particularly with Transit intending to install the units inside a heated parking garage. The cables required to connect to the buses are long, heavy and not easily coiled, creating the potential for the cable or connector to be easily damaged. The small number of buses utilizing each charger and overall low utilization, other than for a few hours each day, means that a single charger going down for service will have minimal operation impact.

A review of Transit's dispatch schedule shows that transit operations could be supported by rotational charging of buses throughout the day. Daily range could be extended by having buses charge 12 times per week rather than seven. Mid-day charging could also reduce the time needed to charge in the evenings which could lower the total number of required chargers.

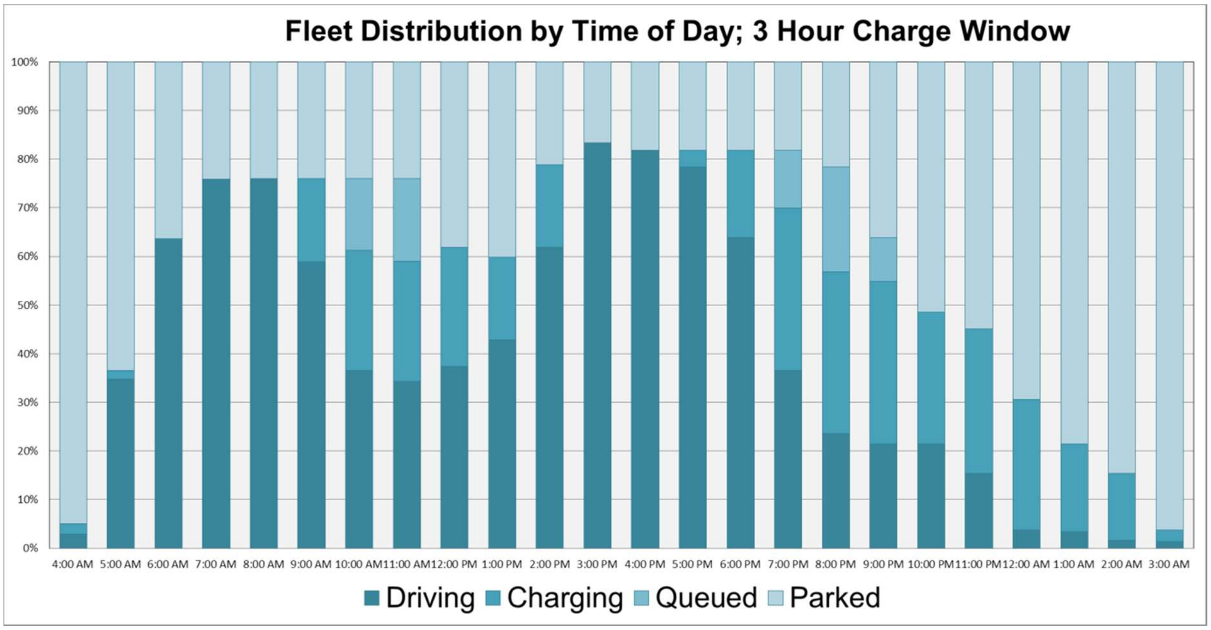


Figure 22: Fleet distribution by time of day; 3-hour charge window

Small deployments of plug-in chargers are low cost and easy to manage, but operating a large fleet of plug-in charged buses is operationally complicated. If a 1:1 bus to charger ratio or sequential charging is not utilized, a dedicated area for charging will need to be established. State-of-charge will need to be monitored, and buses that have reached a full state of charge may need to be moved out of the charging lanes to allow buses waiting to charge access the chargers. Additional personnel would be required for these operations. As not all buses reach full charge at the same time, this is likely not as simple as first in first out. Even with sequential charging, there still may be a need to physically move buses as space limitations will likely require electric and non-electric buses to be mixed in the same row. Each generation of BEB may charge differently, so Transit would need to manage a fleet within a fleet both during the transition from diesel to electric, and each time a new model of bus is purchased. This is difficult to manage as the fleet grows without implementing complex depot management software.

Purchasing one charger for every bus could be very expensive and would greatly increase peak demand. The recommended ratio of buses to chargers varies from 2.2:1 to 6.5:1 based on the expected charge rate and the capacity of the buses. A ratio of 4:1 of buses to plug-in chargers would be recommended to test operational flexibility during a test fleet deployment, while optimizing available sequential charging capabilities. At large-scale, Winnipeg Transit's dispatch schedule should support up to a three-hour charge window with a 4:1 bus to charger ratio; however, the number of buses available for deployment during the afternoon rush will need to be monitored to determine whether this ratio should be adjusted upwards or downwards. Utilizing a strategy with fewer chargers than buses would result in buses waiting in a queue for charging, which impacts the number of buses ready to deploy on an emergency basis. More buses or more chargers may be needed to ensure a minimum number of spares are available at all times.

Concentrating a large number of chargers in one area, such as a parking garage, increases the risk of overloading the grid. It is currently estimated that by 2050, Winnipeg Transit could need as much as 35 MW of power to charge a fleet of long-range buses at 150 kW. This greatly exceeds Manitoba Hydro's single service supply, and as such Transit would need to invest in transformation and switching equipment, or develop alternative power management strategies to manage this demand. Adding back-up generation to supplement this much power during grid outages also adds additional expense.

The majority of the cost from a monthly energy bill for plug-in charging will come from demand charges. The maximum number of chargers used simultaneously with the combined maximum power draw of the chargers is the peak monthly demand. Although maximum charge power can be manually restricted, utilizing bus and charger management software can be used to monitor and control charger power across all connected chargers to ensure maximum power is available to the buses that need it.

With a 4:1 bus to charger ratio, overall charger utilization throughout the week would be less than 40%. There is potential to use a microgrid with energy storage to smooth out peak demand to lower monthly electricity bills. Solar power could also be integrated for further energy reductions [67]. Establishing infrastructure costs of fleet expansion will be far more complex than simply purchasing additional chargers.

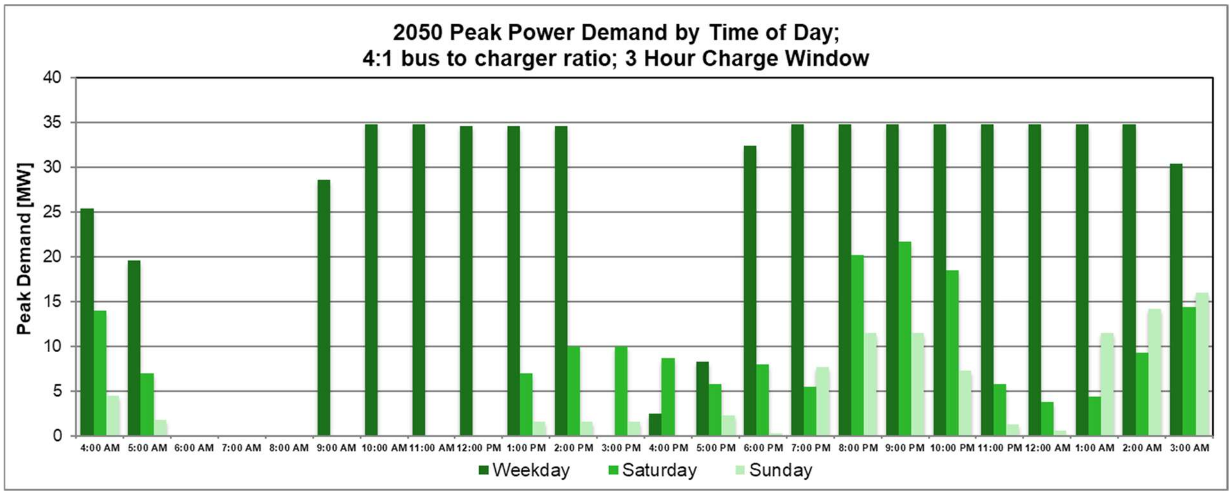


Figure 23: Estimated peak power demand in 2050 by time of day based on 4:1 bus to charger ratio and a 3-hour charge window

Table 15: Pros and Cons of plug-in chargers

Pros	Cons
Multiple suppliers	Limited to 150 kW
Well-established standards, Interoperability between suppliers	Cables & connectors vulnerable to damage
Inexpensive option for small deployments ($200K per charger)	Infrastructure costs increase linearly with fleet size support ($75K-200K per bus)
Sequential charging available to lower cost and increase operational efficiency	Power requirements of full fleet electrification near 35 MW
Can be integrated with smart charging software to more efficiently charge buses	Dedicated floor space required to charge buses for several hours
Indoor installation	Difficult to manage operationally as fleet grows
Low maintenance	Need to buy one charger for every 4 buses purchased
Low impact if one charger goes down	May need to increase fleet size or buy more chargers to maintain spares ratio
No land purchase necessary; Installation at existing transit garages	Weekly charger utilization below 40%
	Power draw needs to be monitored to manage monthly electricity bills
	Prolonged power interruptions will affect ability to deploy buses
	Back-up power generation adds significant cost

4.5 Overhead Depot Charging

While traditionally charge rails have been installed for on-route charging, it is becoming more common to install them for overnight charging long-range buses at a centralized depot. Transit agencies now have the choice to utilize overhead conductive charging via inverted pantographs installed on gantries, either in a garage or storage yard rather than via a plug-in connection. This eliminates the need for cable management and creates the potential for automating the depot charging process.

As with plug-in charging, overhead depot charging poses the same operational challenges with the need for dedicated charging locations, rotating of buses and monitoring of peak power draw.

The main advantage of overhead vs plug-in charging is the potential to increase charge power up to 600 kW. While buses equipped with high-energy packs would be able to take advantage of high depot charge rates, long-range buses are charge limited to C/2 or C/3. Large packs are capable of accepting more than 150 kW of power but not significantly more. The largest currently available pack is advertised to charge in 2.80 hours via overhead charging which works out to an average of just 235 kW, with a peak of 392 kW possible [16]. With faster charge times the bus-to-charger ratio to increase to 6:1.

Based on Transit's current schedule, there is no need to charge at powers higher than 150 kW as there is sufficient time in the schedule to accommodate three to four hours of charging. This may change if battery capacity increases above 660 kWh, or if there is a need to selectively redeploy some buses sooner than others. Overhead charging capacity is flexible allowing for additional power to be added in the future without needing to replace or upgrade the installed pantograph.

Increasing charger power increases the risk of high monthly demand charges. Utilizing the same number of chargers at 300 kW rather than 150 kW has the potential to nearly double the operating cost of the fleet with only minimal operational advantages. Higher charge rates would enable Transit to operate with fewer chargers which would help to reduce demand, but creates further operational challenges. The power requirements need by 2050 based on 300 kW charging would be close to 45 MW or as high as 74 MW if the higher 4:1 bus-to-charger ratio used for plug-in charging was maintained. The amount of back-up generation required to provide resiliency during a grid outage will also be dependent on the bus-to charger ratio utilized, and could be significantly more expensive than what is required for plug-in charging. Utilizing charger management software or integrating microgrids could enable power to be drawn from stored energy banks rather than directly from the grid will be important to minimize operating costs as fleet power requirements increase [67].

The additional power and more moving parts means that the per-charger cost for this option is more expensive to purchase than a plug-in charger, will require more scheduled maintenance, and is at risk for more unscheduled maintenance. Mast-mounted pantograph chargers have an upfront cost nearly ten times higher than a plug-in charger [65]. However, unlike on-route chargers a single charger going down still has minimal operational impact due to the estimated 6:1 bus-to-charger ratio and low overall utilization. Sequential charging options are available with this technology, but currently only two pantographs can be operated from the same charger [76]. To maximum parking flexibility, Transit may need to purchase more chargers than would normally be necessary based on schedule limitations. As with plug-in charging, transit agencies should expect costs scale linearly, with overhead depot charging infrastructure adding approximately $100,000 extra per bus as the fleet grows.

Figure 24: OppCharge overhead depot charging. Source: Adapted from [63]

Figure 25: Depot overhead charger configuration. Source: [77]

With the release of SAE J3105/1, manufacturers have standardized on the use of a bus's front door as a reference point for the positioning of charge rails. This simplifies garage design, but design variations between manufacturers such as front overhang and vehicle length, may still make it difficult to design a pantograph layout that works for multiple manufacturers and different lengths of vehicles.

Table 16: Pros and Cons of depot overhead charging

Pros	Cons
Higher bus-to-charger ratio than plug-in charging	Expensive to install (~$1,000,000 per charger station)
No cords to manage	Higher maintenance than plug-in chargers
Upgradeable up to 600 kW	Difficult to manage operationally
Recently released standard improves interoperability between suppliers	Dedicated floor space required to charge buses for several hours
Low impact if one charger goes down	Weekly charger utilization below 50%
No land purchase necessary Installation at existing transit garages	Reduced flexibility to accommodate buses from different manufacturers and of varying length
Indoor installation	Infrastructure costs increase linearly with fleet size support ($100K per bus)
Can be integrated with smart charging software to more efficiently charge buses	Power requirements of full fleet electrification near 45 MW
Potential to automate charge process	Need to monitor power draw to limit demand charges on monthly utility bill
	Not all power can be utilized due to battery capacity & C-rate limits
	Prolonged power interruptions will affect ability to deploy buses
	Back-up power generation adds significant cost

4.6 On-Board Fuel Cell Charging

On-board fuel cell battery charging is offered by New Flyer and ENC. Buses are equipped with fuel cells and hydrogen storage tanks. Fuel cells convert hydrogen into electricity which charges the batteries while driving. As electricity comes from hydrogen rather than directly from the grid, on-route charging is accomplished by refueling the vehicle with hydrogen.

4.6.1 Hydrogen Overview

Hydrogen is the most abundant element in the universe. It is odorless, colourless and lighter than air. Hydrogen has been used in industrial application for over 100 years [78]. Hydrogen does not occur naturally in its free state on earth and needs to be extracted from other compounds. While using hydrogen to charge buses does not result in any tailpipe emissions, some CO2 may be generated during its production.

Hydrogen is graded as being green, blue or grey based on how much carbon is emitted during its production, with green being the cleanest [79]. Hydrogen can also be created as a by-product of industrial processes. By-product hydrogen can be a result of either carbon or non-carbon emitting processes, but it is not graded by color and is considered a separate category.

The two main production methods for extracting hydrogen are water electrolysis and steam methane reforming (SMR). Both methods require a significant amount of water and electricity to produce hydrogen. SMR utilizes methane (natural gas), water, and electricity, and is currently around 80% efficient. Electrolysis utilizes just water and electricity, and is around 65% efficient [79].

Steam methane reforming is the most common and lowest cost method of producing hydrogen. This process is carbon emitting and is graded grey, but may be upgraded to blue if carbon capture methods are incorporated into the process. In most regions of North America, SMR without carbon capture is common [79]. Utilizing Grey hydrogen still results in zero tailpipe emissions, but has limited climate benefits. Carbon capture adds additional cost, but in general blue hydrogen is still lower cost than green hydrogen produced via electrolysis.

Manitoba does not currently produce natural gas, but there is potential to utilize local renewable methane from biological sources, such as landfills, manure digesters, or sewage treatment plants, along with carbon capture and sequestration to produce blue hydrogen [80]. Hydrogen produced from biomass without carbon capture is considered GHG neutral, while adding carbon capture makes the process GHG negative (i.e. it removes more GHG than are produced) [79]. Implementing and expanding methane capture at Winnipeg's wastewater facilities and landfills have been identified as initiatives in *Winnipeg's Climate Action Plan,* but any methane used to produce fuel grade hydrogen needs to be cleaner than methane used for heating. Any non-methane impurities, such as CO2, N2, O2, sulfurs, and other trace contaminants, need to be removed, adding additional cost to the process [81].

Based on current estimates and the commercial natural gas rate in Manitoba, hydrogen from non-renewable sources would cost approximately $2/kg, versus $3/kg if produced from renewable sources [82] [79]. However, without additional investment from the City of Winnipeg to expand collection of renewable natural gas there is not currently sufficient volumes to support the production of hydrogen for even a small fleet of FC-BEBs.

Hydrogen production via water electrolysis in Manitoba is graded green because Manitoba's electric grid utilizes energy produced from 99% renewable sources [83]. This is considered the most expensive method of producing hydrogen, but Manitoba's low electricity and water prices open up the possibility of producing small volumes of green hydrogen on-site at a price competitive to delivered fuel produced from non-renewable sources.

There are two types of commercially available electrolyzers, Alkaline and Polymer Electrolyte Membrane (PEM). Efficiency is slightly better for alkaline systems, but they require significantly more maintenance, frequent replenishment of caustic catalyst fluids and additional hydrogen purification systems need to be utilized to get the fuel to transportation grade [84]. PEM electrolyzers are more expensive initially, but require very minimal maintenance and produce higher purity hydrogen [84]. Despite the lower efficiency of electrolysis, Manitoba's low electricity and water prices opens up the possibility of producing Green hydrogen here at a cost competitive $3.50-5.50/kg [79] [64].

As an alternative to direct produced hydrogen, by-product hydrogen was identified in Manitoba's 2003 *Hydrogen Opportunities Report* as a good interim source of fuel to support initial hydrogen powered vehicle deployments in the Province [85]. Chemtrade currently operates the world's largest sodium chlorate plant out of Brandon, Manitoba, and has also been identified in British Columbia's Hydrogen Study as a producer of by-product hydrogen in that province [86] [79].

Chemtrade produces sodium chlorate and hydrogen through the electrolysis of sodium chloride. With an annual sodium chlorate production of 320,000 tonnes, the expected amount of by-product hydrogen produced would be around 19,200 tonnes per year [87]. This is six times the amount of fuel that Transit would currently require if the entire fleet was converted to fuel cell battery-electric buses. Some upgrades would be required to purify and compress the hydrogen for vehicle applications. The cost to remove trace amounts of chlorine gas is relatively inexpensive, with total production cost estimated to be less than $1/kg, making by-product hydrogen by far the cheapest source of hydrogen in the province [79].

The presence of a source of delivered hydrogen produced in Manitoba, alongside the potential for Winnipeg Transit to generate its own hydrogen with an on-site PEM electrolyzer, provides significant risk mitigation when considering the addition of FC-BEBs to Winnipeg Transit's fleet.

4.6.2 Hydrogen Dispensing

Regardless of the refueling model utilized, fuel cell battery-electric buses are fueled via gaseous hydrogen which is compressed, chilled and transferred into on-board tanks via a dispenser.

Safe fueling protocols for non-communication enabled fill stations have been established using SAE J2601. This standard specifies that tank temperature must be maintained between -40°C and 85°C during filling. Since the temperature of the hydrogen rises during filling, hydrogen is chilled prior to dispensing to ensure the on-board tank temperatures do not exceed +85°C during filling [88]. The total amount of chilling required depends on several factors, including ambient temperature, tank size, fill speed and working pressure. Lookup tables based on ambient temperature and dispenser capabilities can be developed to establish recommended fill times.

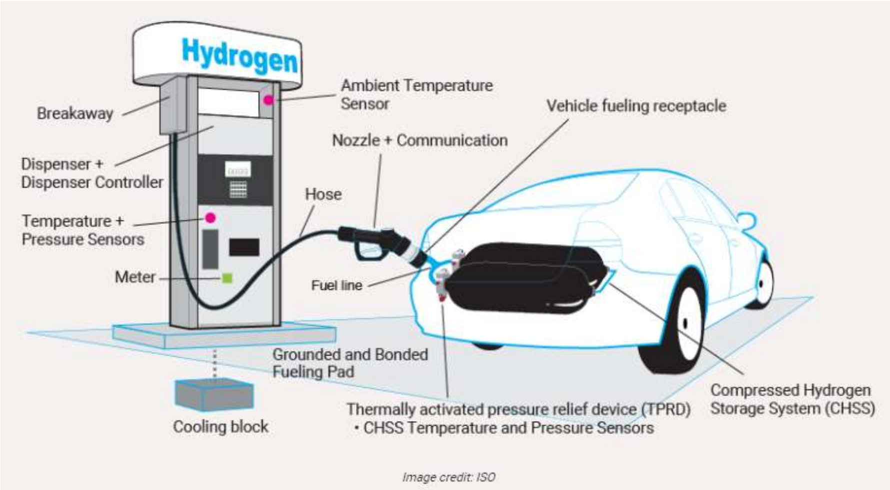


Figure 26: Hydrogen dispenser configuration. Source: [89]

Alternatively, SAE J2799 established a wireless communication protocol which automates the lookup table process, allowing fill stations to adjust chilling and fill rate based on information reported from the vehicle, ensuring that the pressure and temperature stays within the allowable limits. IrDA vehicle communication is the standard wireless communication protocol being adopted by the automotive industry; however, heavy commercial stations may be equipped with either a hard wired or wireless receiver. The IrDA receiver attached to the fill nozzle is expensive and easily damaged, which is why some commercial fill stations designers prefer hard wired connectors, which are more robust and less expensive to replace if damaged. Regardless of which communication method utilized, buses need to be equipped with a transmitter that is compatible with the receiver installed on the station in order for fast filling to function properly. If a link is not established, fill rate will default to the minimum safe rate specified for the station.

Both light-duty and heavy-duty fill stations are regulated by the same safety standards. Standard safety equipment for all fueling stations includes grounding, breakaway hoses and fire sensors, but hydrogen fill stations also include ambient temperature sensors, fuel pressure and temperature sensors, and leak detection. Stations as well as storage tanks are designed to vent hydrogen to atmosphere in an emergency situation such as an engulfing fire [89].

Transit buses in North America fuel to 350 Bar with fill times only marginally slower than current diesel bus fill times for 40-foot buses (6-12 minutes), but nearly twice as long for 60-foot buses (12-20 minutes) [10]. Assuming a maximum refueling window of 4 hours and average of 6 buses per hour, each dispenser would support 24 vehicles. Additional dispensers could be built to accommodate additional simultaneous fueling to prevent backlog.

Net energy consumption for compressing and dispensing hydrogen is approximately 5 kWh/kg resulting in about 15% loss of efficiency [90]. The peak power requirement for fast filling at 700 Bar has been shown to be around 35 kW, while a 350 Bar delivery system has a peak power draw of only 12 kW [91] [90]. With an estimated fleet size of 990 buses by 2050, a minimum of 42 dispensers would be required for bus refueling. The total power required to dispense this much fuel at 350 Bar would only be 500 kW, which is within manageable levels from the grid and likely could be supplied entirely with solar electricity [92]. It is also likely that a back-up generator could operate the station at full capacity in the event of a power outage.

4.6.3 Fueling Model: Hydrogen Production; On-Site Storage and Dispenser

In this model, Transit would need to purchase hydrogen production equipment as well as compression, storage and dispensing equipment. The production volume of hydrogen would need to be evaluated based on expected fuel consumption for the fleet. Several days' worth of fuel could be stored on-site in either underground or above ground tanks to offset temporary increases in demand, such as during extreme hot or cold weather, and to ensure uninterrupted service if the production equipment is taken offline for maintenance or by a power outage. Including storage is not essential for a fueling system design for a small fleet, as a large number of diesel buses would be available to deploy during a fuel outage. As the fleet grows, the need for additional fuel resiliency may necessitate the purchase of back-up production equipment and storage tanks.

Hydrogen production can be varied based on demand, however, it is expected that equipment will run 24/7 at some capacity except during maintenance. Manitoba Hydro has stated that a steady draw across the system is preferred to the cycle load induced by charging. Production can be varied between 10-100% of capacity. Operating cost per month will vary based on electricity and water usage. When the quantity of hydrogen produced no longer meets demand, Transit would need to invest in additional equipment or source fuel from an alternate location.

If Manitoba Hydro introduces time-of-use rates for commercial customers, running equipment 24/7 may not be financially viable. Restricting production during off-peak hours may be necessary, and production capacity during that time would need to increase accordingly.

Based on initial estimates Winnipeg Transit may require as much as 14,000 kg of hydrogen per day by 2050. Depending on whether SMR or electrolysis is utilized, power requirements would vary between 24-30 MW, and could increase further if time-of-use charges are introduced [79]. This is lower than the power required for depot charging, but is still significantly higher than what the grid can easily accommodate, necessitating Transit to invest in transformation and switching equipment, or to develop alternative power management strategies to manage this demand. The use of microgrids with solar or wind power are becoming more common with hydrogen refueling stations as a way of reducing reliance on grid power [93].

Since hydrogen is typically only produced at 30 Bar, it cannot be dispensed directly on-demand. Additional equipment is required to store, compress, cool, and dispense at the 350 Bar pressure required for bus refueling, or at the 700 Bar pressure required for dual fueling of other fleet vehicles [94]. Once fuel is produced it is temporarily stored at low pressure then compressed to approximately 450 Bar (or 800 Bar in the case of dual dispensing) for storage [88].

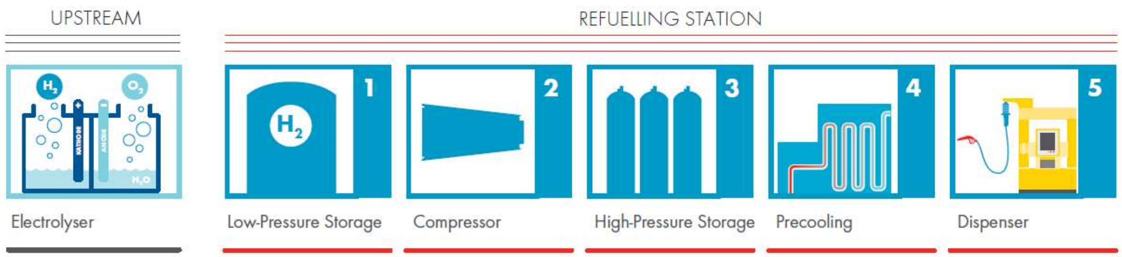


Figure 27: Components of a hydrogen refueling station. Source: [88]

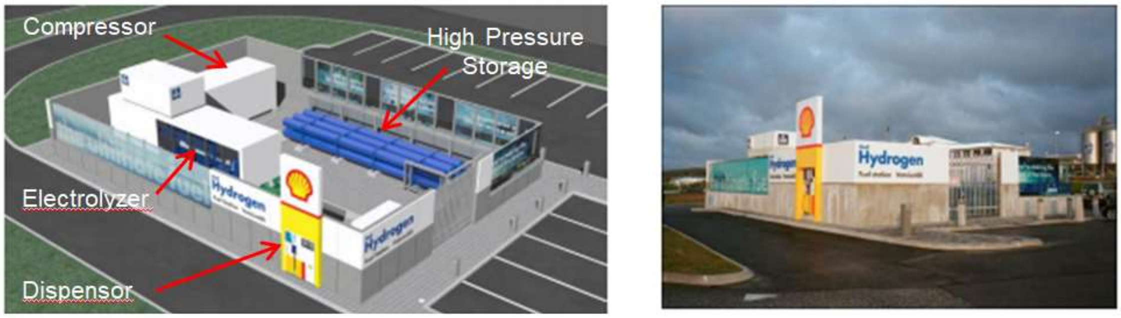


Figure 28: ECTOS Hydrogen Fueling station Reykjavik, Iceland. Source: Adapted from [95]

SMR and electrolyzer equipment can be custom installed or purchased as containerized units (i.e. pre-installed in standard shipping containers). Equipment is designed to operate outdoors, but Winnipeg's cold winter climate may require a custom installation inside a heated space. If Winnipeg Transit's fleet of 640 buses were entirely FC-BEBs, a system capable of producing approximately 8,000 kg of hydrogen per day would be required. A system of this size requires a minimum of 1,340 m2 of space, or the equivalent of 44 parked 40-foot buses to accommodate production equipment as well as compression and storage. Each 500 kg/day increase would require expanding by approximately 60 m^2 (two more buses) to accommodate additional production and storage equipment [96]. Each garage would need to have its own production/dispenser therefore the total area stated would be divided across multiple facilities. Any building built for the purpose of storing hydrogen production equipment should include space for expanding production.

Figure 29: Proposed 4200 kg/day bus depot configurations. Source: adapted from [97]

There is potential to mount equipment and storage on an elevated platform with dispensing equipment situated below if space is at a premium.

Figure 30: Shell Hydrogen fueling station Los Angeles, CA USA. Source: [98]

Initial infrastructure costs are quite high compared to battery-electric if the expectation is to run buses from full to empty every day. A small 446 kg/day system which costs around $4.5 million could support up to 36 forty-foot buses traveling 150 km per day, but only 12 forty-foot buses traveling 450 km per day [99]. This varies the price per bus between $111,111 to $333,333, which is 37-400% more than the per bus price for plug-in chargers (4:1 bus-to-charger ratio) [65]. When the fuel consumption of the entire fleet of 640 buses is considered, a 8,000 kg/day system which is expected to cost between $18.0-$33.2 million, would only cost between $28,125 - $50,000 per bus, 50-70% cheaper than plug-in depot charging, and on par or cheaper than on-route charging [65] [97].

Maintenance of the fueling equipment could be managed by Transit directly, or contracted to a company with experience in alternative fuels or fueling stations.

Figure 31: Pros and Cons of on-site hydrogen production, storage and dispenser model

Pros	Cons
Green hydrogen thru electrolysis	Blue or Grey hydrogen if using SMR
Stable long-term fuel supply	High initial infrastructure investment
Per-bus cost of infrastructure decreases as bus fleet grows	Custom indoor installation increases cost
Can be integrated with solar or wind microgrid to reduce reliance on grid power	Power demand increases as fleet grows
Production can be adjusted up or down based on demand	Prolonged power interruptions will affect ability to deploy buses
Additional storage can be integrated to compensate for downtime	Large footprint which increases as fleet grows
No cost mark-ups for delivery of hydrogen produced on site	Power requirements of full fleet electrification near 30 MW
Could support other fueling at either 350 or 700 Bar	Large amount of Water required
No operational changes required to accommodate re-fueling time	Cost per kg varies based on electricity & water rates
Maintenance of production and dispensing equipment can be outsourced to alternative fuel specialist.	Additional Service & Maintenance costs to maintain production equipment as well as dispenser
Dispensing can be powered by a back-up generator	Fixed amount of range based on available fuel
	Fuel resiliency managed by Transit

4.6.4 Fueling Model: Hydrogen Delivery; On-Site Storage and Dispenser

In this model Transit would purchase, maintain and operate only storage, compression, vaporization (liquid delivery only), and dispensing equipment. Hydrogen would be delivered through a contract with a gas delivery company in either gaseous or liquid form. The quantity of hydrogen required dictates whether gaseous or liquid delivery is preferred. The largest capacity tube trailer for gaseous delivery is 1,000 kg, while liquid tankers can deliver up to 5,000 kg [91]. Liquid delivery via pipeline is also a possibility; however, Transit is not likely to require sufficient volume of fuel on its own to facilitate this amount of investment.

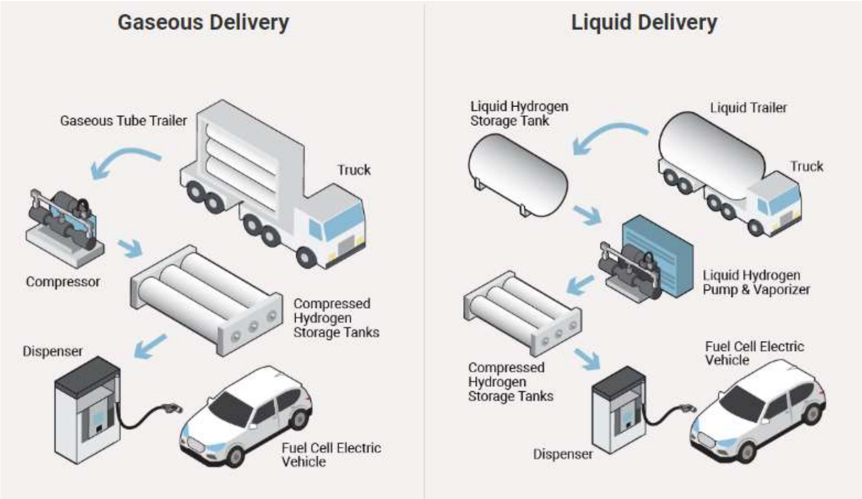


Figure 32: Overview of gaseous vs liquid hydrogen delivery station components. Source: [99]

Typically, Transit would want to operate with a minimum of 3 days of reserve fuel. Storage and delivery schedules would need to be sized appropriately to accommodate this while allowing for some expansion. An increased risk of fuel shortages by operating with less reserve fuel may be acceptable when the fleet size is small, as any vehicle lost time will have minimal impact to overall fleet operations as there are a sufficient number of spare buses with other propulsion systems.

Generally gaseous delivery is recommended as the lowest cost fuel delivery model when demand is 500 kg/day or less [100]. Increasing the number of delivery trailers or frequency of deliveries could potentially expand the capacity of a station optimized for dispensing 500 kg/day to 1500 kg/day or more, depending on the original amount of storage capacity installed.

At a dispensing rate of 1,000 kg per day, liquid hydrogen stations become more cost effective than gaseous stations; however, the price paid per kilogram of hydrogen may initially be higher [100]. The energy required to cool and compress hydrogen into liquid form is significantly higher than gaseous compression, resulting in the higher per-kg price. It is estimated that liquefaction adds $1/kg to the cost of hydrogen [91]. At significant volumes, savings from reduced delivery costs should offset the additional cost of compression and result in lower overall unit price [79].

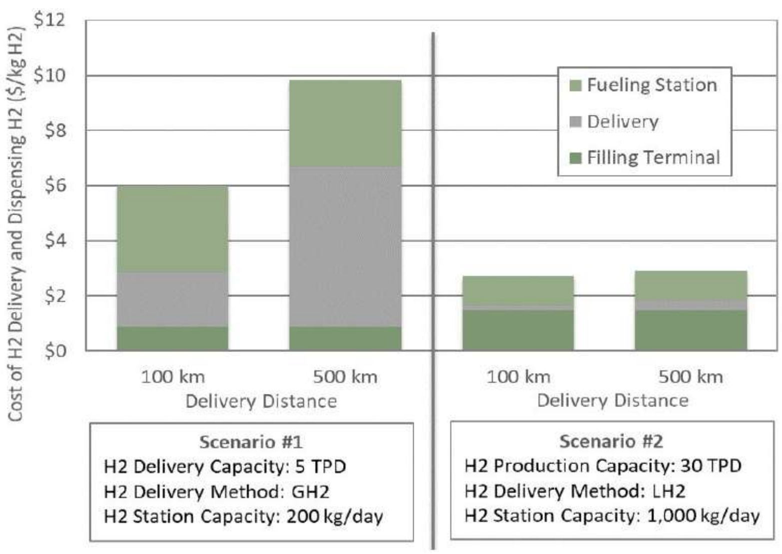


Figure 33: Estimated delivery & dispensing cost based on delivery method, distance, and plant tonnes per day (TPD) production volume. Source: [79]

Full purchase, construction and commissioning of a gaseous station starts around $2.6 million while a larger capacity liquid storage station starts around $3.7 million [99].

Unfortunately, transitioning from gaseous to liquid delivery requires producers to invest a significant amount of capital for liquefaction equipment. Production volumes of 10,000 kg/day may be necessary to justify such an investment [79]. Based on a fleet mix of 80/20 forty-foot or less vs sixty-foots buses and a gradual transition to full electrification by 2050, Transit may not reach this threshold until 2045. Additional demand for hydrogen from other customers would be necessary to drive the transition to liquefaction closer to the 2025 date, when Transit’s usage would potentially exceed 1,000 kg/day usage with a 100% FC-BEB fleet.

Utilizing delivery trucks rather than producing hydrogen on-site increases well-to-wheel greenhouse gas emissions from buses if the trucks used to transport the hydrogen are not zero-emission. While the high capacity of liquid delivery results in approximately just 120 tonnes more lifetime GHG than the cleanest technology, the worst pathway for gaseous delivery could result in more than 485 tonnes. That is the equivalent of an average gasoline vehicle operating for 55,000 km vs 225,000 km [101]. Utilizing a compressed natural gas (CNG) delivery truck rather than a diesel truck running with 5% biodiesel would reduce potential emissions by 13.6% until zero-emission trucks are an option [102].

Delivery based re-fueling is the lowest energy intensity way to power a large bus fleet. A liquid delivery station designed for 1,000 kg/day delivery requires only 45 kW of power, not the megawatts of power required by other methods of refueling [103]. Even with dispensing capacity expected to increase by nearly 15 times this by 2050, it is unlikely than any one garage would require more than 500 kW of additional service.

With the hydrogen production portion of a station eliminated, a refueling station utilizing delivered hydrogen had half the footprint of one with on-site produced hydrogen. A full fleet of 640 FC-BEBs would require a station capable of dispensing approximately 8,000 kg per day. A dispensing station of this size utilizing liquid storage requires a minimum of 595 square metres of space, or the equivalent of eighteen parked 40-foot buses to accommodate liquid storage, vaporization and compression equipment, gaseous storage, and dispensers [97]. Each 3,000 kg/day increase would require expanding by approximately 223 m^2 (seven more buses) [97]. Each garage would need to have its own dispensers therefore the total area stated would be divided across multiple facilities.

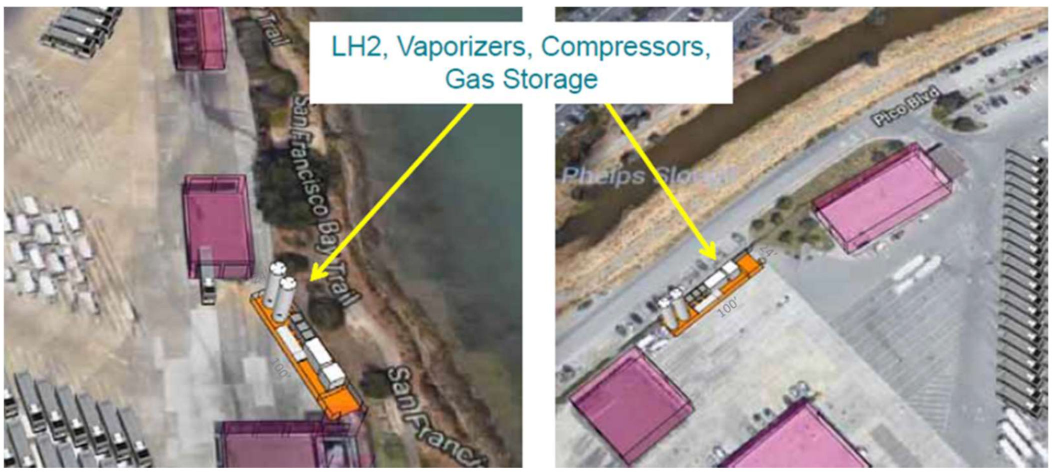


Figure 34: Proposed 3000 kg/day bus depot configurations. Source: adapted from [97]

Figure 35: Linde fill station - liquid hydrogen delivery, on-site storage and dispenser model. Source: adapted from [104]

In a delivery model, increases in production volume are transferred to the gas delivery company. Transit would need to increase storage and dispensing capacity and manage any delivery schedule or contract changes. Transit would have no direct control over the source of the hydrogen unless this it is specifically written into a contract. The cost of hydrogen specified in a contract would include production, mark-up and delivery costs, and could be specified as fixed or variable. Competition from gas distributors or having more than one distributor may help to reduce the overall cost of hydrogen. Any supply chain issues that extend beyond 3 days would result in service disruptions. It would be preferable for any gas supplier to have more than one source of hydrogen so that there are no transit service disruptions in the event of production issues. Supply chain robustness would need to be verified through the contracting phase. Contract language will be very important to minimize Transit's liabilities.

Maintenance of the re-fueling equipment should be contracted to a company with experience in alternative fuels or fueling stations.

There is no difference at the dispenser regardless of whether the fuel is delivered or produced on site, therefore in any re-fueling model the number of dispensers would need to be adjusted to ensure buses fill in the available window.

Table 17: Pros and Cons of hydrogen delivery with on-site storage and dispenser model

Pros	Cons
Power requirements at full fleet electrification less than 1 MW	No control over source of hydrogen unless it is a contractual obligation (Green, Blue, Grey, By-product)
Additional storage can be integrated to compensate for delivery schedule	Price set by distributor includes production plus markup and delivery
Could support other fueling at either 350 or 700 Bar	High volume required for delivered fuel to be cost competitive with on-site production
No operational changes required to accommodate re-fueling time	Late deliveries could interrupt service if storage is not adequately sized
Maintenance of production and dispensing equipment can be outsourced to alternative fuel specialist.	Risk of supply issues with single source of fuel
Per-bus cost of infrastructure decreases as bus fleet grows	Robust contracts required to minimize Transit's liability
Potential for fixed per kg pricing over a contract term	High initial infrastructure investment
Production risk managed by gas supplier	GHG produced by delivery trucks
Potential competition from gas suppliers could reduce cost	Currently no local hydrogen supply chain
Small centralized footprint	
Station can be powered by a back-up generator	

4.6.5 Fueling Model: Blend of Hydrogen Production & Delivery; On-Site Storage and Dispenser

In this model Transit would utilize both on-site production as well as delivered fuel for vehicle refueling. Either system could be set up as the primary method of refueling with the other used to supplement supply during service and maintenance, and to reduce the risk of fueling shortages.

The cost of maintaining two systems would likely be higher, but having a back-up source of hydrogen in the event an emergency significantly reduces the risk of supply shortages.

The high cost hydrogen produced by electrolysis could be supplemented with lower cost delivered fuel to reduce overall operating cost. Similarly, high GHG intensive delivered hydrogen can be offset by low GHG intensity on-site produced hydrogen.

Even if sufficient hydrogen could be produced on-site by Transit, it is likely that a contract for regularly scheduled hydrogen delivery from a third-party supplier would still be required. Without such a contract, it is unlikely that Transit could arrange for sufficient emergency delivery of hydrogen during a sudden unexpected loss of on-site hydrogen production.

Figure 36: AC Transit mixed model fueling stations. Source: adapted from [105]

Table 18: Pros and Cons of mixed vs single source hydrogen supply chain

Pros	Cons
Back-up source of hydrogen in the event of an emergency	Larger foot print than either model separately
Able to reduce carbon foot print by using on-site production	High initial infrastructure investment
Able to reduce cost with lower priced delivered fuel	GHG produced by delivery trucks
Station can be powered by a back-up generator	Need to manage and maintain two systems
	Contract management still required
	Ongoing purchase contract likely required to maintain contractual relationship with a supplier

5 Considerations for Integrating Zero-Emission Buses

Beyond the larger decision on bus refueling infrastructure there are a number of other items that should be considered when comparing technologies such as battery characteristics, range and performance limitations, energy management requirements, and safety.

5.1 Battery Characteristics

5.1.1 Types of Batteries

For transit buses there are two primary battery types; high-energy and high-power. Battery manufacturers optimize batteries based on their application.

- High-energy Batteries
    - Application: Long-Range BEBs
    - High energy Density (160-200 Wh/kg)
    - Usable Capacity 80-90%
    - Low Charge Rate (C/3)
    - Low Cost per kWh (~$600/kWh) [47]
    - Cycle life <5,000 @ 100% depth of discharge (DOD)
- High-power Batteries
    - Application: Rapid-Charge BEBs & FC-BEBs
    - Low Energy Density (>100 Wh/kg)
    - Usable Capacity 70-80%
    - High Charge Rate (2C-5C)
    - High Cost per kWh (~$1,275/kWh) [106]
    - Cycle life >5,000 @ 100% depth of discharge

There is currently no battery technology that enables a bus to both operate continually for 10 or more hours and to recharge fully in under 10 minutes. It is important to understand the limitations of batteries to properly align vehicle and charger performance with Transit's expectations and operational needs.

5.1.2 Battery Chemistry

There are two battery chemistries currently being offered by bus manufacturers in North America; Lithium Nickel-Manganese-Cobalt (NMC) and Lithium Iron-Phosphate (LFP). A third chemistry, Lithium Titanate Oxide (LTO) was previously utilized by one manufacturer but is no longer being advertised.

In both high-energy and high-power applications, there are tradeoffs depending on which battery chemistry is utilized.

- Lithium Nickel-Manganese-Cobalt (NMC) [52]
    - High energy density
    - Good balance of cost, safety, performance, life, and power density
    - Can be optimized for either high-energy (long-range) or high-power (rapid-charge) applications
    - Suitable for all BEBs and FC-BEBs
    - Preferred by long-range BEB manufacturers
    - At greatest risk for price volatility as global demand for Cobalt & Lithium increases
    - High value of cathode and anode material results in lower scrap cost, should second life market not be realized
- Lithium Iron-Phosphate (LFP) [52]
    - Long life
    - High power rating
    - Very safe
    - average energy density
    - High self-discharge rate that may result in balancing issues as the battery ages

  - Suitable to on-route charged BEBs and FC-BEBs
  - Low value of cathode and anode material results in highest scrap cost, should second life market not be realized
- Lithium Titanate Oxide (LTO) [52]
  - Extremely long life
  - Highest charge/discharge rate
  - Safest battery chemistry
  - Low energy density
  - Very high cost per kWh
  - Suitable only for on-route charge BEBs or FC-BEBs
  - High value of cathode and anode material results in lower scrap cost should second life market not be realized

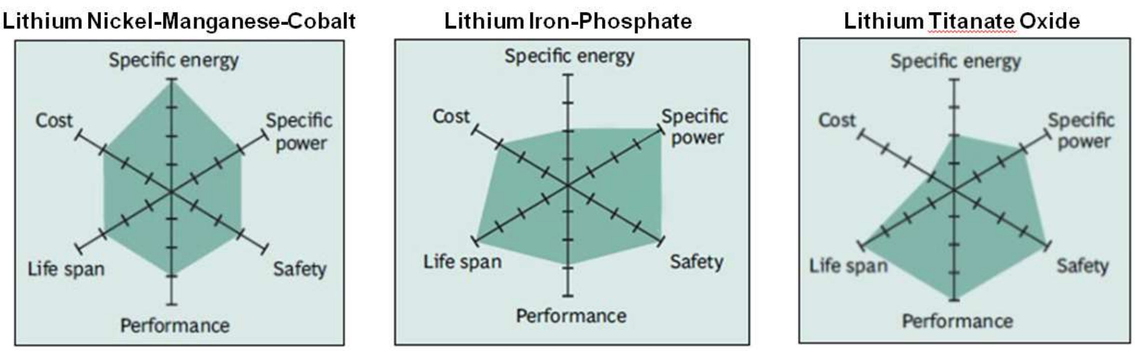


Figure 37: Battery Chemistry Performance Characteristics. Source: Adapted from [52]

Improved manufacturing methods have been driving down the cost of Lithium-Ion batteries over the last decade. It is estimated that automotive batteries could reach the USD $100/kWh cost by 2025 [107]. It is currently estimated that raw materials make up only 10% of a battery cost [107]. However, as manufacturing improvements level off and demand increases, volatility in the minerals market combined with reduced global supplies of lithium and cobalt could reverse the downward battery price trend [107]. Battery manufacturers are continually looking at new ways to reduce the cobalt content in batteries while maintaining the performance and safety associated with this cathode material [107].

5.1.3 Understanding Battery Charge/Discharge Limits

Battery type and chemistry will determine how quickly energy can be discharged and recharged. The maximum speed at which a battery will charge or discharge is called battery C-rate [108]. Both a charge and discharge C-rate are stated, and the two rates can be different. Discharge C-rate gives an indicator of how quickly a battery can respond to power requests, while charging C-rate refers to how quickly a battery can be recharged.

Theoretical maximum charge rate or discharge per hour is calculated by multiplying the total capacity of the battery by the C-rate [108].

The minimum battery capacity of the bus must be matched with the discharge C-rate of the batteries to ensure that the batteries can supply instantaneous power on demand. If capacity is not adequately sized based on battery C-rate, vehicle performance could be impacted. This is generally not a significant consideration as manufacturers offer a minimum capacity that matches the minimum performance specification of the bus.

Matching battery capacity with the charge C-rates of the batteries is also important. If there is a specific amount of energy that needs to be returned in a given charging window to complete a run, C-rate can be used to calculate the minimum battery capacity that could accept that amount of energy. If capacity is not adequately sized based on C-rate, operations could be impacted. If a bus does not charge at the rate expected, it may not have sufficient energy to complete its next run

Batteries will self-adjust charge and discharge power based on their performance limitations. Adding additional charging capacity will not improve charge time if the buses have not been adequately sized for the application.

As an example, consider long-range and on-route rapid-charge buses from the same manufacturer with different capacities;

- Long-range bus with C/3 charge rating and 450 kWh capacity
    - Maximum charge rate is 450/3 = 150 kW/h
- Long-range bus with C/3 charge rating and 300 kWh capacity
    - Maximum charge rate is 300/3 = 100 kW/h

Despite both buses being equipped with the same type of batteries, the bus with the larger battery capacity is capable of accepting more energy over the same amount of time. If both buses plug into a 150 kW charger for one hour, the 450 kWh bus would have charged 150 kWh, while the 300 kWh bus would only have charged 100 kWh. If the charge window is restricted to 1 hour, the smaller bus would have 33% less range than the larger capacity bus.

- Rapid-charge bus with C-Rate of 3C and 200 kWh capacity
    - Maximum charge rate is 200*3 = 600 kW/h
- Rapid-charge bus with C-Rate of 3C and 150 kWh capacity
    - Maximum charge rate is 150*3 = 450 kW/h

With a 150 kW charger both buses would have charged at 150 kW/h. If a 600 kW charger were available, only the larger capacity bus would be able to charge at this rate, while the smaller capacity bus would be capped at 450 kW/h. In practical terms this results in the smaller capacity bus needing a 4-minute charge window for each additional hour of driving, while the large capacity bus may only need a 3-minute window.

It should be noted, however, that actual charge rate will likely be lower than the theoretical maximum. This is due to a number of factors including:

- Battery State of Health
- Battery State of Charge
- Available charger power

Typically, batteries will limit charge as they reach full power. As state-of-charge increases beyond 70%, the rate of energy return slows down and completing the last 5-10% of charge could take several hours. To prevent a battery from trickle charging to full over several hours for minimal benefit, manufacturers artificially restrict the upper charge limit of the battery. By putting this restriction in place, charge cycles have a clearly defined finish. However, this does result in the usable capacity of the battery being lower than the stated nameplate capacity.

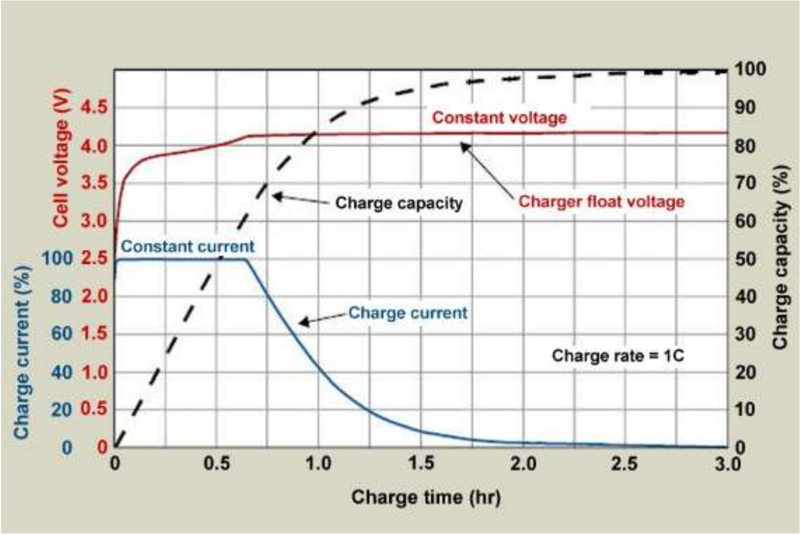


Figure 38: Lithium-Ion Charge cycle Volts/capacity vs. time. Source: [109]

5.1.4 Battery Voltage and Charge Power

It is important to pair chargers with buses and not undersize or oversize chargers based on the manufactures stated nameplate capacity.

The total charging capacity of a given system is a combination of battery and charger properties. Chargers are rated based on maximum potential power of a charger, but actual power output is calculated based on actual battery voltage (V) multiplied by the current (A) rating of the charger;

- Rating: Power output 450 kW, Max current 600A; 150-850 VDC
- Actual Output: P=IV; P=600 A*700 V= 420 KW

Typical battery voltages for buses range between 600 V and 800 V. In theory when attached to the same charger, the 800 V battery will be capable of charging at a faster rate than a 600 V battery. Actual charge rate will, however, be a combination of battery voltage and c-rate.

If available power exceeds the charge rating of the battery then charge power is truncated.

Example 1: Long-range bus (450 kWh, 700 V battery), C/3 C-rate; Paired with 600 A charger (450 kW)
- 700 V*600 A = 420 kW < Max C-rate 450/3 = 150 kW
- Bus is charge limited to 150 kW by batteries

In this case, selecting a battery with a higher voltage would make no difference as the battery C-rate would still truncate charger output.

Example 2: Rapid-charge bus (160 kWh, 700 V battery), 3C C-rate; Paired with 600 A charger (450 kW)
- 700 V*600 A = 420 KW > Max C-rate 160*3=480 kW
- Bus is charge limited to 420 kW by charger

In this case, selecting a battery with a higher voltage would increase charge rate. An 800 V battery would be capable of charging at the maximum 480 kW, but the charger would max out at 450 kW.

Once the actual charge rate is established, the amount of energy returned per minute of charge can be understood and considered along with scheduling restrictions. If necessary, adjustments to battery and charger capacities can be made during planning phases to prevent having to adjust and extend layover times after the buses are in service.

5.2 Range and Performance Fade

Batteries are warrantied to last for 6 to 12 years, but their capacity could decrease by as much as 35% over that time. Fuel cell stacks are warrantied to last 6 years, but their efficiency may decrease by as much as 25% over this time. Battery capacity and fuel cell output is usually stated as being either Beginning-of-Life (BOL), or End-of-Life (EOL), but in reality, the actual on-board energy and fuel cell performance will be somewhere between these two values over the life of the bus.

5.2.1 Battery Capacity Fade

Battery capacity fades based both on calendar aging and cycle aging, and some range and performance losses over time are unavoidable.

For battery-electric buses, battery capacity fade results in both less range range and slower charge rate. For fuel cell battery-electric buses, battery capacity fade will likely only be noticed by Transit if buses are operating in battery-only mode (i.e. fuel cell intentionally turned off or when out of hydrogen), or if traveling at speeds above 80 km/h for prolonged distances. Loss of fuel cell efficiency will result in loss of range.

5.2.2 Controlling Battery Capacity Fade

While Transit cannot prevent capacity fade, steps can be taken to slow the rate of decline.

- Calendar aging
    - Battery capacity decreases with age regardless of duty cycle.
    - Can't be controlled; rate is linear and specific to manufacturer.
    - Calendar aging information should be provided by the battery manufacturer.
- Top of Charge Limit
    - The maximum voltage the battery can produce. Generally stated as a percentage of nameplate capacity.
    - The longer a battery stays at the top of charge, the quicker an oxide layer develops on the cathode.
    - Build-up of an oxide layer on the cathode can lead to sudden capacity loss.
    - Damage is not predictable based on the number of charge cycles.
    - Vehicle manufacturers will recommend an upper top of charge limit between 85-95% to reduce the likelihood of failure during the warranty period.
    - If range is not an issue Transit should consider selecting a top of charge limit between 85-90%.
- Depth of Discharge (DOD)
    - The percentage that a battery is discharged before charging.
    - The greater the percentage of discharge per cycle, the faster capacity will fade.
    - To prevent damage and extend battery life, bus manufacturers restrict battery state-of-charge between an upper limit of 85-95% and a lower limit of 2-10%. Most buses typically have a total usable capacity between 80-90%.
    - Transit Operators will need to ensure buses are dispatched on routes/runs that will not excessively discharge the battery, which will greatly complicate how dispatching is handled.

  - It is recommended Winnipeg Transit set range limits based on End of Life (EOL) capacity to ensure that all buses are capable of finishing a route regardless of age;
  - Restrict usable capacity to 65% of name plate. This will result in lower DOD at BOL, and higher DOD at EOL.
- Cycle count
  - The number of the times the batteries charge and discharge.
  - Battery capacity fades each time batteries are cycled.
  - High-power batteries typically have longer cycle life than high-energy batteries.
  - Need to balance Cycle Count against Depth of Discharge, particularly with rapid-charge buses.
  - Based on Transit's current 18-year replacement schedule and 90% utilization the following cycles are estimated:
    - Long-range buses: 5,900 -10,100 cycles.
    - Rapid-charge buses: 12,000-41,500 cycles depending on daily expected range.
  - Select battery size and capacity based on required lifetime cycle count to avoid mid-life replacements.
  - Plan to charge buses no more than 12 times per week.
  - Monitor and track charge cycles and battery capacity fade
  - Develop strategies to ensure all buses in the fleet are ageing at similar rates.

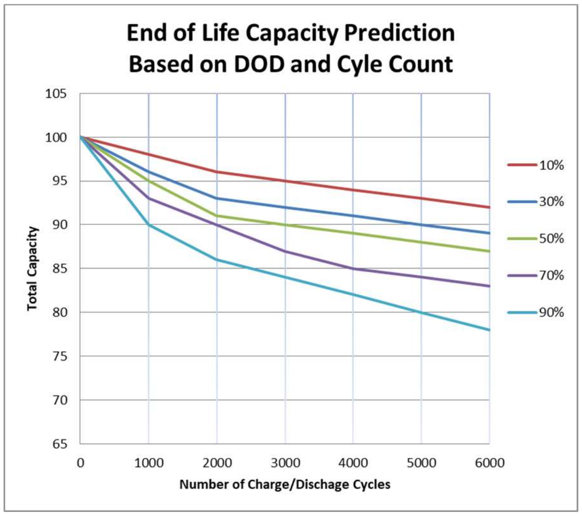


Figure 39: Capacity fade per number of charge/discharge cycles based on varying depth of discharge. Source: [48]

- Temperature
  - Battery temperature rises during a charge & discharge cycle.
  - The more times a battery operates above its ideal temperature the faster it will age.
  - Ensure manufacturers have robust battery thermal management system.

For battery-electric buses, a battery management strategy would need to be developed based on both end of life capacity expectations and targeted life.

In the case of fuel cell battery-electric buses, battery capacity fade is automatically managed through programming. Top of charge is limited to 80%, depth of discharge is limited to no more than 50% under normal operating conditions, and battery charge and discharge rate is actively managed to limit temperature rise. Transit would be required to monitor but not actively manage battery capacity fade.

Based on Transit's operating expectations it may be acceptable to operate older buses on shorter routes, and as such actual useful life may extend beyond the manufacturers stated EOL performance threshold without having to replace battery packs. However, this places limitations on the use of older buses and requires sophisticated automated bus parking and dispatching tools to restrict the assignment of older buses to specific shorter runs.

5.2.3 Fuel Cell Efficiency Loss

Fuel cell efficiency and power output both decrease based on operating hours. Currently, fuel cell stack performance is expected to fade between 15-25% over a 20,000-hour warranty life [110]. However, some transit agencies have operated fuel cell buses for longer than 35,000 hours without having to replace stacks [111]. For FC-BEBs the loss of power would result in additional power being drawn from the battery during acceleration and high-speed driving, but no noticeable performance changes, such as decreased acceleration, top speed, or speed on grades. Fuel consumption directly aligns with efficiency reductions so range will subsequently decrease up to 25% as well.

5.2.4 Controlling Fuel Cell Efficiency Loss

While Transit cannot prevent capacity fade, steps can be taken to slow the rate of decline.

- Calendar Aging
  - Fuel cells are not impacted by calendar aging.
- Power Output
  - The higher the power level the fuel cell operates at, the quicker the fuel cell will age.
  - Minimize the amount of time the fuel cell is outputting full power through programming modify transitions to fixed low/medium/high/max power levels.
  - Selecting a larger capacity fuel cell will help to minimize aging.
- Fuel Quality
  - Ensuring that hydrogen fuel exceeds the SAE J2719 standard for contaminant levels through industry recommended testing and maintenance [112].
  - Hydrogen produced on-site should be periodically tested to ensure fuel quality standards are maintained.
  - Any contracts for delivered hydrogen should include fuel quality specifications.

With a typical operating speed of 22 km/h and annual travel of 52,000 km per year, it may be possible for Transit to operate a FC-BEB greater than 12 years (30,000 hours) without having to replace stacks. If performance declines to the point that the bus performance is no longer meeting expectations, fuel cell stacks can be refurbished at minimal cost in order to restore performance to new.

5.3 Energy Management Systems

Energy Management Systems (EMS) can be utilized to monitor, report, optimize, and control networked charging infrastructure to improve efficiencies and lower energy costs. High peak demand charges associated with plug-in charging drive up the per kWh cost of electricity, while increasing charger utilization and creating a steady power draw reduces the total cost per kWh.

By using a single circuit to control multiple chargers, transit agencies can potentially simplify electrical infrastructure and better manage utility charges. Using software, multiple chargers can be operated simultaneously at a controlled rate or turned on and off as required [113].

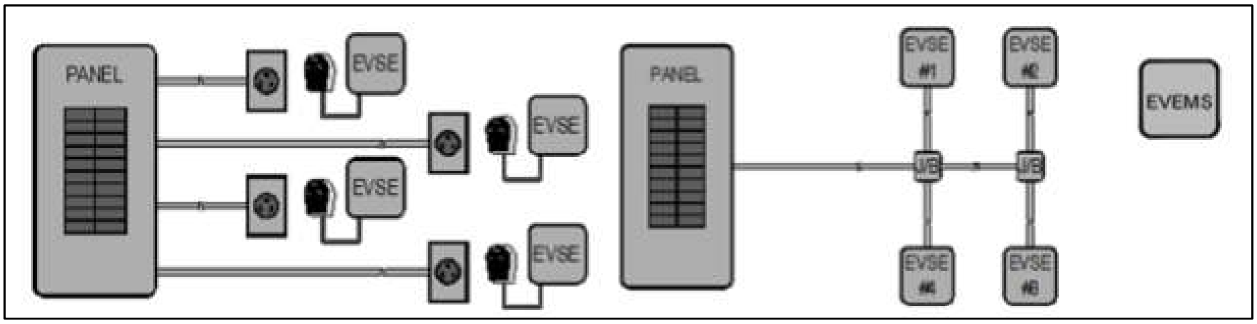


Figure 40: Utilizing Charger manager systems to simplify electrical infrastructure. Source: Adapted from [113]

Light-duty and heavy-duty vehicles operate at different voltages which means that it is not currently possible to utilize bus chargers for fleet support vehicle charging. If vehicle voltages align in the future, there is potential to increase charger utilization by using Energy Management Systems (EMS) to transfer power to light duty charging stations when the chargers are not being utilized for bus charging. This would maximize charger utilization and potentially reduce the number of dedicated light duty charging stations required for auxiliary support vehicles.

5.4 Safety

Buses are one of the safest modes of transportation. Between 1990 and 2018, less than 30% of accidents involving buses resulted in injury, and only 0.067% resulted in a fatality [114]. Of the fatalities involving transit buses, fewer than 10% were transit riders or operators [115].

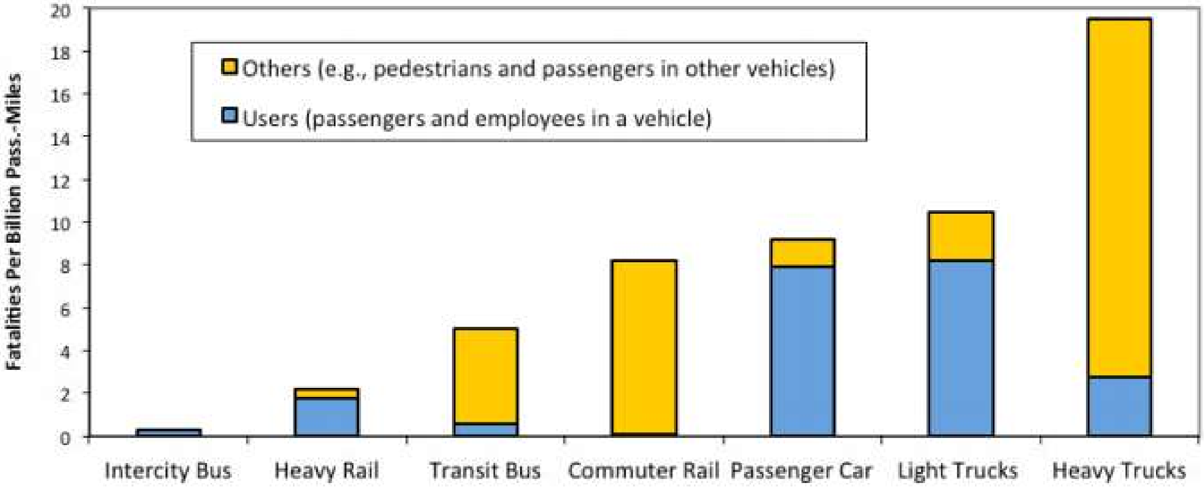


Figure 41: Transportation fatalities by mode. Source [115]

With the introduction of new technology there is some inherent risk for an increase in accident occurrence or severity. However, a report from the National Highway Traffic Safety Administration concluded that risk of fire and explosions from lithium-ion batteries as a fuel source is anticipated to be comparable to or lower than that of gasoline or diesel fuels [116].

Transit staff, including mechanics, electricians, other service technicians will be the most exposed to the risks associated with high voltage electricity, lithium-ion batteries and compressed gases. Transit will need to ensure that training is available to all people that interact with the bus so that they are aware of the difference between zero-emission and diesel buses. Training must also extend to first responders.

Some safety training is available directly from manufacturers either free of charge or included with the price of a bus. Similar in-house training could be developed to provide a greater number of Transit employees with general high voltage safety information, while local community colleges could be leveraged to develop more in-depth programs or certifications for zero-emission bus technicians. Winnipeg Transit is currently working with Red River College to develop an “Intro to Electric Vehicle Technology” course which will include high voltage safety and safe work procedures.

While training will help prevent accidents, any buses, chargers or refueling equipment purchased should be compliant with all applicable Federal, Provincial, and Municipal regulations, codes, and standards. Transit should request proof of compliance where applicable. Transit buses are still mostly built by hand and as such, a robust quality control and assurance program is necessary to ensure buses are being built to compliance. A quality audit is also recommended to ensure that all internal manufacturing standards, quality inspection and testing guidelines crucial to safety are followed during the assembly process. Quality reports should also be made available upon request.

Because standards are still evolving and because manufacturers utilize different battery technology and energy management strategies, each may have different methods for detection, prevention, or response to failures. It is recommended that manufacturers provide proof that a Failure Mode and Effects Analysis (FMEA) or Hazard Analysis has been completed to confirm that their design effectively manages or eliminates risk of electrification, arcing, fires, toxic exposure, etc. through design or training.

Despite design best practice and robust training, the presence of high voltage, lithium-ion batteries and compressed hydrogen each have their own associated risks which need to be considered.

5.4.1 High Voltage Safety

All current zero-emission buses utilize high voltage electricity for propulsion. Bus system voltages are between 600 and 800VDC. Even at low currents electric shock could be deadly. Any location where high voltage is present should be clearly identified with decals for high voltage and shock hazard. Access to high voltage connections should be behind physical barriers that require tools to remove. High voltage cables should be easily identifiable by orange colored sheathing or conduit. Procedures and equipment must be in place to restrict access only to those who are properly trained and require access as part of their work.

Electrical shock and arc flash are the two main hazards when working with high voltage equipment. Shock occurs when an electrical current passes through the body. Effects vary based on the magnitude of the current and the path and duration of exposure, and can range from a minor tingling sensation to muscle spasms, seized muscles, heart fibrillations, internal and external burns and death [117]. Arc flash is a release of energy caused by an electric arc [117]. An arc flash causes an ionization of the air resulting in temperatures reaching thousands of degrees in an instant. The force associated with an arc flash can knock people over and potentially throw them, as well as any loose objects and potentially molten metal, across a room. The sound wave from the rapid expansion of air can cause eardrums to rupture resulting in temporary or permanent hearing loss. The heat and light from the arc can also cause fires, severe burns, and temporary or permanent blindness [118]. Arc flashes are caused by a fault or short circuit as a result of accidental contact, or the failure of an underrated or damaged component that is unable to manage available current.

There is minimal risk of exposure to high voltage electricity for passengers and operators, particularly if batteries and cables are outside of the passenger compartment and the high voltage system is isolated from the chassis. Some risk of high voltage exposure is unavoidable for Transit employees who need to service the bus and first responders who access the bus in an emergency. In these cases, the use of personal protective equipment (PPE), including insulated gloves, eye protection, insulated safety shoes, and insulated tools, must be mandatory. No one should ever work on the buses unattended, and a hot stick must be easily accessible to separate a person from electrical contact in an emergency situation [119].

Any work on the high voltage systems must be properly planned, documented and approved prior to starting. At minimum a plan should include:

1. Identification of the qualified technician assigned to the work
2. A detailed description of the work to be completed
3. Identification of the electrical hazards associated with the tasks
4. A shock risk assessment
5. An arc flash risk assessment
6. Work procedures, special precautions and energy mitigation strategies [117]
   Electrical work permits may additionally be required depending on the nature of the work.

A barrier clearly identifying the presence of high voltage must be established around the buses at an appropriate distance based on the arc flash risk assessment. All staff in the area must be made aware of the open HV work, and only approved trained workers are allowed inside the work zone.

When a bus is running there is potential for short circuits to create voltage in unintended locations. The master run switch should always be turned off prior to opening any service panels. Adding interlock switches to panels and enclosures which turns off HV power when they are opened can further prevent accidental exposure. Vehicles continuously monitor for isolation loss resulting from short circuits, and detected losses will result in fault codes, warnings, or potentially a vehicle shutdown depending on the severity of the issue [120]. Short circuits are caused by bridging of circuits by an object or fluid. If a problem is detected, an insulation tester or megohmmeter should be used to locate the short and correct it before it becomes a larger issue.

EV batteries are designed with normally-open contactors that will remove battery voltage from the system when the master run switch is turned off. There is a possibility of the contactors closing and the system being energized anytime there is 12/24V power supplied to the vehicle. For added security, the 12/24V master disconnect switch should also be turned off and locked out/tagged when servicing, and off before approaching the bus in an emergency [121]. Even with the master run switch and the master disconnect off, the system may remain energized for up to 4 minutes [121]. It is recommended to wait at least 10 minutes after the high voltage is turned off before servicing the bus. When approaching a bus, it should always be considered live. A multi-meter should be used to confirm the absence of electricity prior to servicing any components.

If the drive shaft is not disconnected, electric motors have the potential to generate electricity anytime the bus moves. Any energy created by small movements is likely to be small and discharged quickly, but the use of chock blocks is recommended to prevent accidental movement of the bus and unexpected electricity during service. Moving the buses long distance such as when towing can generate significant amounts of energy. Tow charging is sometime used as an emergency charge method if the battery state of charge is low and the bus is otherwise operating normally but not accepting charge. Tow charging when the battery state of charge is high creates a risk of overcharging the batteries, which could potentially lead to a thermal run-away event. For field service calls where flat towing is not available it is recommended that the drive shaft be disconnected before moving the bus.

Batteries are always live. Battery service disconnect fusing is available to isolate strings of batteries and de-rate the potential energy on the bus, but individual packs or cells cannot be fully de-energized. Battery packs should only be serviced by qualified technicians. The bus industry seems to be moving towards non-serviceable, sealed HV battery packs with touch safe connectors for improved safety. Most batteries are housed inside metal enclosures to limit environmental exposure and protect against external damage. Battery enclosures are grounded but, in an accident, there is risk that a metal enclosure could become energized.

High voltage cables are a major point of failure and should be inspected regularly for damage. Vibration, abrasion, UV, and environmental exposure can all lead to loose connections and damaged cables which increases risk of shock and arching. Visual inspection of cables and re-torquing of connections should be part of a preventative maintenance program. Manufacturers reduce the risk of failure by using UV resistant cables, adding conduit around cables, avoiding metallic cable clamps, and utilizing keyed connectors rather than torqued connections where ever possible.

Water intrusion into cables and enclosures is another concern. Water can enter waterproof and dust proof rated enclosures if cable glands are incorrectly sized or not installed properly, or if water is inside the cable sheathing. Condensation may form on cooling lines or the walls of the enclosure as well. Adding cable drip loops helps prevent any potential buildup of water in a cable from entering enclosures. Drains on the bottoms of sealed enclosures will prevent significant water build up, and moisture sensors can be installed if drainage is not possible such as in sealed battery packs. Enclosures should be inspected regularly for water and the formation of rust. If rust on connections is an issue, high voltage rated dielectric grease can be added to electrical connections to help repel moisture and protect against corrosion.

5.4.2 Lithium-Ion Battery Safety

Lithium-ion safety standards are still evolving and while the technology is not considered unsafe, industry consensus on safe system design and performance-based test methodologies has not been achieved [116]. Battery safety is still very reliant on manufacturer in-house expertise and testing.

The largest area of uncertainty involves the long-term impact of abuse on lithium-ion battery safety. While rigorous battery abuse testing exists, including electrical, mechanical, and environmental testing, the qualifications for meeting compliance are single abuse events and short-term fixed-time assessments of damage rather than reviewing long-term effects from damage on cumulative life cycle durability and damage tolerance [116]. Minor undetected damage caused by abuse over time may grow into a more serious problem through multiple charge/discharge cycles. This does not necessarily mean any greater risk for thermal events to occur, but Transit would not be able to rely on the fact that batteries subjected to abuse would survive to their warrantable life. The post-crash behaviour of batteries would need to be closely monitored.

Zero-emission buses are designed with multiple layers of protection to detect issues that could lead to a thermal event, and actively take measures to stop or prevent problems from propagating. These include battery thermal management systems, battery fault detection, physical barriers around batteries, elimination of sources of ignition, electric circuit protection, electrical isolation, and pressure relief devices.

Batteries heat up both when charging and discharging. Bus manufacturers utilize either air cooling or liquid cooling to maintain batteries at their ideal temperature. Cells within a battery are separated with a thermal barrier which prevents overheating of adjacent cells if a single cell becomes unstable. If the barrier is compromised, heat rise can propagate to adjacent cells. This spread can be very quick or very slow depending on the type of damage. Battery thermal management systems are utilized to continuously monitor battery temperature and react when temperatures are out of range. Over temperature battery warnings will appear on the dash to alert the operator to issues with battery overheating. If internal battery safety features and controls do not correct the problem, it is possible that a thermal run-away event could occur.

The temperatures associated with thermal run-away are very high and cannot be extinguished with traditional fire suppressants. Water is the recommended medium to extinguish a lithium-ion battery fire; however, it may take several thousand gallons of water applied directly to the battery to cool it down sufficiently to extinguish the fire. It may take up to 24 hours to extinguish a battery fire, and batteries may reignite several hours or several days after they are initially extinguished [121] [122].

There is risk of batteries over-pressurizing when they are exposed to high temperatures. If this occurs they are designed to vent electrolyte rather than risk the pack exploding. Batteries contain many toxic chemicals that are heavier than air, corrosive, and flammable, including hydrogen fluoride which is toxic both by skin contact and inhalation [116]. If water is used to extinguish a battery fire, hydrogen fluoride gas may combine with water to produce hydrofluoric acid which can additionally cause severe chemical burns. If left untreated, exposure could lead to severe skin, tissue, and bone damage, as well as chronic pain [123].

Lithium plating is a failure mode that can occur when batteries are overcharged, which potentially leads to a thermal run-away event. The heat rise associated with overcharging can cause the formation of metallic lithium dendrites which grow with each charging event. In minor cases dendrite growth will result in premature battery aging, while in extreme cases the dendrites may cause a short circuit between electrodes causing the cell temperature to rise [124]. Charging protocols and battery management software is designed prevent overheating during charging, and bus manufacturers further set restrictions on the maximum state of charge to further protect the batteries.

5.4.3 Hydrogen Safety

Hydrogen vehicle standards, although still evolving, are considered to be mature, and industry consensus is that the technology has achieved an adequate level of safety through design and testing validation [125]. Abuse testing of tanks considers not just single events, but also cumulative life damage to the tanks as a result of the abuse.

Hydrogen is the most abundant element in the universe. It is odorless, colourless, and lighter than air. Hydrogen has been used in industrial applications for over 100 years [78]. Like all fuels, there is some degree of risk associated with hydrogen. Hydrogen is a flammable gas with a wide flammability range and relatively low ignition energy. Unlike battery fires, small hydrogen fires can be extinguished with dry powder retardant, carbon dioxide, a halon extinguisher or a fire blanket, but the fuel supply needs to be shut off to prevent the fire from spreading [126]. Hydrogen fuel safety focuses on preventing situations where combustion factors, such as ignition sources, oxidants, or fuel, are present.

Codes and standards have been developed for the design, operation and storage of hydrogen powered vehicles as well as hydrogen production, dispensing, and storage equipment. With the establishment of design guidelines and implementation of appropriate engineering controls hydrogen is considered a safe vehicle fuel [127].

The development of emergency response plans and engaging employees as well as first responders in regular training drills will help ensure safety protocols are understood and are being followed.

5.4.3.1 Hydrogen Refueling & Storage Codes & Standards

Codes and standards have repeatedly been identified as a major institutional barrier to deploying hydrogen technologies. There are currently no overarching codes or standards in Canada regulating heavy duty hydrogen vehicles [128].

Overall vehicle safety is covered in the Canadian Motor Vehicle Safety Standards (CMVSS) and their supporting Technical Standards Documents. There are currently no regulations within the standard regarding hydrogen, but the need to update the standard to include hydrogen fuel safety has been identified and is in development. This change is not expected to be released prior to Fall 2021.

In the absence of direction from CMVSS, standards such as the National Fire Protection Agency's (NFPA), NFPA 2 Hydrogen Technology guide, ISO 19881:2018, and CSA Standard ANSI/HGV 2-2014 are used to provide guidance for design, operation and storage of hydrogen powered vehicles. While safety and performance requirements for hydrogen fueling stations are established by SAE J2600, J2601 and J2799, and ANSI/CSA HGV 4.3-2016.

In most provinces, including Manitoba, the construction and operation of hydrogen production and dispensing facilities are regulated under the same set of provincial regulations that enforce building codes, electrical codes, and technical standards for equipment [129]. The distribution of fuel from production sites to fueling stations are governed by both federal and provincial legislation in their respective Transportation of Dangerous Goods acts.

The Canadian Hydrogen Installation Code CAN/BNQ 1784-000 released in 2007, sets requirements for both vehicles and associated infrastructure and has been approved by the Standards Council of Canada, but it is out of date and has only been adopted by Ontario and Saskatchewan. This code is in the process of being updated to better align with recent changes to other codes and standards, and is expected to be released sometime in 2020 [130]. It is hoped that more widespread provincial adoption will occur with the next release.

5.4.3.2 Safe design, operation and storage of hydrogen powered vehicle

Hydrogen buses should be identified with decals identifying both the presence of hydrogen and high voltage.

Most regulations around hydrogen vehicle safety revolve around on-board storage tanks. All tanks must pass stringent CSA qualification testing to be certified safe which includes drop, burst, bonfire, penetration, corrosion, vibration and shock, and extreme temperature cycling tests amongst others. Bus manufacturers generally add additional protections around the tanks and impact sensors to ensure that the tanks are well protected during operation.

Hydrogen is a very small molecule and some molecules will permeate out of the tanks. Hydrogen embrittlement is a known issue which is caused by hydrogen attacking certain types of metals, including some grades of stainless steel, and may result in more serious leaks. Transit should ensure that manufacturers are utilizing material and hardware that is compatible with hydrogen. Regular inspections of materials using magnetic particle testing or ultrasonic testing may catch any developing cracks on or below the surface before they become problematic [131].

Tanks are equipped with flow sensors and solenoids which will detect and prevent significant leakage events but small leaks may go undetected and result in high hydrogen concentrations inside buses or buildings. Tanks are typically mounted on the roof or in the engine compartment, but hydrogen lines run from the tanks to the fill panel and fuel cell. Hydrogen lines should never be run through the passenger compartment and pathways for hydrogen to easily vent to atmosphere are important to avoid pockets where high amounts of hydrogen could accumulate.

Hydrogen is not toxic but because it is lighter than air, major leaks could pose an asphyxiation risk to people working near the ceiling of the building. Hydrogen intrusion into the passenger compartment is also possible from fuel lines running outside of the passenger compartment if the compartment is not adequately sealed. Hydrogen leak detection, both on the bus and in buildings where buses are parked or serviced, is important to identify significant hydrogen accumulations.

The bigger risk of hydrogen leakage is self-ignition events. Hydrogen has the potential to self-ignite at concentration levels between 4-75% by volume, and requires only a small spark to ignite at higher concentration levels [132].

Service garages where sources of ignition are common are required to have both detection and active mechanical ventilation, while parking garages are not required by code to have mechanical ventilation if natural ventilation levels are sufficient, but detection is still recommended [133].

If a thermal event is detected on the bus while operating, the hydrogen supply and any fans should turn off to prevent propagating the spread. Hydrogen tanks are certified to withstand both localized and engulfing fire and are equipped with thermally-activated pressure relief devices (TPRD) which if activated, vent the tanks to atmosphere to prevent an explosion. Because hydrogen is pressurized and lighter than air, hydrogen fires burn out quickly once the fuel is eliminated from the vehicle.

To test the effects of a hydrogen fire versus a gasoline vehicle fire, researchers determined that no single failure other than a major tank rupture could result in a discharge of hydrogen significant enough to produce a flame. In all other circumstances, redundant safety systems prevented any significant amount of hydrogen from being discharged and ignited. Conversely, even a small leak in a gasoline vehicle created an easy source of ignition.

Figure 42: Comparison of severity of hydrogen vs gasoline fire [134]

Hydrogen fires are nearly invisible in daylight, produce very little radiant heat and do not produce smoke [122]. Temperature sensors will typically detect a hydrogen fire but optical sensors may not unless surrounding materials are burning. Optical sensors with infrared detection should detect a hydrogen fire. Any potential fires should be approach with extreme caution. A handheld thermal imaging camera is recommended when approaching a suspected hydrogen fire.

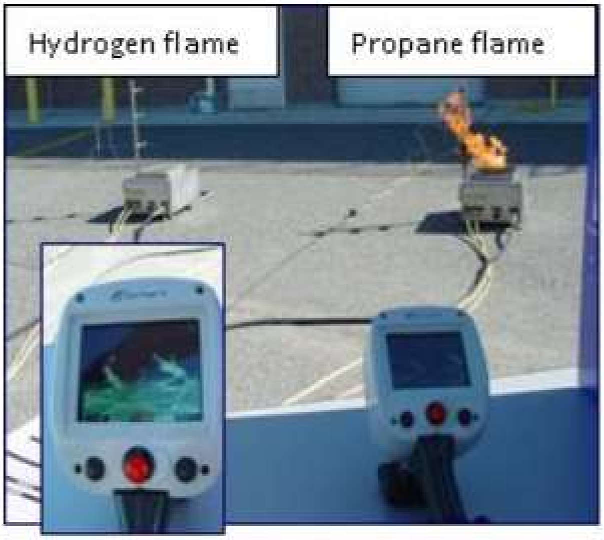


Figure 43: Visibility of hydrogen fire by eye and with thermal imaging camera. Source [132]

Caution needs to be taken when servicing hydrogen tanks. Any air in the tanks creates a fire hazard. Tanks are sealed from the atmosphere and can be drained down close to empty in normal operation without any concern. Flow valves and vehicle programing both prevent the tanks from over discharging. If the tanks need to be serviced, they should be emptied and purged with nitrogen several times prior to opening the lines. Tank pressure should be verified to be empty prior to opening. A similar nitrogen purge process should take place prior to filling with hydrogen after the tanks are reinstalled to ensure no air remains in the tanks.

5.4.3.3 Safe hydrogen production, dispensing and storage equipment

Hydrogen refueling is safe if proper filling procedures are followed. Only authorized individuals who are properly trained should dispense hydrogen fuel or service hydrogen equipment. Areas around fueling equipment should include appropriate signage to alert people to the presence of flammable hydrogen gas. “No Smoking” and “No Open Flame” warnings should also be clearly visible.

Compression and storage equipment should be outdoors within a fenced enclosure to restrict access. Electrolysis equipment can also be located outdoors, but based on Winnipeg’s climate it is recommended that equipment be housed in a heated building.

Hydrogen fueling stations are equipped with many of the same safety features as the buses, including flow sensors, solenoids, temperature sensors, and leak detection. Stationary storage tanks are required to pass the same stringent testing similar to on-board tanks. In extreme emergencies, stationary storage systems just like on-board tanks, are designed to safely vent hydrogen to the atmosphere, quickly eliminating any source of combustion.

Other standard safety equipment required for hydrogen fueling stations includes, rupture disks to prevent overpressure, pressure relief devices, redundant and repetitive valve isolation throughout the system, emergency stops, a breakaway valve at the fueling hose, leak detection during fueling, flame detection, grounded concrete fueling pads, fueling logic, and fault testing during performance evaluation [135].

Design features such as remote monitoring of storage tank pressures, emergency shut downs, and segmented storage banks, can be added to lessen the impact if a fire were to occur on site [136]. FMEA or Hazard Analysis should be completed for any station design to ensure any site-specific risks are eliminated or adequately mitigated.

As with vehicle on-board equipment, hydrogen embrittlement can be a problem for filling stations. Regular inspection of materials for crack propagation is recommended to prevent major failures. Generally, hydrogen fueling equipment is located outdoors so slow leaks do not pose a serious risk. Any canopy designs covering an outdoor dispenser should be designed to prevent hydrogen accumulation.

NFPA 2 does allow for indoor fueling, if the fueling area is physically isolated from other parts of the building via an explosion proof wall, and if adequate detection and mechanical ventilation are provided. Depending on the size of the system, fueling may need to take place inside a dedicated building. Building modifications, or construction to support indoor fueling, is generally not cost effective for small deployments.

There are no size restrictions with outdoor fueling, but the required setbacks from buildings, property lines, and other obstructions vary by station capacity. If hydrogen buses are to be part of Transit's long-term electrification plans, consideration for location of fuel equipment, inside and outside the building, should be included in future garage designs.

Hydrogen tank temperature needs to be managed during filling. Fill rates have historically been determined based on using the SAE J2601 lookup table or MC formula methods [137]. These methods base fill rate on ambient temperature or dispensed fuel temperature, while also considering things such as targeted fill pressure, tank size, and tank type. Communication fill is a more recent development that allows buses to fuel at a faster rate without risk of over pressurizing tanks or exceeding their temperature rating. If the bus and the station are compatible, the dispenser is able to monitor pressure and temperature information from the buses and adjust the fill rate dynamically. If the communication protocol fails, the station will revert to a safe fill rate as defined by either the default lookup table or MC Formula method.

5.4.4 First Responder Safety

First responders, and firefighters in particular, are especially at risk when responding to accidents involving zero-emission buses. Emergency responses can be complicated by the presence of battery fires, high voltage electricity, and potentially hydrogen. Heat from battery and hydrogen fires can be much more intense than that of traditional fuels, the chemicals vented from batteries can potentially be toxic, and cutting in the wrong location could lead to injury or death.

The first step when approaching any buses involved in an accident are:

1. Identify
2. Immobilize
3. Disable [122]

Buses are supplied with First Responder Guides which are intended to quickly familiarize first responders with the specific dangers associated with the bus [121]. The guide is generally a laminated back-to-back card which can be easily grabbed by the operator in an emergency. The front side provides an overview of the location of vehicle controls and the emergency shutdown switches, as well as highlighting “No Cut” areas which contain high voltage equipment, fuel tanks, high voltage cables, and gas lines. The back side of the card includes detailed instructions of emergency shutdown procedures.

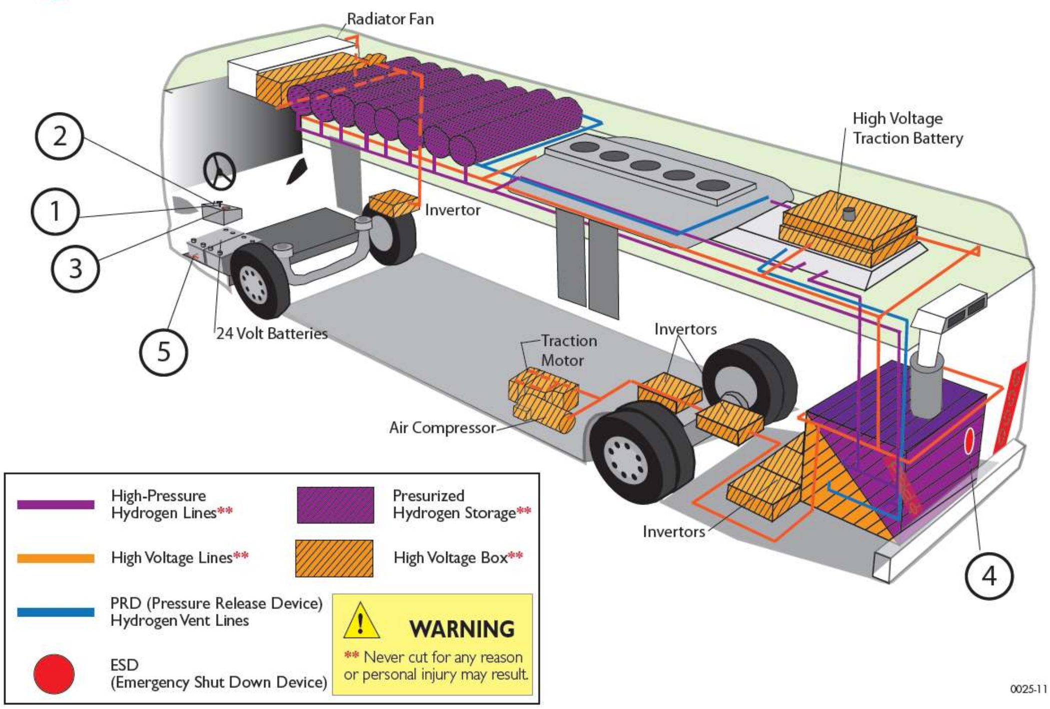


Figure 44: Example First Responder Guide first page [121]

It is recommended that Transit work with first responders to develop emergency response plans specific to the types of buses operated by Transit, as each bus requires different responses. First responders should be familiar with potential risks with each model of bus, and have the appropriate PPE for responding to a zero-emission bus accident. It is recommended that Transit conduct regular training drills, which include first responders, to ensure safety protocols around zero-emission buses are understood and followed, both by Transit employees and first responders.

Zero-emission buses should be equipped with easily distinguishable markings for quick identification. Most transit agencies produce unique decal packages for zero-emission buses that make them easy to identify. The battery-electric demonstration buses operated by Winnipeg Transit between 2014-2018, featured a unique body-wrap which made them easily identifiable.

Figure 45: Winnipeg Transit battery-electric bus decal package 2014-2018

There are very few transit agencies operating zero-emission buses from multiple manufacturers or multiple propulsion technologies. AC Transit in Oakland, California, is one of the few that can be used as an example for best practice. First, unique decal packages for zero-emission buses help distinguish these buses from the diesel fleet. While all their zero-emission buses appear very similar at first glance, there are subtle differences that help first responders to visually differentiate the buses. Each technology is distinguished with large color-coded zero-emission decals, as well as smaller decals on the side screens that clearly state the propulsion system. While New Flyer electric drive and fuel cell electric drive buses appear very similar, an obvious difference is a rear radiator vent on the fuel cell bus. Each manufacturer also has its own recognizable design features. For example, Van Hool buses have plunging side window glass at the front of the bus and feature full length glass, while New Flyer buses have fully horizontal windows and white rear quarter-panels. Each bus would also feature badging or logos on the front and rear of the bus which identify the manufacturer.

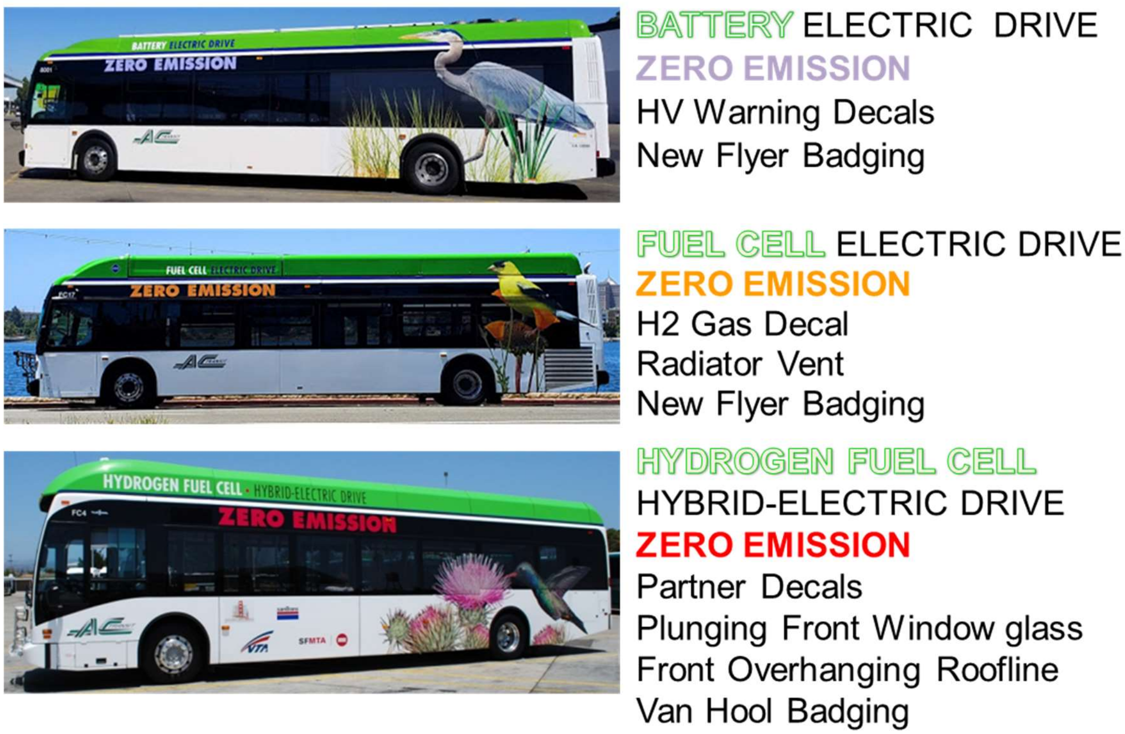


Figure 46: Decal differences on AC Transit Zero-Emission Buses. Source: [138] [139]

First responders should be familiar with hazard decals conforming to ANSI, OSHA, and SAE standards, which are commonly applied on zero-emission buses.

Figure 47: Identifiable decals on zero-emission buses

Regardless of the model of zero-emission bus, the response to a fire on a zero-emission bus is similar, and the NFPA has created some standard guidelines. Full PPE, including a self-contained breathing apparatus, is required to protect against electricity and toxic chemical exposure. Large amounts of water are required to extinguish to a lithium-ion battery fire. Small amounts of water should never be used, as small amounts of water interacting with vented battery chemicals can create toxic gas. It may take several thousand gallons of water applied directly to the battery, to cool it down sufficiently to extinguish the fire [121] [122]. Fire-fighting efforts may be better focused on containing a battery fire and preventing it from spreading to adjacent areas, rather than extinguishing it. Because batteries can continue to reignite after they are initially extinguished, a safe perimeter of 15 meters should be maintained around the bus until the accident is cleared [122].

Compressed hydrogen tanks on fuel cell buses are equipped with TPRDs, which are designed to activate and vent hydrogen if the tanks are engulfed in flames. If a fuel cell battery-electric bus is on fire, water should not be sprayed directly onto the tanks as this could prevent the TPRD from activating, which may lead to a tank explosion [122]. As tanks and batteries are sometime located in close proximity to one another, first responders would need to confirm that tanks are empty prior to applying significant amounts of water to the batteries.

Hydrogen fires are nearly invisible in daylight, produce minimal radiant heat, and generate no smoke. Because hydrogen requires very little energy to ignite, first responders should approach fuel cell battery-electric buses that have been involved in an accident with caution. Leaking gas will generally create an audible hissing noise. The bus should be surveyed with gas detection meters and a thermal imaging camera to check for hydrogen leaks or fires. Hydrogen burns very hot and is difficult to extinguish, but it will self-extinguish when the supply of fuel runs out. If a hydrogen fire is detected and the flow of gas cannot be stopped, the fire should be monitored while it burns itself out over the course of several minutes. As with battery fires, the focus should be on preventing a hydrogen fire from spreading to adjacent areas.

If any zero-emission bus needs to be physically removed from an accident and cannot move on its own power, wherever possible it should be shipped on a flat bed. If this is not possible, the drive axle must be disconnected to prevent energizing a potentially safety compromised electrical system. Because batteries can continue to reignite hours or days after they are initially extinguished, damaged vehicles should not be stored within 15 meters of structures, or other vehicles, until thermal imaging tools can confirm the danger of thermal run-away has passed [122].

6 GREENHOUSE GAS EMISSION AND ENVIRONMENTAL IMPACT

It has been well established that zero-emission buses will result in lower community emissions inventory; however, concerns have been raised regarding the global environmental impact of zero-emission buses.

To evaluate these concerns, the upstream and downstream impact of electric propulsion systems on global greenhouse gas emissions were reviewed based on battery chemistry, battery capacity, fuel cell capacity, source of electricity, and source of hydrogen. The environmental and social implications associated the extraction, processing, recycling and or disposal of the cobalt, lithium, copper, nickel, and platinum needed for zero-emission vehicles were also considered.

6.1 Manitoba Electricity Grid

Manitoba's electricity grid consists of greater than 99% green energy, coming from predominately hydroelectricity, with smaller portions from thermal and wind power as well [83]. Industrial energy rates in Manitoba are the lowest in the country [140]. This unique combination of clean and inexpensive energy creates the opportunity for bus electrification to have a significant impact to the reduction of GHGs in the City of Winnipeg.

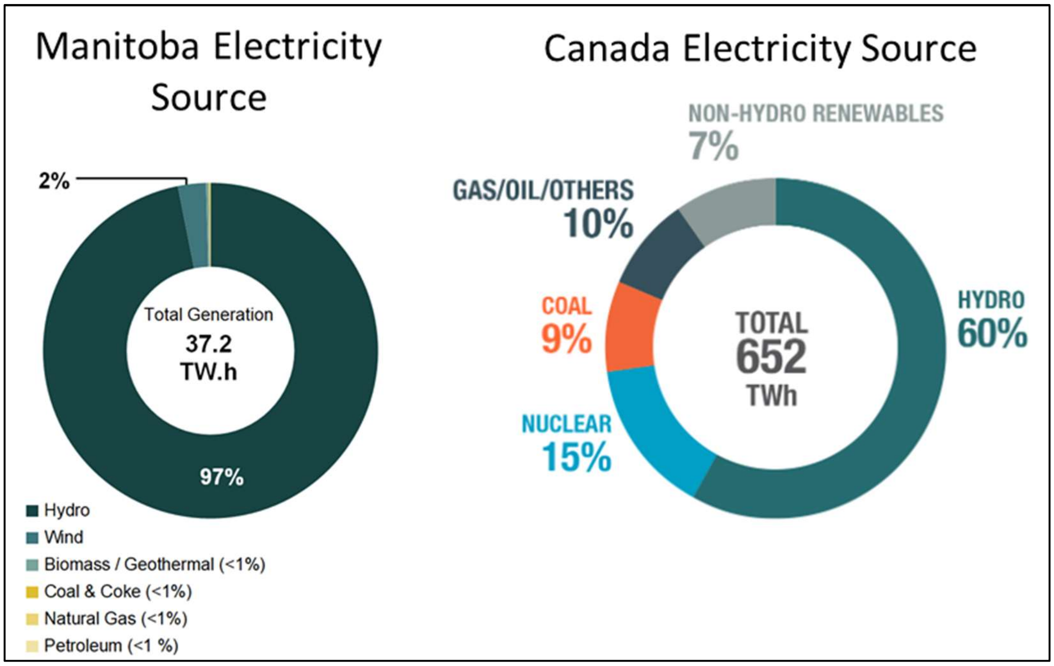


Figure 48: Electricity Generation Source Manitoba vs Canada. Source: Adapted from [83] [140]

6.2 Environmental and Social Implications of Zero-Emission Vehicles

Both battery-electric and fuel cell battery-electric buses utilize high voltage lithium-ion batteries for either primary or supplemental power. Unlike low voltage batteries which are mainly built from readily available materials and are highly recyclable, high voltage batteries contain metals with limited global supply and have low recyclability.

There are three battery chemistries that have been used by bus manufacturers in North America: lithium-iron phosphate (LFP), nickel manganese cobalt (NMC), and lithium titanate oxide (LTO). A fourth battery chemistry, nickel cobalt aluminum oxide (NCA), is growing in popularity in the automotive market, but is not currently being offered by transit manufacturers. An NCA battery is essentially an NMC battery with a portion of the cobalt replaced with aluminum. While globally LFP batteries hold a large market share, NMC and NCA batteries are dominating the North American market due to demands for extended range. The high cost of LTO batteries, combined with improvements to the charge rate and energy density of NMC batteries, has eliminated this chemistry from the market.

Mining the raw materials for lithium-ion batteries has a variety of consequences, with the environmental impact varying both by chemistry and energy capacity.

6.2.1 Cobalt

Cobalt is considered a critical safety component in lithium-ion batteries. It is estimated that 75% of all lithium-ion batteries produced contain some amount of cobalt [141]. 70% of the world's cobalt is mined in the Democratic Republic of Congo (DRC) which is politically unstable, and in which companies employ questionable labour practices which expose miners to dangerous working conditions and long-term health issues [107] [142].

Battery manufacturers are being pushed to trace their cobalt supply chain and report publicly that it is sourced responsibly [142] [143]. Vehicle manufacturers are also pushing to reduce the amount of cobalt in their batteries, both in an effort to avoid dependence on the DRC, but also to extend global reserves [143] [144] [145]. It is predicted that cobalt supplies could become strained as early as 2025 based on the current trends in EV adoption [107] [145]. If new sources of cobalt are not discovered, shortages of sustainably sourced cobalt could result in increased reliance on the DRC [107].

90% of cobalt is extracted as a by-product of copper and nickel [107]. The high value of cobalt is now causing mining companies to explore expanding or re-opening copper and nickel mining operations, not previously considered profitable based on the quantities of copper or nickel alone.

6.2.2 Copper & Nickel

Copper is a critical component in all vehicles, but an electric vehicle requires approximately 4 times more copper than a traditional vehicle powered by an internal combustion engine [146]. Nickel is currently used in more than 40% of all lithium-ion batteries, and that amount is expected to increase [141]. Like cobalt, neither copper nor nickel are typically mined in their pure form. They are typically found as copper and nickel sulfides [147].

Pure metals need to be extracted through smelting. Smelting produces both CO_2, a known GHG, and sulfur dioxide, a toxic gas which combines with water in the atmosphere to produce acid rain [148] [149]. Acid rain is a major contributor to both deforestation and water acidification [150].

While nickel and copper both have a high recycling potential, the increased need to mine material in the pursuit of electric vehicles could lead to increases in environmental impact from smelting activities.

6.2.3 Lithium

All EV batteries currently contain some amount of lithium. While the quantity of lithium used in the batteries is very small, the environmental impact from lithium mining is substantial [151]. The majority of lithium is produced in one of two ways: direct mining of crystalline mineral deposits containing lithium;

or through brining. Brining is a process which involves drilling down to underwater lithium brine deposits, pumping the brine to a surface pond, then collecting Lithium chloride precipitate as the water evaporates [107] [151]. Currently, mining produces over half the world's supply of lithium [152], but the cost of extracting lithium via brining is generally lower cost [107]. With more than half of the world's lithium reserves easily accessed using brining, extraction through brining is likely to increase in the future [151].

Because brining involves pulling ground water to the surface and evaporating it, millions of gallons of water are being depleted from the areas immediately surrounding brining operations. This loss of water directly impacts production of local agriculture and farming [153]. In addition, toxic chemicals are mixed with the brine to assist with processing the lithium. While these are supposed to be filtered out, there is potential for these chemicals to leach back into the ground water supply before the pool is fully evaporated. Lithium mining activities have been linked to water table pollution, poisoning of fish and other wildlife, destroying agricultural land, and endangering local communities [151].

6.2.4 Platinum

Today, platinum is used in catalytic converters to control emissions of internal combustion engines. Platinum is also a critical catalyst material for fuel cells. It is estimated that an 85 KW fuel cell (Typical for transit applications) contains 16 grams of platinum [154], while the average catalytic converter on a diesel bus contains only 3-7 grams [155].

Platinum deposits are very rare, processing of the metal is difficult, and it can take up to 6 months to fully refine [156]. Extraction is energy intensive, utilizes toxic chemicals, such as nitric and hydrochloric acid, and produces both carbon dioxide which is a GHG, and sulfur dioxide, which produces acid rain [148] [149] [156]. The two main countries producing platinum are South Africa and Russia, both of which are heavily reliant on coal and other non-renewables for electricity [156] [157] [158].

Fortunately, because of limited sources and the difficulty in mining and processing, platinum recycling is common. Currently, approximately 29% of global demand is met with recycled material [159]. Fuel cell manufacturers seem to be ahead of battery manufacturers with respect to recycling programs, claiming 95% of the platinum used in their stacks can be recovered through recycling [160].

6.3 Recycling & Second Life of Batteries

Manitoba regulates the disposal of EV batteries under the *Waste Reduction and Prevention ACT, Household Hazardous Material and Prescribed Material Stewardship Regulation, Regulation 16/2010.* This regulation specifies that batteries cannot be directly landfilled, and must be either repurposed, recycled or safely disposed. Call2Recycle Canada Inc. has been collecting and recycling consumer batteries on behalf of Manitobans; however, they do not currently take batteries over 5 kg. [161]

There are currently no regulations in place in North America specifying whether the manufacturer or the end user has responsibility for battery end of life management. Manufacturers offering battery leasing have indicated that end of life repurposing or disposing of batteries would be their responsibility, but no similar claim is being made for purchased batteries. If buses are purchased outright, Transit may be responsible developing an end of life strategy for dealing with batteries when they are no longer able to meet minimum range or performance requirements.

It is conservatively estimated that as the first generation of electric vehicles reach end of life, more than 250,000 tonnes of EV batteries will need to be recycled [153]. Despite the high value of metals in lithium-ion batteries, the current complexity of extraction and low yield from recycling makes profitability of recycling unsustainable [162]. Globally less than 5% of lithium-ion end of life batteries are recycled. Recycled lithium makes up close to 0% of the global lithium market, while 32% of the cobalt market is produced through recycling efforts [163].

Battery Chemistry	Metal value (per ton)*	Recycling
Lithium cobalt oxide	$25,000	Subsidy needed
Cobalt	$50,000	Relevant, subsidy
Lithium iron phosphate	$400	Subsidy needed
Lead acid	$1,500	Profitable
Nickel	$10,000–$17,000	Subsidy needed
Cadmium	$2,200	Subsidy needed

Table 1: Metal value per ton of battery.

Lead acid remains the most suitable battery to recycle; 70% of its weight contains reusable lead.

* 2017 Reference prices only; purity and supply govern value.

Figure 49: Relative value of battery raw materials by Battery Chemistry. Source: [162].

Recycling processes are energy intensive, with the Argonne National Laboratory estimating that approximately 12 kg of CO_2 emissions are produced per kilogram of material recovered. This is as much as eight times the amount of CO_2 produced through mining [162] [164]. The purity of raw material required for EV batteries also makes it unlikely that any recovered materials would be sufficient for reuse in new batteries [162].

From an economics and GHG reduction standpoint, there are currently no potential savings from recycling EV batteries. However, if predicted supply chain issues do occur, the value of recycled materials may increase. Any recycling that is occurring is mostly being driven by government regulation and safety concerns over potential soil or ground water contamination from heavy metals or other toxic chemicals, rather than recovering metals. [164].

It is possible that bus batteries which no longer meet performance minimums, will retain some residual value for use with grid management applications, solar and wind farm installations, or home energy storage systems [163]. It is highly recommended that if possible, batteries be re-purposed as second life batteries rather than recycled, unless recycling processes improve significantly [153] [163]. It is unclear how large, or for how long, demand for second life batteries will continue as many first-generation batteries are approaching end of life within the next year or two, which could lead to market saturation. There are also challenges associated with certifying batteries for second-life use applications. Consumer desire for new product may also prove challenging to overcome [141] [164].

If selling retired bus batteries for second-life applications is not an option, recycling or disposal will need to be considered. Both of these alternatives would potentially result in additional cost being incurred by Transit. It is difficult to find exact pricing on battery recycling or disposal, but initial estimates received by Red River College for disposal through incineration of EV batteries were in the range of $15/kg. With the largest battery capacity systems weighing close to 2700 kg, end of life disposal could be as high as $40,000 per bus. Disposal through this method involves controlled incineration of the battery to eliminate risk of land fill fires and to capture noxious off gases.

There are currently no EV battery recycling facilities in Manitoba, so any end of life batteries from Winnipeg Transit would need to be shipped out of province for recycling. There are currently a handful of recycling companies in Canada equipped to deal with EV batteries. Retriev based in British Columbia has been operational for over 20 years, while two new upstart companies, including Lithion based in Quebec, and Li-cycle based in Ontario, are new entrants into the recycling market. All are claiming improved hydrometallurgical recycling processes that significantly improve material recovery [165] [166] [167]. None advertise process emissions, but a small net reduction in GHG emissions is generally associated with this technology [164]. Current cost estimates for shipping and recycling batteries is $2000-4000 per tonne, or $5,400 to $10,800 per bus.

6.4 Evaluation of Greenhouse Gas Emissions

6.4.1 Overview of GHG Life Cycle Analysis

Canada reports its greenhouse gas emissions in Environment and Climate Change Canada's National Inventory Report (NIR). The NIR considered only emissions generated within the jurisdiction under consideration itself. In the case of buses, this effectively means that only emissions generated within the province of Manitoba are counted in the provincial inventory. This ignores any emissions throughout the supply chain that are created outside of the province. Of particular concern with electric vehicles is the impact of battery production on global GHG emissions.

Electric propulsions systems, and batteries in particular, are known to contain raw materials such as copper, cobalt, and nickel which produce a significant amount of emissions during extraction and processing.

Beyond just looking at the NIR, there are other ways in which lifecycle greenhouse gas emissions of electric vehicles can be evaluated, including Tank-to Wheel, Well-to-Wheel, and Cradle-to-Grave.

Tank-to-Wheel considers only energy usage and emission generation during vehicle operation, i.e. tailpipe emissions only. Only zero-emission buses are being considered by Winnipeg Transit, and as such when evaluated using tank-to-wheel, zero-emission buses generally produce no GHG emissions. The one exception is battery-electric buses that are equipped with a diesel auxiliary heater. Due to extreme winter temperatures in Winnipeg, the use of a diesel auxiliary heater is recommended for BEBs to mitigate significant seasonal reductions in range. Buses equipped with these heaters will produce some tailpipe GHG emissions. The impact of diesel auxiliary heaters is discussed in further detail later in this report.

Well-to-Wheel considers energy usage and emissions generated during vehicle operation as well as during fuel production and delivery. It does not consider emissions created during the manufacturing of the glider (bus body), batteries or powertrain. Well-to-Wheel is useful for comparing emissions between fuel sources. For example, hydrogen created from electrolysis would create fewer emissions than hydrogen created from methane. Similarly, hydrogen created by electrolysis in Manitoba would produce fewer emissions than hydrogen created by electrolysis in Ontario. Total energy consumption as well as the source of fuel (electricity, hydrogen and diesel) are used to compare well-to-wheel emissions across propulsion systems.

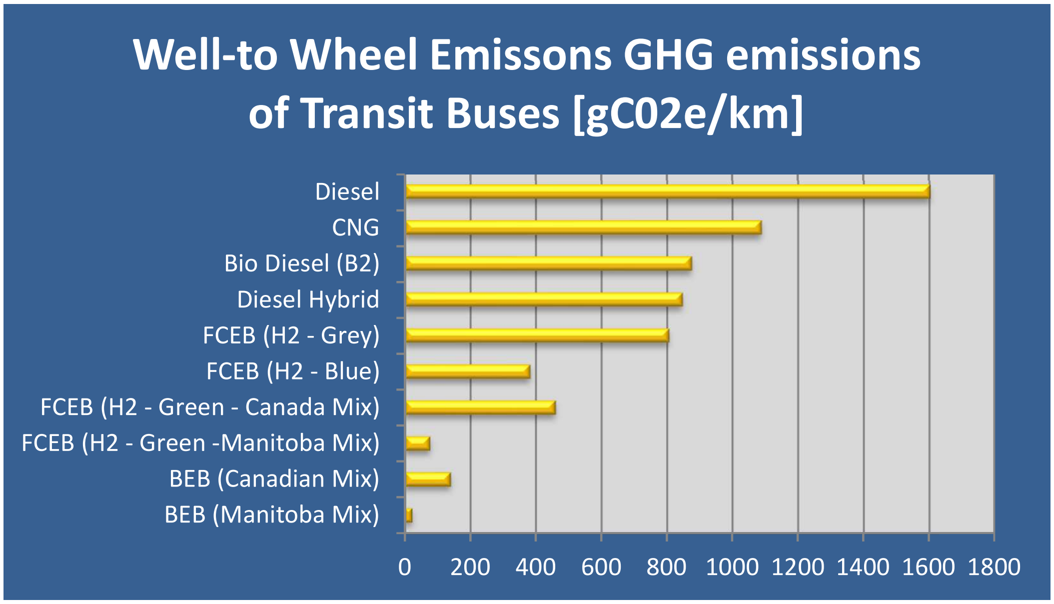


Figure 50: Summary of Well-to-Wheel GHG Emission Reductions by Propulsion [168] [169] [170]

Cradle-to-Grave considers energy usage and emission generation during vehicle operation as well as during fuel production and delivery, but also considers all energy consumed and emission generated from the time raw materials are extracted from the earth, to the time the vehicle reaches end of life and is disposed or recycled. This method of calculating GHG emissions is also referred to as Life Cycle Analysis (LCA).

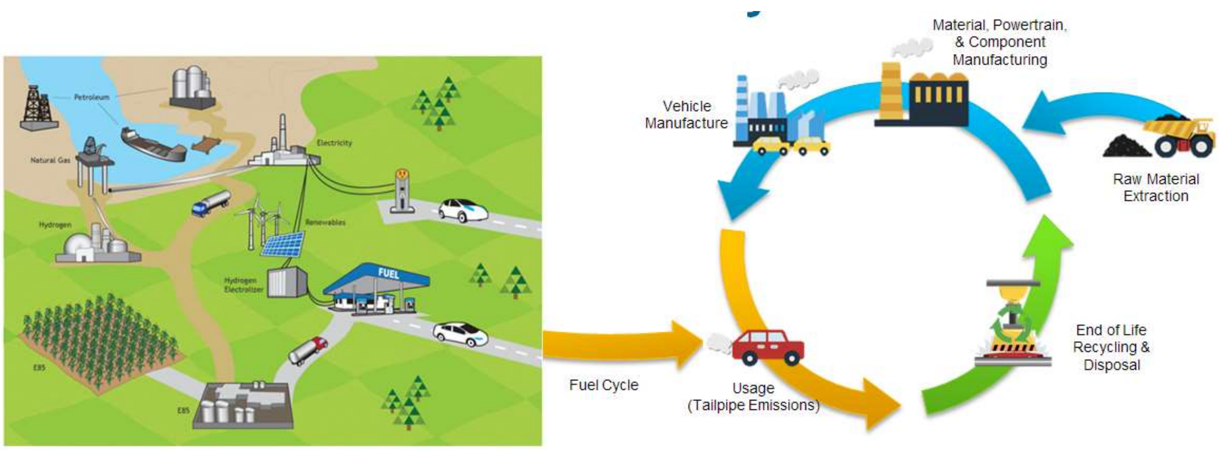


Figure 51: Life Cycle Analysis. Adapted from Source: [171] [172]

The mix of renewable vs non-renewable electricity used from cradle-to-grave can have a significant impact on the total lifetime GHG's of electric vehicles. The illustration below highlights the total lifecycle emissions from the same electric vehicle operated and charged in various different countries, and how a vehicle operated in Manitoba would rank based on our percentage of renewable energy.

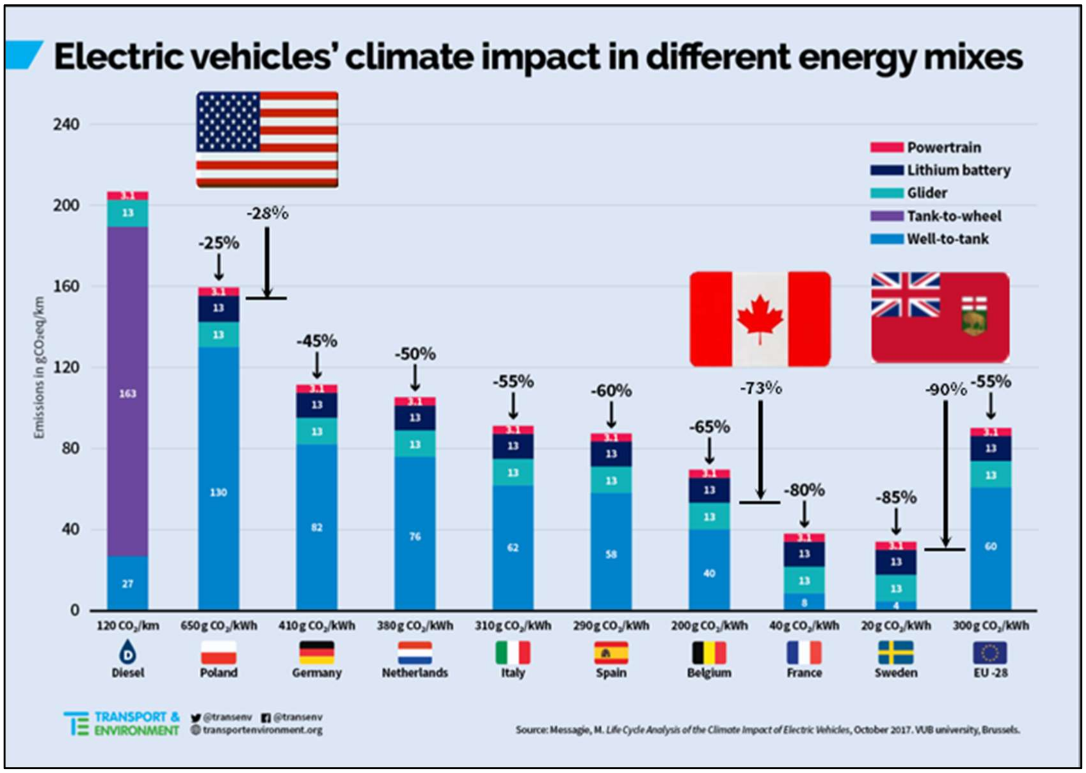


Figure 52: Cradle-to-Grave analysis of Vehicle Electrification by country. Source: Adapted from [168]

It has previously been well established that zero-emission buses can significantly reduce local emissions [5] [53] [173]. While it is the intent of the City to reduce its local GHG inventory, a full lifecycle analysis is the only method that considered emissions generated from cradle to grave, including from mining, raw material processing, manufacturing, assembly, and end of life disposal and recycling, in addition to well-to-wheel emissions generated during the usage phase. A full LCA will look beyond local impact to evaluate the global impact of transit electrification.

Extensive studies have been undertaken to understand the environmental impact of electric vehicles, including battery and fuel cell manufacturing. Unfortunately, cradle-to-grave reviews are not readily available from bus manufacturers for use as a direct comparison. It will be assumed for the purpose of this LCA, that emissions generated during the manufacturing of the glider and powertrain are essentially the same across all manufacturers. The comparison will instead focus on technology differences such as battery chemistry, battery and fuel cell capacity, energy consumption, component life expectancy, and energy sources, to assess the overall environmental impact of each commercially available zero-emission bus.

6.4.2 Emissions Impact from Bus Manufacturing

Generally speaking, most LCA reports conclude that emission variations between vehicle technologies resulting from the manufacturing and assembly of a glider and propulsion system are insignificant for comparison purposes, as lifetime emissions are dominated by well-to-wheel factors [174]. Without completing a detailed climate lens on each manufacturer, it can be realistically assumed that there is no significant GHG benefit from a manufacturing standpoint between either an electric or diesel bus glider. Variations between technologies diverge once the powertrain is considered [168] [169] [170] [174].

A report published in the journal Transportation Research - Part D: Transport and Environment, reviewed the lifecycle emissions of buses with various propulsions systems. Body, Chassis and Frame, Electric Powertrain, and Conventional powertrain were the provided parameters [175]. A Volvo 7900, which is similar in size to a North American heavy-duty bus, was used as the baseline.

Table 19: Global warming potential from vehicle manufacturing and assembly [174]

	$kgC0_2e$/Vehicle
GHG from Manufacturing – Conventional Powertrain	91,000
GHG from Manufacturing – Electric Powertrain	92,000

6.4.3 Cradle to Grave Impact of Batteries

A report, published by Transport & Environment, sought to summarize the various studies on the lifecycle impact of batteries on GHG emissions and human toxicity based on battery chemistry [175]. All aspects were considered, including raw material extraction, material and energy used for production of components and battery assembly, transportation, and end-of-life disposal. The energy mix utilized throughout the production lifecycle was considered in the results.

Table 20: Global warming potential of batteries by chemistry [175]

	$kgCO_2e$/kWh
GHGs from NMC:	160
GHGs from LFP:	161

The environmental impact of batteries based on capacity is assumed to be adequate for this evaluation, as the energy mix in Manitoba does not influences results. The impact based on lifetime energy throughput will be adjusted based on predicted energy/fuel consumption of buses operating in Winnipeg, and the dominance of hydroelectric power in Manitoba.

6.4.4 Cradle to Grave Impact of Fuel Cells

A report published by Energy Science & Engineering detailed a life cycle analysis of a simplified 1-kW PEM fuel cell [176]. The environmental impact of the manufacturing phase was broken down by Balance of Plant, PEM Stack, and electricity usage during production.

Table 21: Global Warming Potential of fuel cells and fuel cell stacks [176]

	$kgCO_2e$/kW
GHG from Balance of Plant	17.30
GHG from PEM stack	87.90
GHG from Electricity usage	7.04
Total GHG from 1 kW Fuel Cell	112.24

As with batteries, the environmental impact of fuel cells based on power is assumed to be adequate for this evaluation as the fuel cells are not built or assembled in Manitoba, and therefore Manitoba's clean energy does not influence results. The impact based on lifetime fuel consumption will be adjusted based on the predicted energy/fuel consumption of buses operating in Winnipeg, and various potential sources of hydrogen.

6.4.5 Emissions Impact of Using an Auxiliary Heater in Winter

Winnipeg currently requires 35 kW of combined heating on diesel buses. Supplying this amount of heat with an all-electric auxiliary heater has a significant impact on zero-emission bus range [49]. Based on the results of Winnipeg's battery-electric bus trial, a diesel auxiliary heater was deemed necessary to ensure adequate range in winter conditions [53]. New Flyer's Xcelsior ChargeH2 fuel cell buses have not been supplied with diesel auxiliary heaters, and instead utilize a 20 kW electric auxiliary heater combined with a heat exchanger which captures approximately 15 kW of waste heat from the fuel cell [54].

Winnipeg Transit battery-electric buses will include a Spheros/Valeo Thermo Plus 350, a 35 kW diesel auxiliary heater with a fuel consumption rating of 3.6L/hour, while fuel cell buses will include the Thermo DC 200, a 20 kW electric heater with a maximum consumption of 20 kWh/h [177] [178] [179].

Diesel auxiliary heaters only run seasonally when ambient temperature drops close to freezing. Based on data collected during the Winnipeg battery-electric bus demonstration, it has been estimated that diesel auxiliary heating consumes approximately 450L of diesel fuel annually. This translates into approximately 125 hours of operation. The actual operating time of the electric heater on an FC-BEB may be lower because of its use of a heat exchanger, but 125 hours of operation will be assumed as a worse case scenario.

Based on the following assumptions, annual emissions from both diesel and electric auxiliary heaters can be calculated:

Table 22: Emissions by auxiliary heater energy source

GHG produced by 2% biodiesel (B2)	0.002674173 tonnes	$CO2_e$/L [101]
GHG produced by hydroelectricity	0.0000185 tonnes	$CO2_e$/kWh [170]

Diesel auxiliary heater: 450*0.002671473 = 1.202 tonnes CO_2e/year
Electric auxiliary Heater: 125*20*0.0000185 = 0.04625 tonnes CO_2e/year

6.4.6 Life Cycle Analysis of Greenhouse Gas Emissions

The lifecycle emissions from zero-emission buses have been evaluated based on battery chemistry, battery capacity, fuel cell capacity, source of electricity, and source of hydrogen.

NMC and LFP are the only two battery chemistries currently being used by North American transit manufacturers. Capacities of 160 kWh, 450 kWh, and 660 kWh were considered for battery-electric buses, while only 100 kWh was considered for fuel cell battery-electric buses. The fuel cell was assumed to have an 85 kW capacity. Based on available warranties, the high-energy batteries from long-range buses (including fuel cell buses) were assumed to last 12 years, while the high-power batteries from rapid-charge buses and fuel cell stacks were both assumed to last six years.

While some variations in materials are likely, emissions produced during the manufacturing of the bus glider itself were assumed to be the same regardless of propulsion system. Variations between ICE and electric propulsion were considered.

As hydroelectricity is the predominate source of electricity in Manitoba, emissions from hydroelectricity were considered for both charging and on-site generation of hydrogen [170]. Five production methods of hydrogen were considered: Electrolysis, steam methane reforming (SMR) from compressed natural gas (CNG) without carbon capture and sequestration (CCS), SMR from CNG with CCS, SMR from renewable natural gas (RNG) with CCS, and by-product hydrogen from sodium chlorate production.

Emissions from hydrogen production were based on estimates from a recent hydrogen study from the province of BC, as well as reported efficiency from electrolyzer manufacturers [79] [94]. Delivery distance and tail pipe emissions were considered in the case of delivered fuel. To minimize the emissions impact of delivery, transport of fuel was assumed to be via CNG truck [180].

For comparison purposes, the total emissions from diesel and CNG were broken down into tailpipe emissions and emissions at the point of dispensing. This resulted in approximately 75% allocated to tail pipe emissions for diesel and 85% for CNG [101] [181].

Table 23: Assumptions of zero-emission bus performance for LCA

Lifetime mileage accumulated	1,060,000	km
Diesel fuel consumption	59.6992	L/100 km [180]
Battery-electric energy consumption:	1.303*	kWh/km [53]
Fuel cell battery-electric fuel consumption:	12.314**	km/kg [56] [177] [53]

*Average winter performance in Winnipeg January to March 2017.
**330mile range on hydrogen only; adjusted for HVAC load based on battery-electric bus demonstration. 528 km/36 kg*(1.094/1.303)

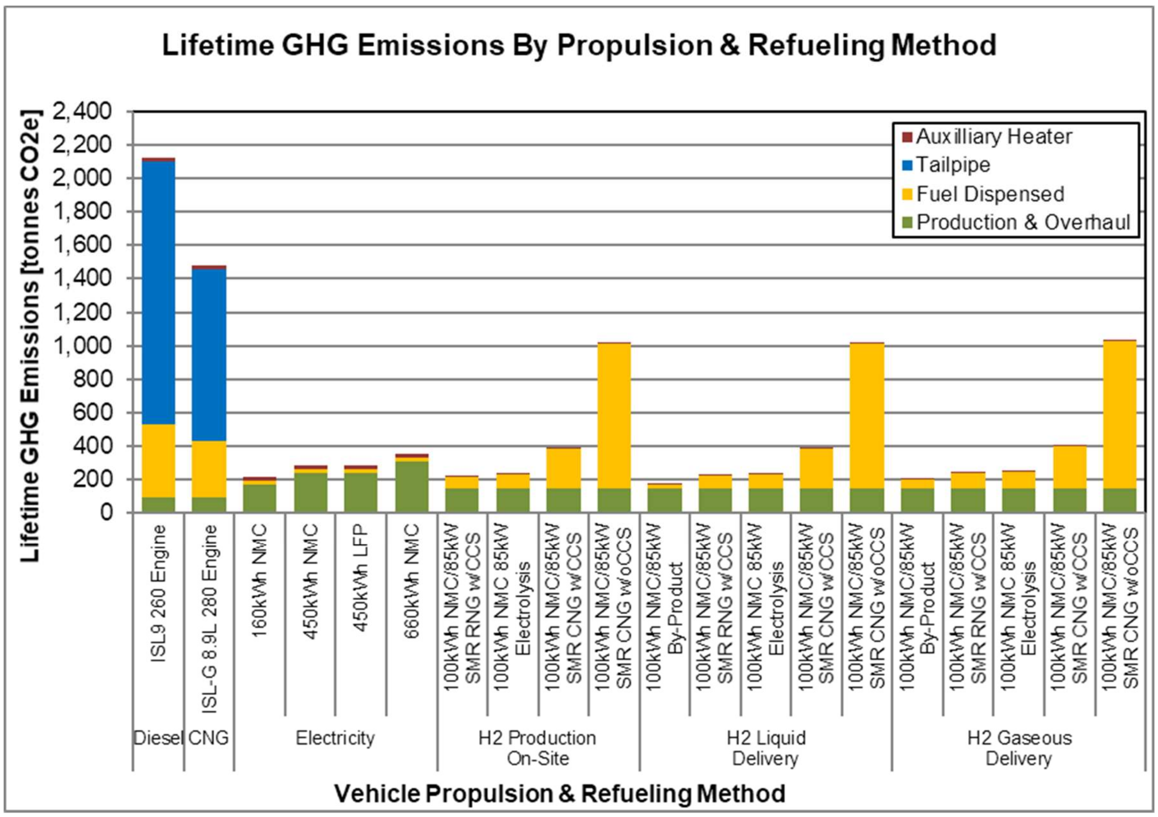


Figure 53: Summary of lifetime global warming potential of available bus models based on refueling strategy

In all cases regardless of technology or capacity, zero-emission buses generate significantly less GHGs than diesel buses over their lifetime. Even when non-renewable sources of hydrogen and delivery with GHG producing vehicles were considered, fuel cell battery-electric buses still produce 50% fewer lifetime GHG emissions than a diesel bus. While the use of diesel auxiliary heaters has a small impact on lifetime GHG emission for BEBs, GHG emissions generated during the production and disposal of batteries has the largest overall impact with this technology, with capacity and life both being factors. For FC-BEBs the hydrogen supply chain has the greatest impact on the lifecycle GHG emissions.

1. FC-BEB utilizing by-product hydrogen
    a. Liquid delivery of by-product hydrogen (92.61%)
    b. Gaseous delivery of by-product hydrogen (91.26%)
2. On-route rapid-charge BEB (90.68%)
3. FC-BEB utilizing SMR hydrogen from renewable natural gas with CCS:
    a. Production on site (90.33%)
    b. Liquid delivery (90.16%)
    c. Gaseous delivery (89.49%)
4. FC-BEB utilizing hydrogen from electrolysis:
    a. Produced on-site (89.80%)
    b. Liquid delivery (89.63%)
    c. Gaseous delivery (88.46%)
5. Long-range BEB – Mid Capacity (450-466 kWh):
    a. Nickel Manganese Cobalt Batteries (87.82%)
    b. Lithium Iron Phosphate Batteries (87.79%)

6.5 Evaluation of Secondary Toxicity Factors of Propulsion Systems

Toxicity factors are any non GHG related emissions that affect air, soil, and water quality and can negatively impact human life. Diesel production and combustion produces nitrous oxide and particulate matter which are the major contributing factors to air, soil, and water toxicity. Zero-emission buses generate no tailpipe emissions, and when powered by renewable electricity or green hydrogen, no additional emissions are created downstream during the operational phase of the buses. There are, however, sources of toxicity directly related to the extraction and processing of the raw materials used to create batteries and fuel cells [174] [183]. There are currently very few studies that consider secondary toxicity of batteries, and even fewer that consider secondary toxicity from fuel cells. Information around Human Toxicity is the most commonly reported.

Table 24: Assumptions regarding Human Toxicity Factors

High-energy Battery Life	12	Years
High-power Battery Life	6	Years
Fuel Cell Life	18	years
Fuel Cell Stack life	6	years
Human Toxicity from NMC:	482	Kg 1,4-DCBeq/kWh [175]
Human Toxicity from LFP:	260	Kg 1,4-DCBeq/kWh [175]
Human Toxicity from fuel cell system:	228	Kg 1,4-DCBeq/kW [176]
Human Toxicity from fuel cell stacks:	110	Kg 1,4-DCBeq/kW [176]
Total Toxicity from Diesel	4.2528	1,4-DCBeq/kg [181]

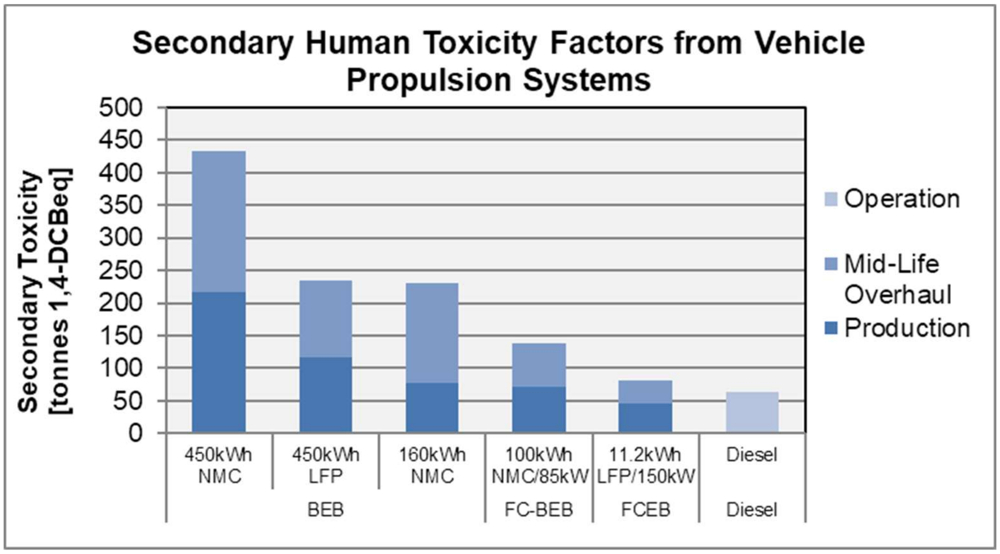


Figure 54: Summary of Human Toxicity of available zero-emission bus powertrains

When just propulsion systems are compared, zero-emission buses are much more harmful to the environment than diesel buses, even when just human toxicity is considered and other factors such as water and soil toxicity are ignored. Smelting activities associated with the extraction of cobalt, copper, nickel, and platinum are the largest contributing factors to human toxicity [175]. LFP batteries contain no cobalt or nickel and thus have lower overall toxicity levels than NMC batteries, but still much higher levels when compared to diesel fuel. Non-battery-dominant zero-emission technologies such as fuel cell-electric buses have significantly lower human toxicity due to their use of small capacity battery packs. While this technology is not being considered for reasons stated previously, it has been included here for the purpose of comparing the impact of batteries vs fuel cells. In Transit's application, both batteries and fuel cell stacks will likely need to be replaced before the bus reaches 1,060,000 km. This doubles the human toxicity impact of electric propulsion systems.

Beyond human toxicity factors, it should be noted that the production of platinum, used as the primary catalyst in PEM fuel cell as well as in catalytic converters for diesel engines, is known to produce high levels of water toxicity [176]. Manufacturers have been working to reduce the platinum content in fuel cells, and today's fuel cell contain over 75% less platinum than previous generations [154] [176]. Unlike the metals used in batteries, the platinum used in fuel cells is easily recycled. Increasing the quantity of recycled platinum used in fuel cell production will likely minimize the impact of secondary toxicity with this technology.

Local concerns regarding reducing global warming should be weighed against overall environmental concerns of zero-emission technology [182]. When looking at both GHG reduction and secondary toxicity together, fuel cell battery-electric buses potentially have the lowest overall environmental impact of all zero-emission buses.

7 COMPARISON OF ZERO-EMISSION BUS TECHNOLOGIES BY MANUFACTURER

All commercially available heavy-duty zero-emission battery buses manufactured in North America, have been compared against Transit's current fleet of New Flyer Xcelsior diesel buses, based on physical dimensions, weight, performance, noise, energy consumption, and safety.

7.1 Physical Dimensions

The American Public Transportation Association (APTA) periodically publishes an updated Standard Bus Procurement Guidelines, often referred to as APTA White Book. Manufacturers utilize this document as a technical specification for buses. White Book allows for variations, which means overall vehicle length, width, and height, differs from manufacturer to manufacturer. The dimensional specification for bus length allows for a range of -0/+4ft,11in, while width and height are both specified as a maximum.

7.1.1 Length

With the exception of Proterra's 40-foot buses, the length of both 60-foot and 40-foot zero-emission buses are similar to Transit's current fleet of New Flyer diesel buses. Proterra's 40-foot buses are nearly two feet longer than Transit's current 40-foot New Flyer buses.

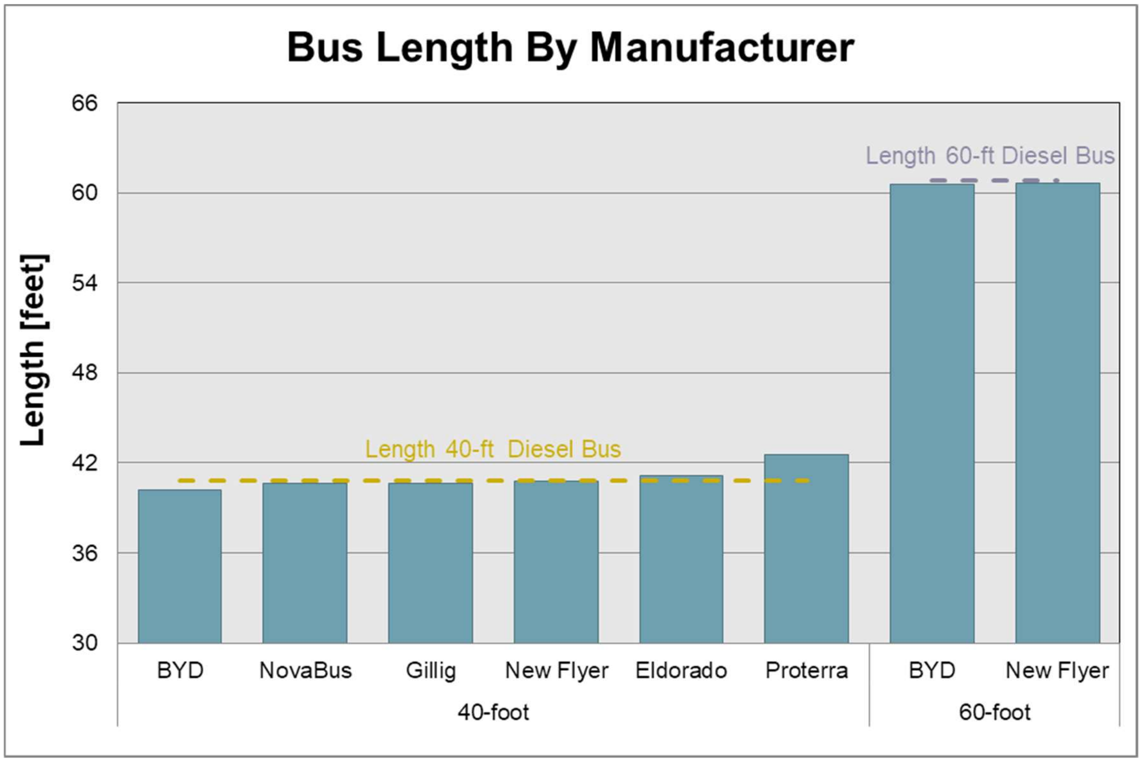


Figure 55: Bus length by manufacturer versus diesel buses.
Source: [13] [20] [50] [54] [55] [177] [180] [183] [184] [185] [186] [187] [188].

Brandon garage, the likely location for zero-emission bus storage, is currently designed to fit seventeen 40-foot buses equipped with bike racks, parked nose to tail, with a minimum of 1.00 meter between buses. Additional allowances for 1.50-meter walkways are located after buses 3, 6, 9, 12 and 15. This generally allows for four 30-foot buses, three 40-foot buses, or two 60-foot buses to be parked between each walkway.

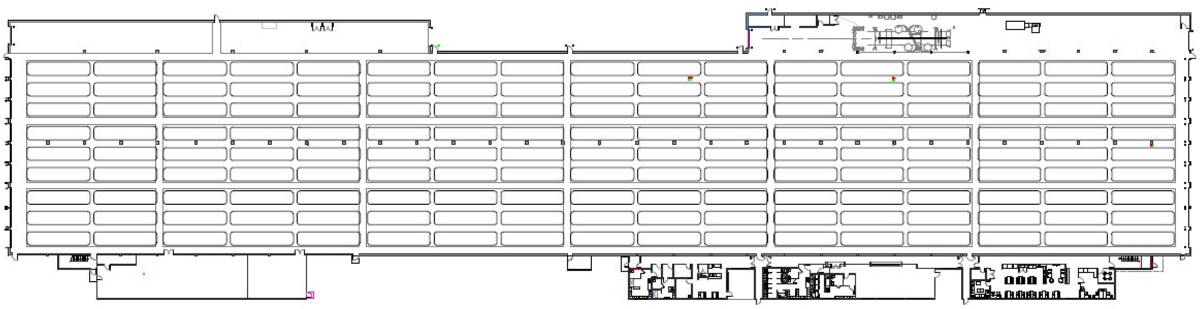


Figure 56: Overview of Brandon garage parking layout

While an equal number of Proterra buses could physically fit in the garage, at minimum Transit would need to reduce the spacing between buses and eliminate walkways to do so. It may not be either safe nor practical to do so, especially when battery-electric buses make up only a small percentage of the total fleet. Eliminating the front mounted bike rack could be another space saving option, but this does not align with the Winnipeg Transit Master Plan.

Based on the current building configuration, only 11 Proterra buses with bike racks could fit in each track at Brandon garage without impacting the 1.50-meter pathways, but 16 could be accommodated while maintaining the 1.00-meter spacing between buses. In a zero-emission bus test trial, a maximum of four Proterra buses per track could be intermixed without impacting garage capacity. If more than 36 Proterra buses ever needed to operate out of Brandon Garage, the capacity of this garage would need to be reduced, and buses would need to be relocated to a different garage.

7.1.2 Width

Upon review, width of a zero-emission bus was consistent across all manufacturers and with Transit's current diesel fleet. No garage configuration changes would be necessary to accommodate the width of zero-emission buses.

7.1.3 Height

Zero-emission buses are taller than diesel buses due to the addition of roof mounted propulsion equipment such as batteries, charge rails, hydrogen tanks, and power electronics. Proterra recently completed testing of their 5th generation battery-electric bus body. The new ZX5 body has similar length and width to the outgoing model, but a significantly reduced height.

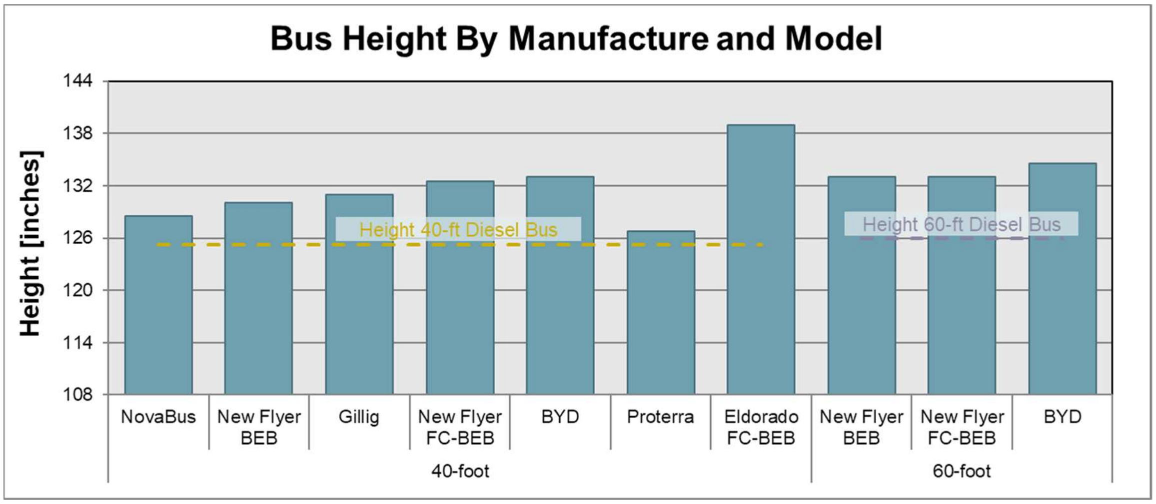


Figure 57: Bus height by manufacturer versus diesel buses.
Source: [13] [20] [50] [54] [55] [177] [180] [183] [184] [185] [186] [187] [188].

Current service requires that transit buses do not exceed 3.7 meters (12.1 ft / 145.7 in) in height, while transit garage restrictions such as access doors and bus wash racks further restrict bus height to 12.0 feet (144 in). Aging doors tend to sag, and sand and ice build-up in winter may further reduce clearance at maintenance and parking facilities as well as underpasses. Because of these potential restrictions, Winnipeg Transit's preference is to restrict maximum vehicle height to 11.5 feet (138 in). All zero-emission buses, with the exception of ENC's Fuel Cell battery-electric bus, would meet this requirement. If ENC FC-BEB buses were purchased, their service and operation would need to be restricted to specific runs and specific garages to avoid potential seasonal related clearance issues.

7.1.4 Front Overhang

There is no specification in the White Book regarding front overhang, and as such there is significant variation between manufacturers. OppCharge, which uses the front axle as a reference point for vehicle mounted charge rail positioning, was initially adopted in Europe and started to emerge as the preferred standard in North America. Variations in front overhang and door positioning relative to front axle location were seen as a roadblock to interoperability in North America, due to potential accessibility issues cause by roadside charging masts designed to work with one bus, blocking wheelchair ramp deployment on another. With the release of SAEJ3105-1 the reference point for positioning overhead charge rails has been specified to the centre of the front door. While this resolves issues relating to accessibility of on-route rapid-charge buses, it does not completely eliminate interoperability issues relating to overhead depot charging.

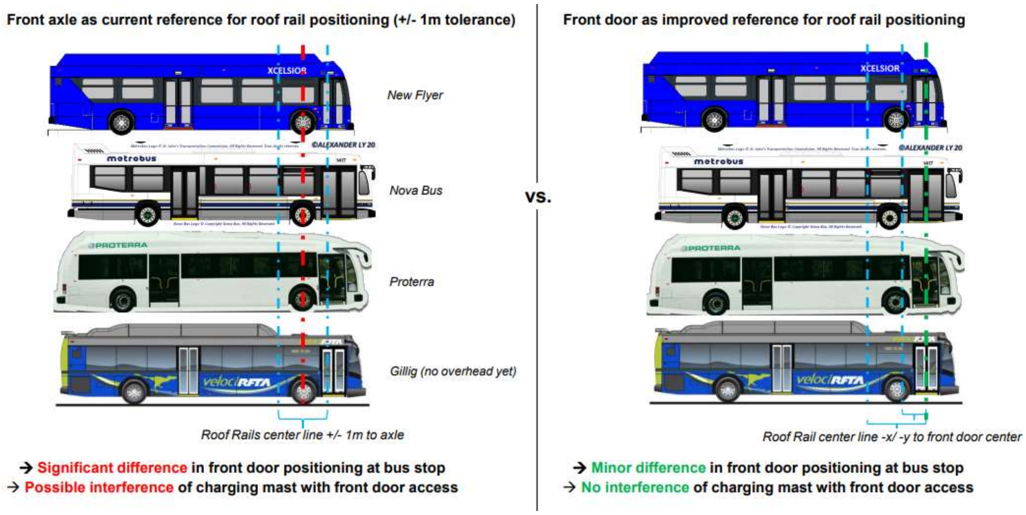


Figure 58: Release of SAE J3105/1 and its impact on improved interoperability. Source [189]

If Transit opts to install overhead depot charging, spacing between buses could become critical as rail positions could move buses forward or rearward in the allocated bus slot depending on manufacturer or model. Transit should consider increasing spacing around garage doors and walkways in future garage designs to allow for future manufacturer make or model variations.

7.2 Weight

Weight results from Federal Transit Administration (FTA) Altoona testing were compiled and converted to kilograms for comparison. In all cases zero-emission buses are heavier than the diesel buses they would potentially replace.

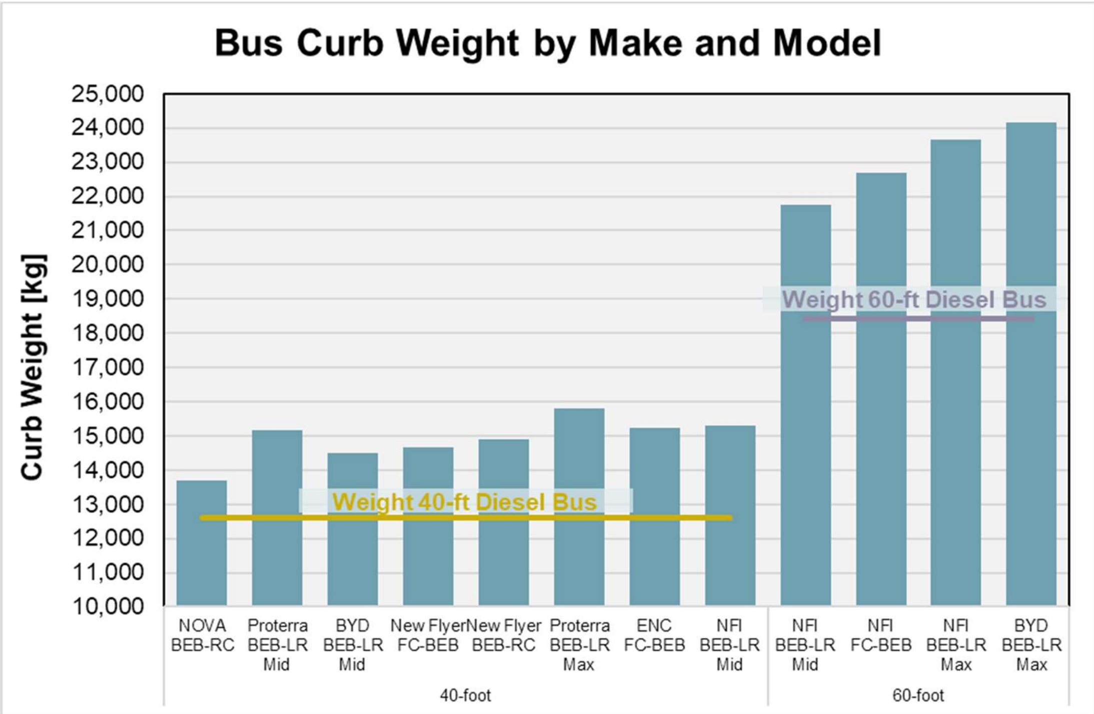


Figure 59: Bus curb weight by bus make and model compared to diesel.
Source: [13] [20] [50] [54] [55] [177] [180] [183] [184] [185] [186] [187] [188].

Provincial regulations set limits for axle weights of commercial vehicles, including transit buses at 7,300 kg and 9,100 kg, for the front steering axle and dual-tire single rear axle respectively [190]. Beyond axle weight restrictions, transit buses must comply with various federal and municipal regulations, policies, and programs relating to safety, accessibility, vehicle service life, and emissions among other things, many of which result in additional weight [191]. Because items such as wheelchair lifts and pollution filtering systems have been deemed critical, Transit has been permitted to operate its current fleet of diesel buses within the City of Winnipeg with an overweight permit.

Adding zero-emission propulsion systems further increases both curb weight (CW) and axle loading. Many items such as batteries, motor inverters, inductors, and other power electronics, directly increase vehicle weight, while others such as electric drive motors, a fuel cell, and hydrogen tanks offset items such as an engine, clutch, gearbox, fuel tanks, etc. While all buses tested at Altoona were significantly heavier than Transit's current fleet of diesel buses, 60-foot buses saw the largest increase. All three 60-foot ZEBs tested included interior batteries to maximize on-board energy. New Flyer has since stopped offering interior batteries on their battery-electric buses, limiting their capacity to just 466 kW on their long-range buses, and 320 kWh on their rapid-charge buses, and trimming off 1,245 kg of weight. Their fuel cell battery-electric buses have not been redesigned and still include interior batteries.

Increasing battery capacity to extend range directly impacts bus weight. On-route rapid-charge BEBs with small capacity batteries are the lightest option. Fuel-cell battery-electric buses are generally lighter than long-range BEBs, but not lighter than rapid-charge BEBs. Weight of long-range BEBs vary greatly by manufacturer. Proterra is the only manufacturer to utilize a composite structure. This significantly lowers their curb weight, making their mid-capacity long-range bus the lightest long-range BEB option and even lighter than the lightest FC-BEB. Even with maximum battery capacity, a Proterra bus is lighter than the mid-capacity buses from other manufacturers [192].

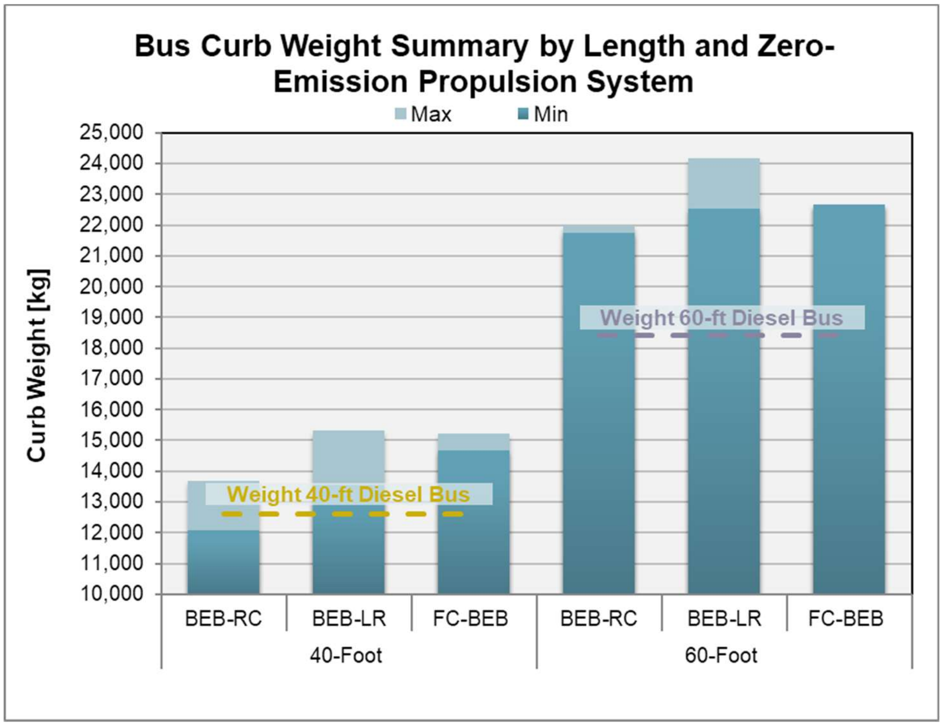


Figure 60: Summary of bus curb weight by bus type versus diesel buses

While overall zero-emission vehicles are expected require less maintenance than diesel buses, one area of concern is the impact of bus weight on structural wear and tear. Mounting heavy equipment not traditionally associated with diesel buses onto the same structure induces additional stresses onto the bus frame, which may result in increased body work over the life of the bus. Increased use of composite materials, including composite structures, may also affect maintenance costs. While these materials are significantly lighter they are also more complicated to repair if damaged. Without proper training or equipment in-house, composite repair work may need to be outsourced.

While Altoona testing validates structural durability over quarter life, some manufactures complete additional third-party structural durability testing. Tire coupled 4 & 6 post road simulation, commonly referred to as shaker table testing, is the most common method used by bus manufacturers for full life structural validation. Requiring manufacturers to complete full-life validation testing may help to alleviate concerns over long-term durability of zero-emission buses.

7.2.1 Passenger Seated/Standee Capacity

Increased range often comes at the sacrifice of passenger capacity as batteries replace people. Weight ratings of axles and tires are often exceeded with zero-emission buses at less than full standee load, and the addition of interior batteries often eliminates seating positions.

Passenger capacity results from Federal Transit Administration (FTA) Altoona tests were compiled. Where applicable, manufacturers were contacted to obtain updated axle loading information based on currently available models.

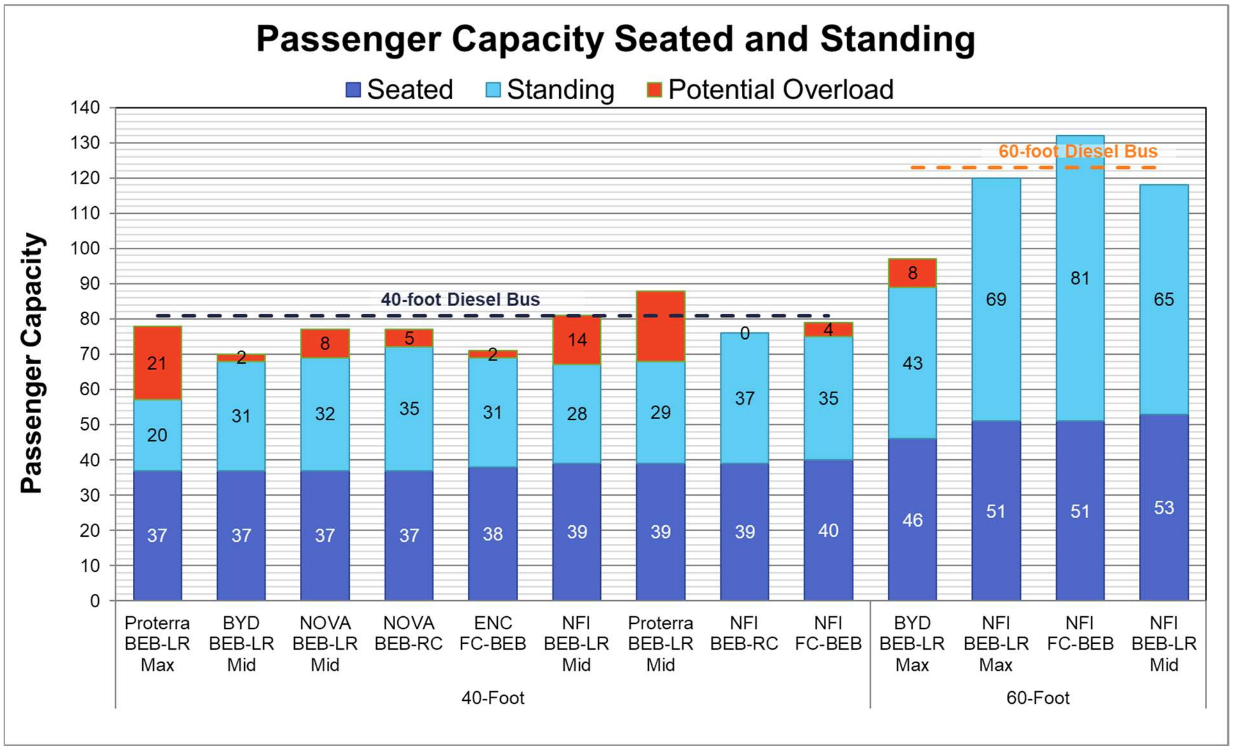


Figure 61: Passenger capacity seated and standing by manufacturer and propulsion type versus diesel. Source: [13] [20] [50] [54] [55] [177] [180] [183] [184] [185] [186] [187] [188].

Many of the buses tested at Altoona were first generation zero-emission buses. The models being sold today are significantly different than what was tested. Early generations of buses were mainly on-route charged with small battery capacities, while most manufactures are now focusing development on long-range BEBs. Most manufacturers have not re-tested their long-range 40-foot buses, but some have provided updated curb weight loading and axle weight ratings, based on their current product offerings. In the case of Proterra's recently re-tested ZX5 and ZX5Max buses, changes have not resulted in improvements to standee capacity.

Based on available floor space, nearly all zero-emission buses have some level of risk to overloading axles, tires or rims with a full standee load. Most manufacturers are aware of this issue and post a sign restricting standee capacity [188]. In reality there would be no effective way for drivers to restrict passenger capacity while the buses are in operation, so this does not resolve the issue, but rather passes liability onto the operator.

It can be reasonably assumed based on available curb weight data, that each 100 kWh increase to battery capacity above what was tested removes approximately 5 passengers from a bus [16]. This problem is not entirely restricted to 40-foot buses. While it should be noted that the 60-foot bus tested by BYD was a 5-door model with considerably less overall passenger capacity than Transit's current 3-door buses due to elimination of seats and reduced standee allowances around the entrances, this model is also at risk for axle overloading with maximum available battery capacity.

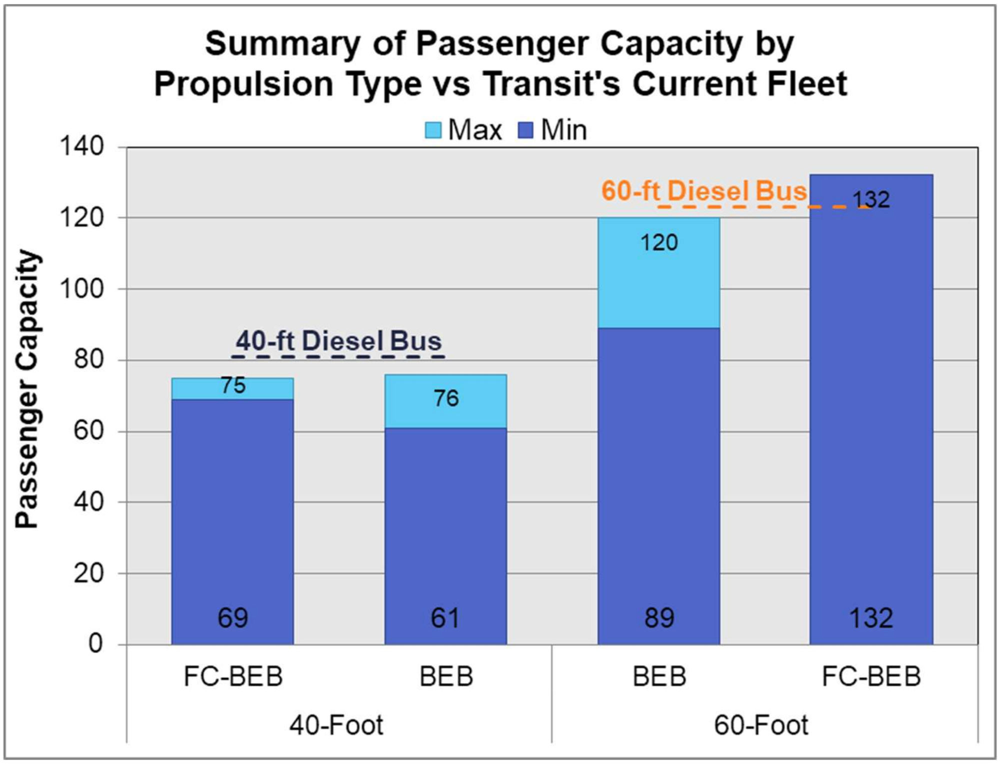


Figure 62: Summary of Passenger Capacity of ZEB compared to Transit's diesel fleet

It is unlikely that Transit will be able to directly replace the capacity of a 40-foot diesel bus with a 40-foot zero-emission bus on a 1:1 basis, without increasing the risk of overloading axles with a full standee passenger load. Options for 60-foot zero-emission buses with similar passenger capacity to diesel buses are available, but careful review will be necessary to ensure weight data accurately reflects the model being advertised. Transit should be conscience of single axle loading and not just the Gross Vehicle Weight Rating (GVWR) of the vehicle when comparing models, as both can impact passenger capacity. Any models that restrict standees are at risk for overloading.

7.2.2 Weight Induced Road Damage

Beyond the impact to the buses and bus service, increased weight induced road damage is one potential side effect of transitioning to zero-emission buses.

Equivalent Single Axle Load (ESAL) is a common method of comparing damage between different vehicles. A higher score indicates greater loading, and greater loading leads to greater pavement damage and more road and bridge maintenance [191]. It is typically used to calculate the cumulative damage of all vehicles operating on a roadway for the purpose of designing pavement.

While the actual formula for calculating ESAL can be cumbersome, it is generally simplified to the sum of axle load divided by a “standard load” to the power of four [193].

Generalized Fourth Power Law:

$$\text{ESAL} = \left(\frac{\text{front axel weight}}{18{,}000}\right)^4 + \left(\frac{\text{centre axle weight}}{18{,}000}\right)^4 + \left(\frac{\text{rear axle weight}}{18{,}000}\right)^4$$

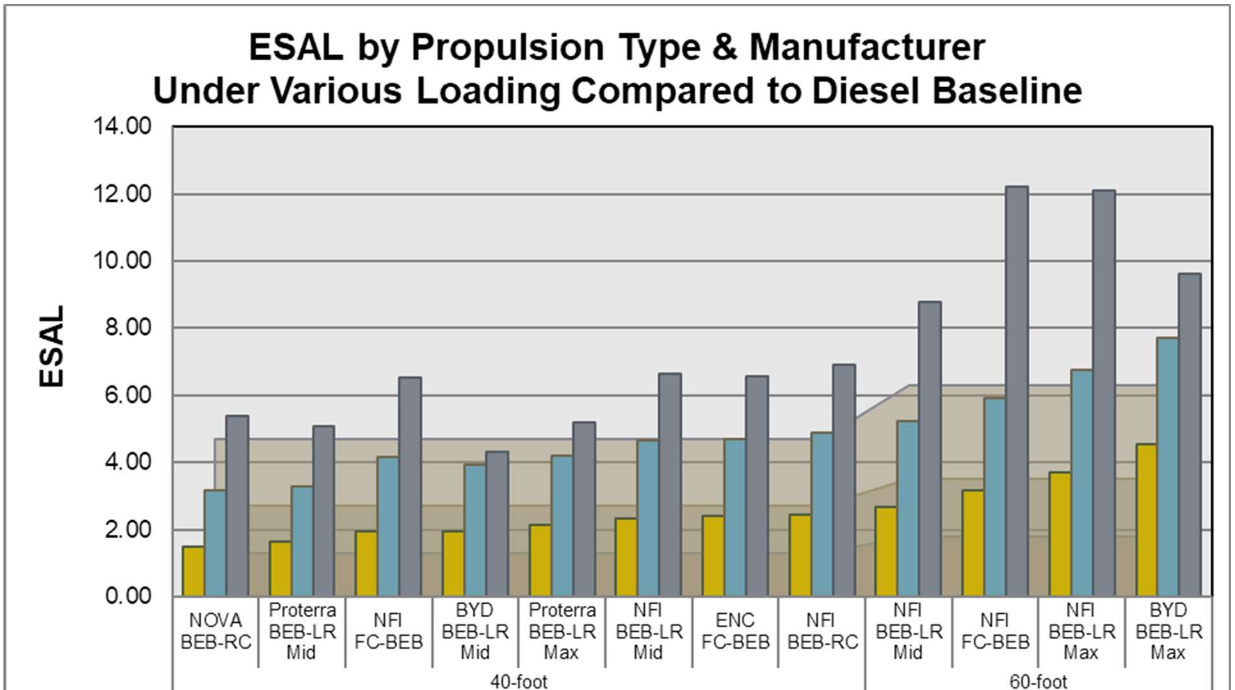
While buses typically only make up a small percentage of overall road usage, buses are known to be a significant contributor to pavement structural damage due to high single axle loads [193].

Winnipeg Transit’s diesel buses have an ESAL between 1.29 and 6.31 depending on length and passenger load.

While zero-emission buses are heavier than diesel buses, the impact of weight increase due to electrification varies between manufacturers mainly due to how battery weight is distributed.

Designs that shift weight to the front axle result in a lower ESAL and will likely induce less road damage, but they also tend to have lower passenger capacity. Reported numbers for damage at full passenger capacity (i.e. GVWR) may not be reliable as they do not consider over capacity passenger loads. This artificially makes models with larger passenger capacity appear worse than those that restrict standees. As most manufactures offer a similar number of seating positions, ESAL at seated load weight (SLW) is a better comparison.

All 60-foot ZEBs tested to date had interior batteries installed directly over the centre axle, resulting in two heavily loaded axles and significantly higher ESAL values when compared to their diesel counterparts with only one heavily loaded axle. Interior batteries are currently permitted; however, with safety concerns being raised by some transit agencies, the ability to provide interior batteries may be eliminated as heavy-duty electric vehicle standards evolve. New Flyer has stopped offering interior batteries on their 60-foot battery-electric buses. Based on the updated weight distribution they provided, this does translate into a lower ESAL and potentially reduced road and bridge damage, but at the loss of range.



	NOVA BEB-RC	Proterra BEB-LR Mid	NFI FC-BEB	BYD BEB-LR Mid	Proterra BEB-LR Max	NFI BEB-LR Mid	ENC FC-BEB	NFI BEB-RC	NFI BEB-LR Mid	NFI FC-BEB	NFI BEB-LR Max	BYD BEB-LR Max
	40-foot								60-foot			
Diesel CW	1.292	1.292	1.292	1.292	1.292	1.292	1.292	1.292	1.811	1.811	1.811	1.811
Diesel SLW	2.720	2.720	2.720	2.720	2.720	2.720	2.720	2.720	3.521	3.521	3.521	3.521
Diesel GVW	4.678	4.678	4.678	4.678	4.678	4.678	4.678	4.678	6.311	6.311	6.311	6.311
ESAL CW	1.492	1.628	1.953	1.954	2.145	2.318	2.396	2.440	2.672	3.183	3.691	4.536
ESAL SLW	3.160	3.295	4.143	3.943	4.202	4.639	4.710	4.902	5.225	5.925	6.737	7.708
ESAL GVW	5.376	5.092	6.520	4.321	5.203	6.656	6.561	6.903	8.785	12.207	12.107	9.633

Figure 63: ESAL by manufacturer and propulsion type under various loading conditions Source: [13] [20] [50] [54] [55] [177] [180] [183] [184] [185] [186] [187] [188].

While a higher ESAL would potentially result in more road and bridge damage, it is not necessarily a 1:1 increase in total cumulative damage. When evaluating the lifetime impact of ESAL damage, frequency of use is also considered. Buses operate at relatively low frequency compared most other vehicles on shared roadways, therefore even though the damage from a bus is relatively high, the low number of load cycles results in the buses inflicting much less total damage than other types of vehicles.

Two studies from the University of Manitoba have reviewed former Transit route 162, an express route with high density traffic, to quantify the impact of bus weight on road damage using ESAL [194] [195]. The damage contribution by type of vehicle operated on the shared roadway was broken down as follows:

- Approximately 95.88% of overall damage is caused by freight vehicles;
- Approximately 3.85% of overall damage is caused by transit buses; and
- Approximately 0.27% of overall damage is caused by light-duty passenger vehicles.

The ratio of incremental impact to pavement from transitioning from diesel buses to heavier ZEBs would therefore be:

$$\frac{[ESAL_{ZEB} + ESAL_{Freight} + ESAL_{LightDuty}]}{[ESAL_{DieselBus} + ESAL_{Freight} + ESAL_{LightDuty}]}$$

Even in a worst-case scenario where $ESAL_{ZEB}$ is double that of $ESAL_{DieselBus}$, the incremental increase to road damage may only result in a 3.69% increase in road maintenance on shared roadways.

On dedicated transit corridors, doubling of lifetime damage would directly multiply the cost of building and maintaining roads; however, the lower frequency of travel may result in lower overall damage when compared to a shared roadway.

Assuming a maximum frequency of 1,080 buses per week on the transitway (180 weekdays, 90 weekends), with an average $ESAL_{ZEB}$ of 7.5, the resulting 25-year cumulative road damage from a zero-emission articulated bus would be around 10.5 million ESALs. A 2015 preliminary design report released by the City's Public Works Department regarding a roundabout at the intersection of Sturgeon Road, Murray Park Road and Silver Avenue, included ESAL estimates for these three multi-use roads ranging from 1.30 to 17.59 million ESALs based on a 25-year design life [196]. This would indicated that while the loading on a BRT transitway would be high, it would not be unusually high compared to other high volume multi-use roads within the City of Winnipeg.

Weight restrictions relating to bridges need to be considered in addition to pavement design life. The Public Works Department reviewed the design specifications of currently available heavy duty zero-emission buses and concluded that there is an approximate 5% increase in the maximum rear single axle weight from what has been allowed for existing buses in the City of Winnipeg. A maximum single rear axle load of 12,837 kg would likely be accepted. The new buses would require an annual permit to operate on any City street, with the exception of those with a posted weight restriction of 36.5 Tonnes or less. If a proposed vehicle has a single axle load higher than 12,837 kg value then a tandem would be required. Consultation with the Public Work Department during the procurement process will be required to confirm any proposed zero-emission buses are in compliance.

Transit will need to work closely with the City of Winnipeg Public Works Department to ensure that the weights of zero-emissions buses, especially 60-foot buses, are considered when designing and estimating the lifecycle cost of new transit ways.

While it is likely that weight reductions will occur as zero-emission technology matures, Winnipeg Transit should consider specifying light weight options for non-propulsion specific items, such as aluminum rims, seating, flooring, and windows, to offset the impact of additional propulsion system weight.

7.3 Performance

Acceleration, gradeability, top speed, and braking are the baseline performance criteria measured at Altoona. Results were compiled from Federal Transit Administration (FTA) reports.

It should be noted that performance parameters on test buses are typically optimized for fuel economy rather than performance, and may be configurable. Additionally, Altoona testing is a type test, not a model specific test, and as such performance data is not available for models of zero-emission buses currently being sold. The information presented may not accurately reflect the performance of current offerings.

The same New Flyer bus tested at Altoona was later operated in Winnipeg as part of the battery-electric bus demonstration project. It is not clear whether or not any performance parameters were adjusted following Altoona, but these buses had no reported performance issues during the 4-year demonstration at Winnipeg Transit. Because performance varies between manufacturers, it is highly recommended that any performance parameters deemed critical be validated by the manufacturer with a demonstration in Winnipeg, prior to purchase.

7.3.1 Top Speed

At the time of testing, all zero-emission buses, with the exception of BYD's 40-foot test bus, were capable of meeting a minimum top speed of 80 km/h [186]. Most manufacturers now advertise a top speed of at least 100 km/h for 40-foot buses, and 90 km/h for 60-foot buses [12] [16] [13]. As Winnipeg Transit buses are top speed governed to 90 km/h, zero-emission buses are capable of matching the top speed performance of diesel buses.

7.3.2 Acceleration

Generally speaking, zero-emission buses are capable of high acceleration rates due to the availability of instant torque from electric motors. Rapid acceleration produces high amounts of gravitational-force which will affect rider experience and potentially impact rider safety. Like top speed, acceleration rates can be adjusted based on operator specifications. As a typical transit bus in Winnipeg operates at speeds below 60 km/h, acceleration time from 0 to 64 km/h (40 mph) will be used for comparison. Transit currently specifies a maximum time of 30 seconds for 0-64 km/h acceleration in their diesel bus specification.

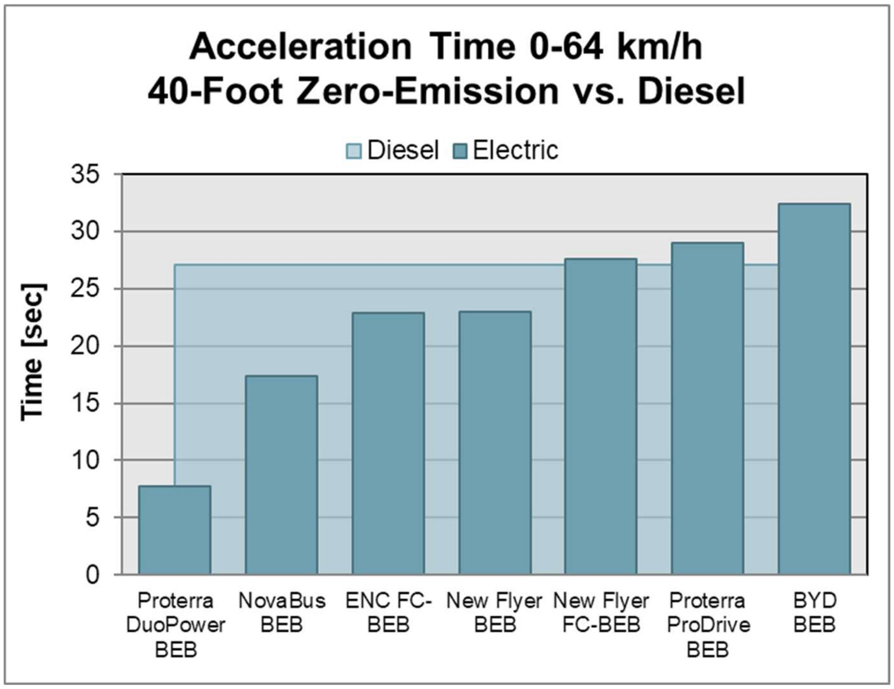


Figure 64: Acceleration time 0-64 km/h of 40-Foot electric versus diesel bus Source: [50] [54] [177] [180] [185] [186] [187] [188].

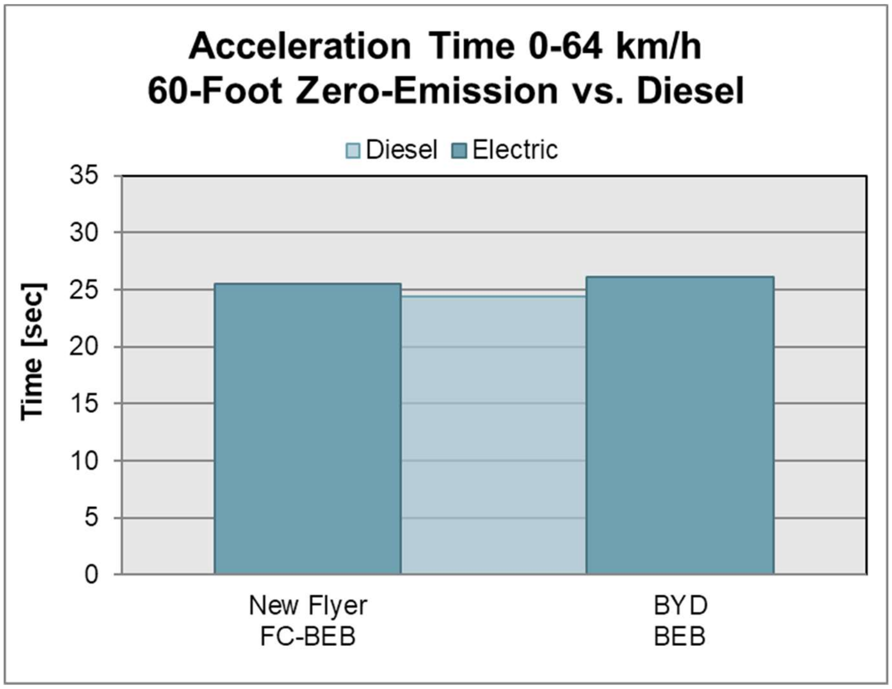


Figure 65: Acceleration time 0-64 km/h of 60-Foot electric versus diesel bus Source: [20] [55] [183] [184].

The 40-foot bus originally tested by BYD included 2x90 kW in-wheel motors, and was the only bus not capable of meeting the 30 second threshold. BYD's heavier 60-foot bus more recently completed testing using their now standard 2x150 kW in-wheel motors, and accelerated 0-64 km/h in 25.05 seconds [20] [12]. Equipped with these same motors, it is likely that their 40-foot model would now also meet this requirement. With this improvement, zero-emission buses from all manufacturers are now capable of matching the acceleration performance of diesel buses.

7.3.3 **Gradeability**

The FTA estimates gradeability based on acceleration times at seated load weight. Buses that are acceleration limited may perform better on grades than estimated.

The steepest on-road grade in Winnipeg is the Arlington Bridge at 7.1%, which is well below the gradeability limitations of a zero-emission bus [197]. While Transit does not currently operate on this bridge due to weight restrictions, 7.1% will be used for comparison purposes as a worst-case scenario for comparing zero-emission bus gradeability performance in Winnipeg.

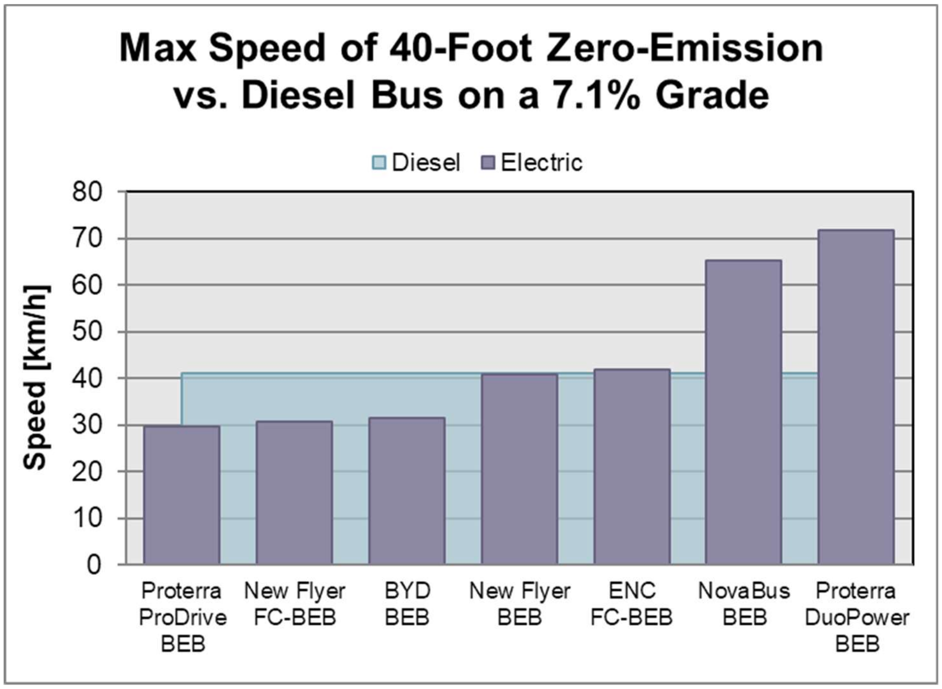


Figure 66: Max Speed on 7.1% Grade 40-Foot electric versus diesel bus. Source: [50] [54] [177] [180] [185] [186] [187] [188].

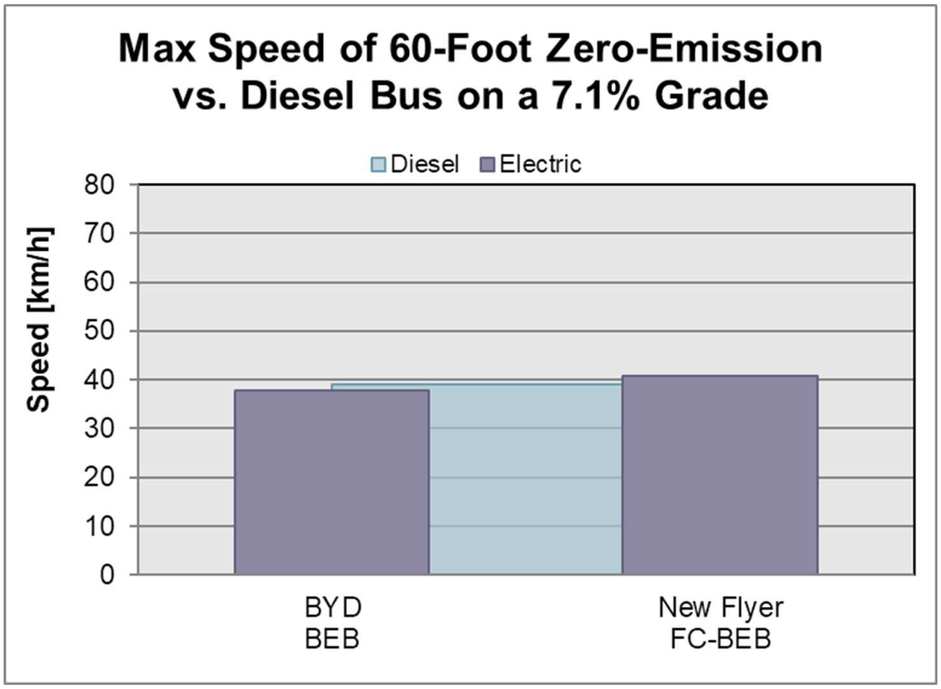


Figure 67: Max Speed on 7.1% Grade 60-Foot electric versus diesel bus. Source: [20] [55] [183] [184].

As predicted the buses with slower acceleration times have lower predicted speeds on grade. New Flyer's BEB and FC-BEB were tested with the same motor at approximately the same weight, so presumably the two vehicles should have had similar performance on grade. However, the slower acceleration times of the FC-BEB results in lower predicted speed on grade. The difference in gradeability should be contributed to tuning rather than technology limitations.

While early zero-emission buses struggled on hills, many manufacturers now offer high-gradeability packages which have resulted in significantly improved gradeability [16] [9] [12]. Cities known for steep hills such as San Francisco, Seattle, and Vancouver, have all recently purchased battery-electric buses which should give Transit increased confidence in zero-emission bus performance on Winnipeg's comparably flatter terrain. The buses tested by Nova Bus and Proterra both included high-gradeability motors, and are more representative of the current limitations of zero-emission bus propulsion systems.

It is generally recommended that if there is a route of concern within a city, a demonstration bus loaded with weight should be operated on that route to confirm performance rather than relying on predicted performance. It should be noted that high gradeability packages are generally offered as an upgrade over a standard motor at additional cost. While they do improve gradeability, they also use more power which translates into higher energy consumption and lower range.

7.3.4 Braking

As a typical transit bus in Winnipeg operates at speeds below 60 km/h, braking distance from 64 km/h (40 mph) under dry conditions will be used for comparison. Testing under wet conditions was only performed at 32 km/h (20 mph). Brake tests are completed at GVWR, so Transit should expect similar performance from all models of the same length offered by a given manufacturer.

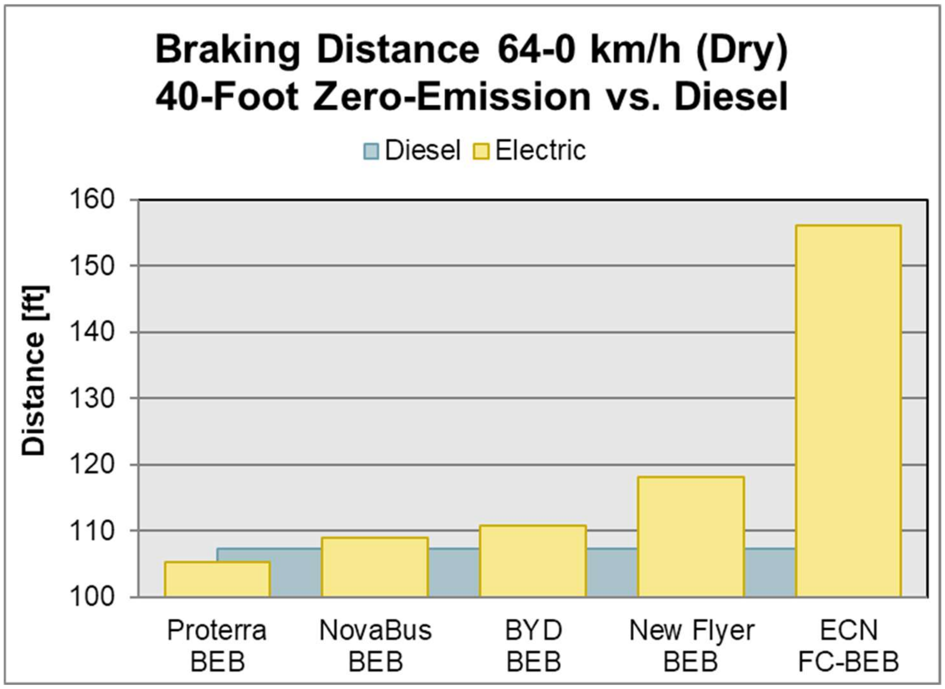


Figure 68: Braking distance from 64 km/h (Dry) 40-foot electric versus diesel bus. Source: [50] [54] [177] [180] [185] [186] [187] [188].

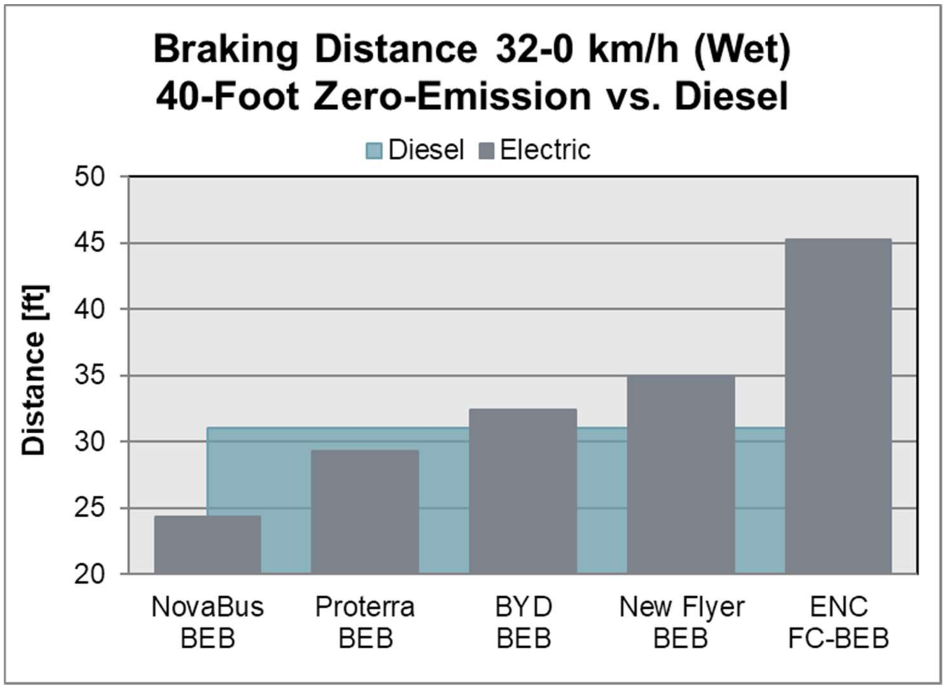


Figure 69: Braking distance from 32 km/h (Wet) 40-foot electric versus diesel bus Source: [50] [54] [177] [180] [185] [186] [187] [188].

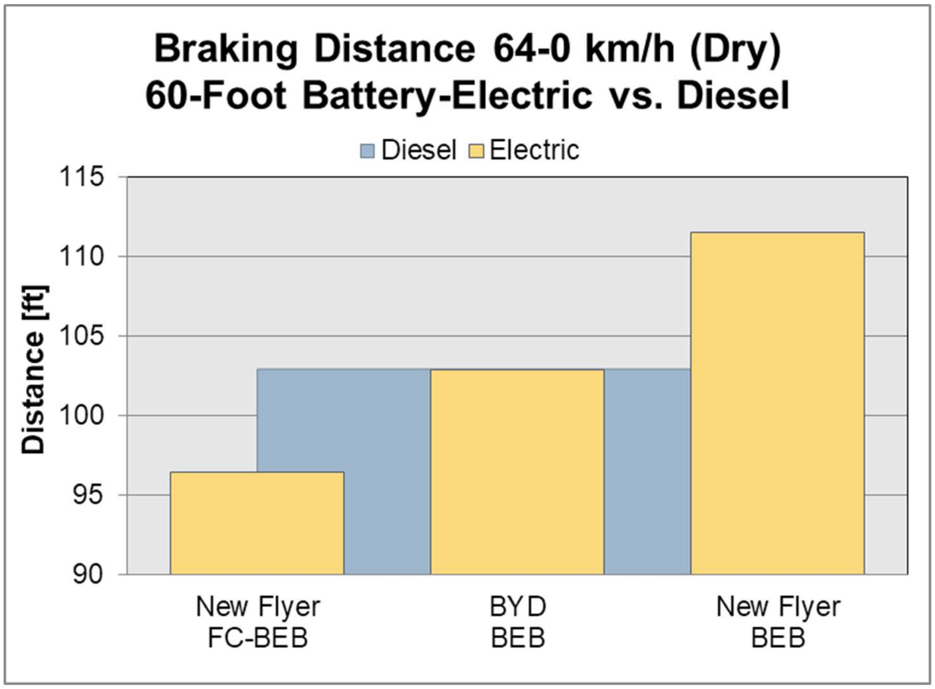


Figure 70: Braking distance from 64 km/h (Dry) 60-foot electric versus diesel bus. Source: [20] [55] [183] [184].

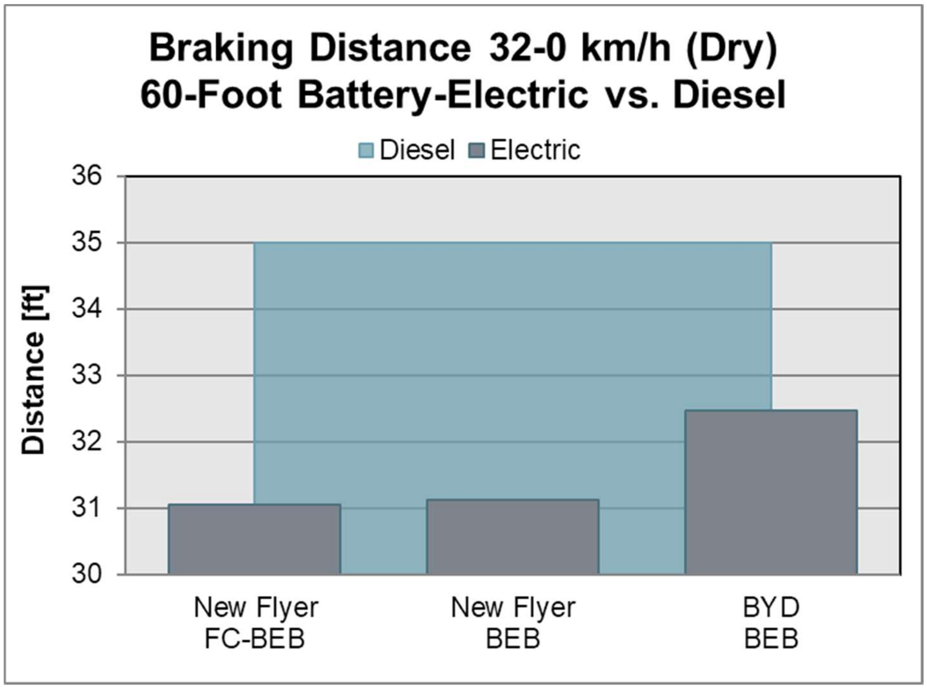


Figure 71: Braking distance from 32 km/h (Wet) 60-foot electric versus diesel bus
Source: [20] [55] [183] [184].

The older model Proterra and BYD test buses both had undersized front axles, which resulted in significantly lower maximum weight ratings than either of the New Flyer or Nova Bus test buses. Both manufacturers have since increased their capacity by 1,900 kg. Proterra has recently completed testing of their 5th generation platform which has substantially improved braking capacity over the outgoing model despite the additional weight being added [198]. It is unclear whether any other manufacturer has made similar changes to improve braking performance.

Braking performance varies widely and may be a result of programming as much as brake design. All New Flyer Xcelsior buses utilize the same physical brakes which should result in similar braking performance, yet stopping distance varies greatly between models despite only minor weight differences. Maximizing regenerative braking improves range and shortens stopping distance, but the high gravitational-force induced while braking will affect rider experience and potentially impact rider safety. It is possible for a test bus to utilize higher levels of regenerative braking during testing than may be acceptable to transit riders. Like top speed and acceleration, regenerative brake settings should be adjusted based on transit agency requirements. If regenerative braking settings are adjusted, braking distance may change as well.

7.3.5 Turning Radius

Turning radius is not tested at Altoona, but all buses are expected to be compliant with the APTA White Book design specifications. White Book allows for 40-foot buses to have a maximum turning radius of 44ft, and 60-foot buses to have a maximum turning radius of 44.5ft. Turning radius is reported by each manufacturer as follows:

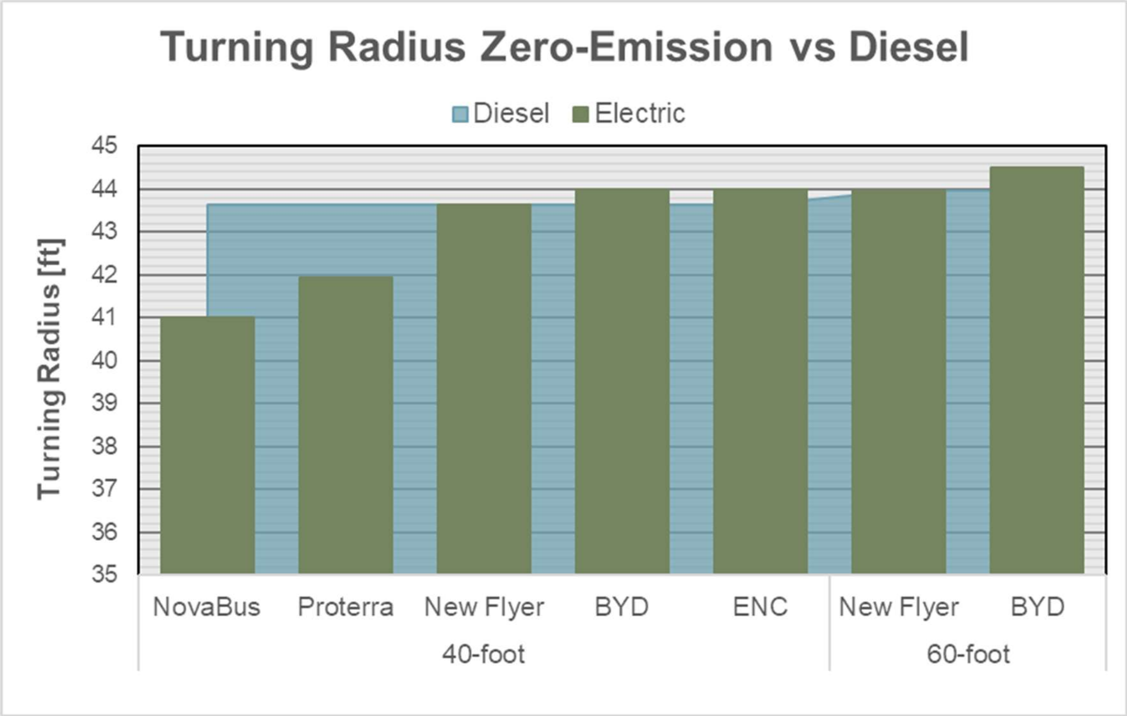


Figure 72: Turning radius of zero-emission buses vs. diesel.
Source: [11] [12] [13] [16] [199] [200].

All manufacturers are compliant to the current specifications and would have a similar turning radius to Transit's current diesel buses.

7.4 Noise

The FTA measures both interior and exterior vehicle noise. Results of testing were compiled and are presented below.

Vehicle design, insulation, window and door fitments, suspension, tires, and overall build quality, will all contribute to interior road noise. New Flyer's diesel buses are considered to be one of the quietest diesel buses on the market. Zero-emission bus models from manufacturers that offer multiple propulsion systems are generally quieter than their diesel models, but not all zero-emission buses will necessarily be quieter than Transit's current New Flyer diesel buses.

Proterra and BYD only produce only battery-electric buses, while ENC, New Flyer and Nova Bus produce buses with multiple zero-emission and non-zero-emission propulsion systems.

7.4.1 Interior Noise

Interior noise is measured in the operator area as well as in the passenger area. Measurements are taken while stationary and during acceleration events.

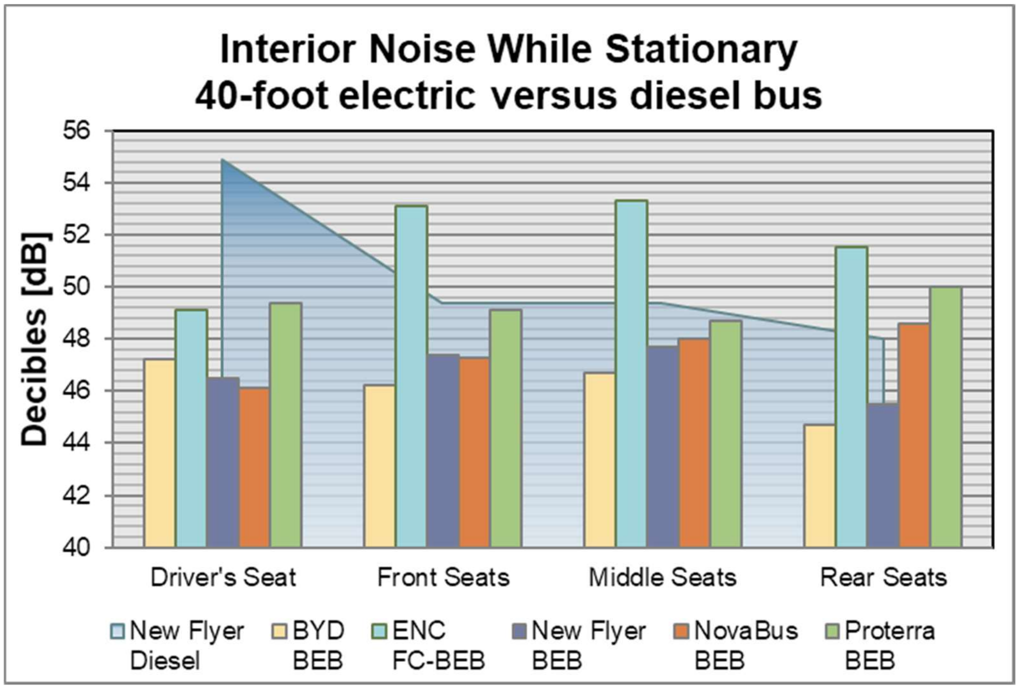


Figure 73: Interior noise while stationary 40-foot electric versus diesel bus. Source: [50] [54] [177] [180] [185] [186] [187] [188].

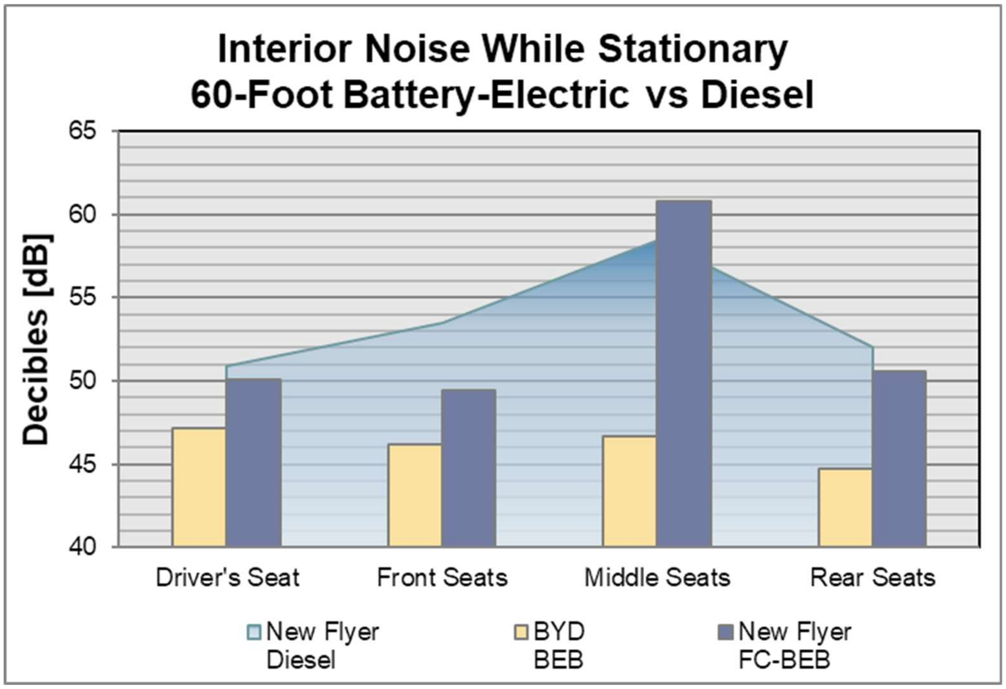


Figure 74: Interior noise while stationary 60-foot electric versus diesel bus. Source: [20] [55] [183] [184].

In general, zero-emission buses are signficantly quieter than diesel buses while stationary. The one notible exception seems to be high noise levels near the articulated joint of New Flyer's 60-foot fuel cell battery-electric bus. All New Flyer 60-foot zero-emission buses utilize a centre driven axle with in-wheel motors rather than a traditional axle. New Flyer has stated that they've increased vehicle insulation to reduce motor and axle noise on both their 40-foot and 60-foot buses, but revised numbers have not been published.

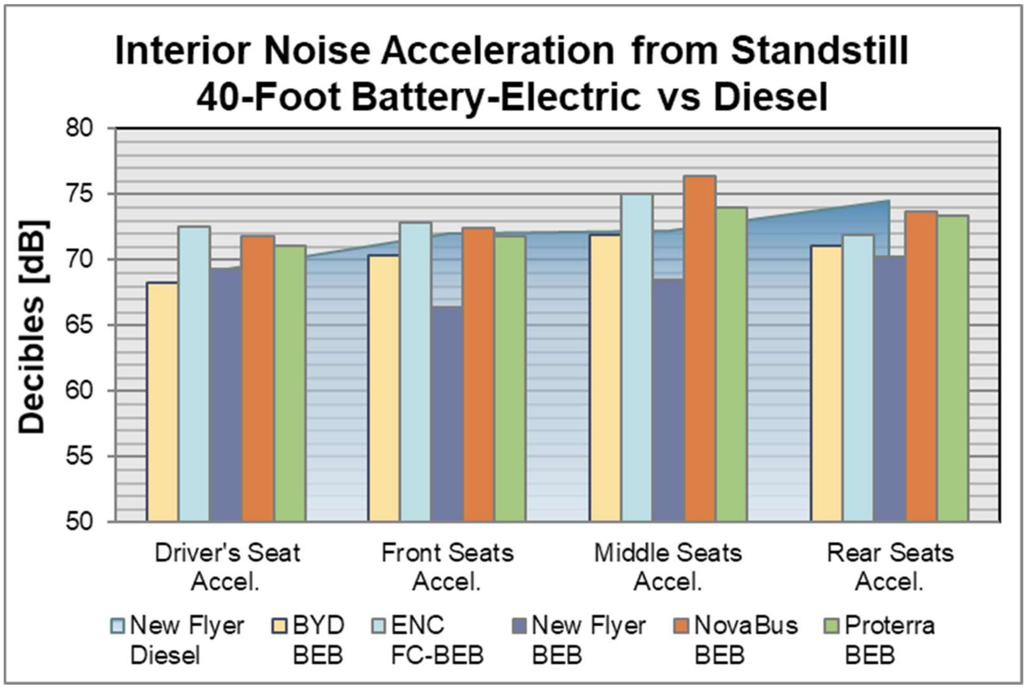


Figure 75: Interior noise acceleration from standstill 40-foot electric versus diesel bus

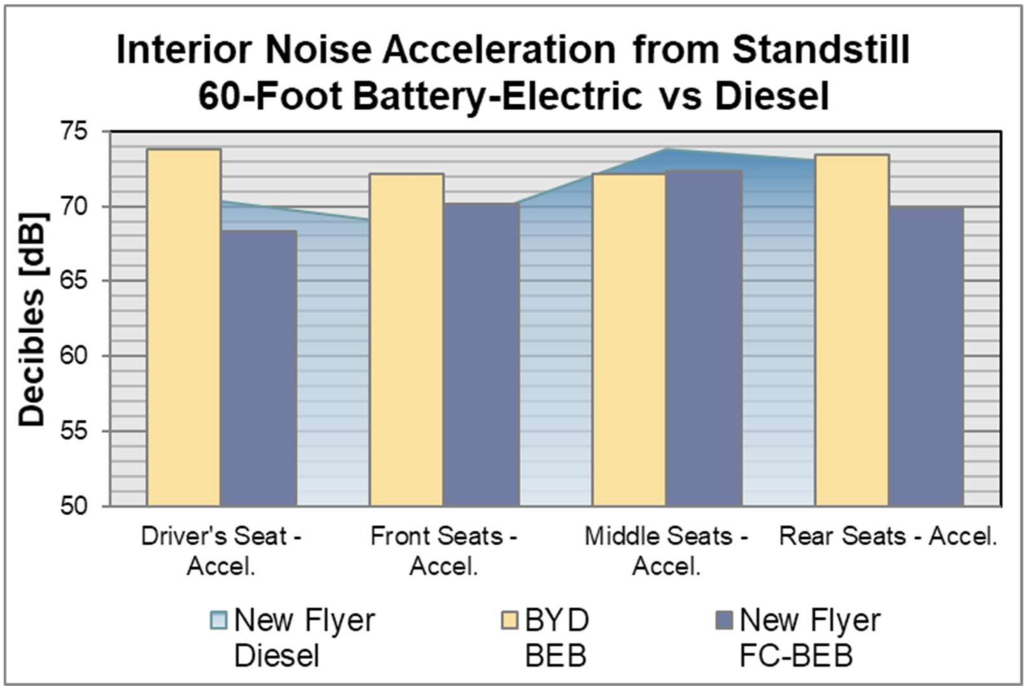


Figure 76: Interior noise acceleration from standstill 60-foot electric versus diesel bus

Interior noise levels vary from manufacturer to manufacturer. During acceleration events, most zero-emission buses have similar, or higher, noise levels when compared to Transit's current diesel buses. New Flyer zero-emission buses are notably quieter than those from other manufacturers. The centre axle motor noise from New Flyer's zero-emission 60-foot buses, noticeable while stationary, is actually quieter than the gear noise made by a traditional axel during acceleration.

7.4.2 Exterior Noise

Exterior noise is measured during a vehicle drive-by during acceleration at full throttle, from a speed above 56 km/h (35 mph) and from a standstill.

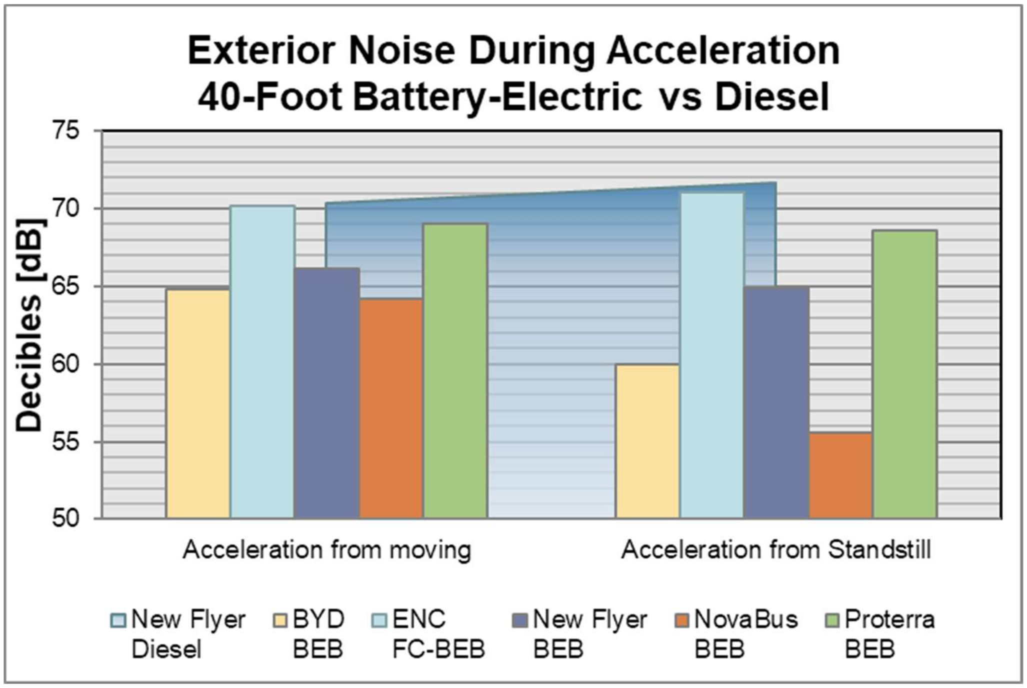


Figure 77: Exterior noise during acceleration 40-foot electric versus diesel bus

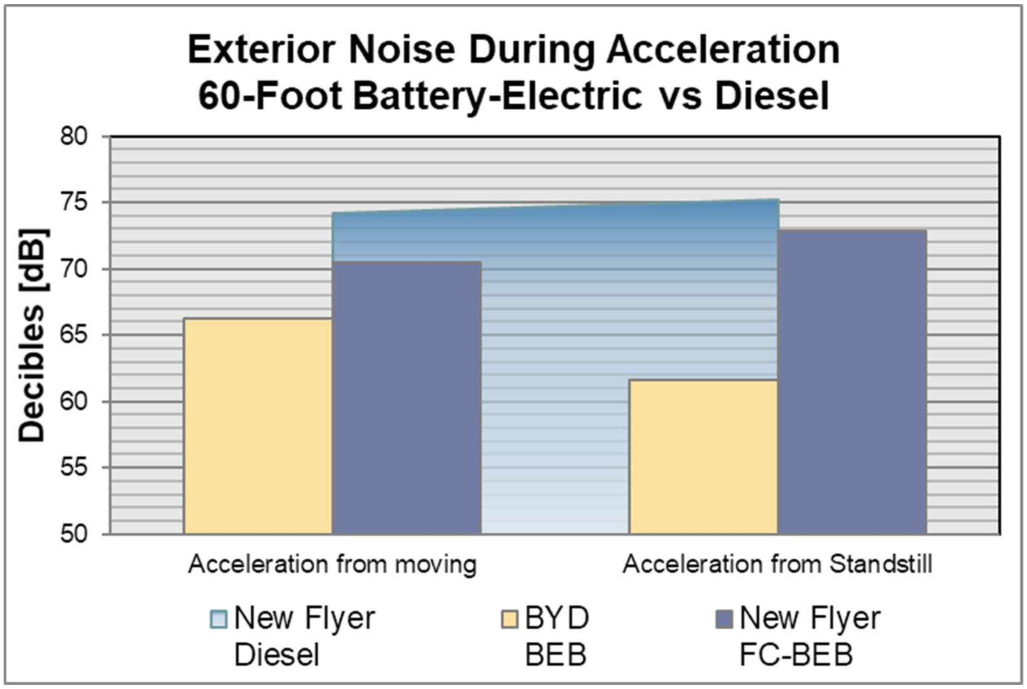


Figure 78: Exterior noise during acceleration 60-foot electric versus diesel bus

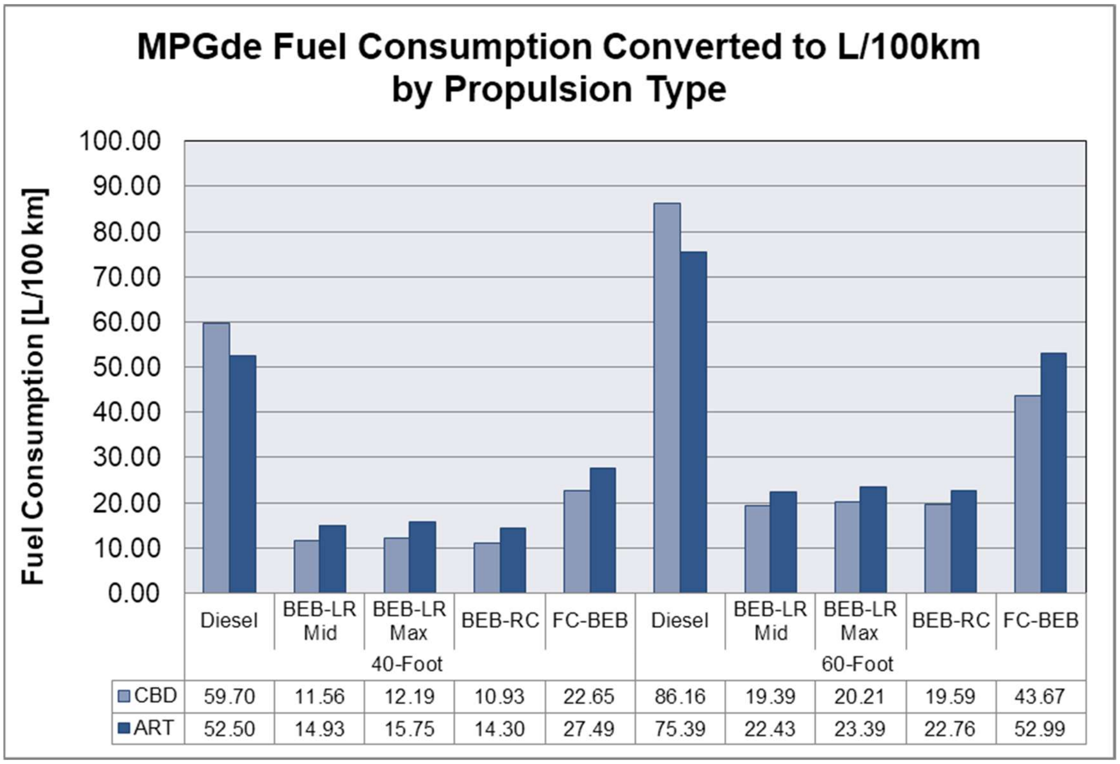
In all cases both 40-foot and 60-foot zero-emission buses project less exterior noise than Transit's current diesel buses. Exterior noise generated by zero-emission buses can be as much as 65% quieter.

Because zero-emission buses are so much quieter than diesel buses, concerns have been raised regarding the safety of visually impaired persons and vulnerable road users such as cyclists and pedestrians, and their ability to recognize an approaching bus. Transport Canada is currently reviewing the introduction of Canadian Motor Vehicle Safety Standard CMVSS 141 which would impose minimum noise requirements for hybrid and electric vehicles, similar to standards adopted by the United States and the United Nations. A decision on amending the Canadian safety regulations has been delayed pending a decision from the UN on the development of a Global Technical Requirement regarding quiet vehicles [201]. Current regulations are only applicable to light-duty vehicles under 4,536 kg, therefore the addition of audible alerts may not be mandatory for transit buses.

7.5 Energy/Fuel Consumption [L/100km equivalent]

Average energy/fuel consumption from results of Federal Transit Administration (FTA) testing were compiled and converted to litres per 100 kilometers for comparison.

Note: Results for 40-foot BEB-LR Max, FC-BEB, and 60-foot BEB-Mid are estimated as fuel economy testing at Altoona was completed using different duty cycles and different battery capacities. All buses were tested at seated load weight. Adjustments for weight were used based on an SAE estimate of a 5% increase in fuel economy for each 10% reduction in weight [202].



	Diesel	BEB-LR Mid	BEB-LR Max	BEB-RC	FC-BEB	Diesel	BEB-LR Mid	BEB-LR Max	BEB-RC	FC-BEB
	40-Foot					60-Foot				
CBD	59.70	11.56	12.19	10.93	22.65	86.16	19.39	20.21	19.59	43.67
ART	52.50	14.93	15.75	14.30	27.49	75.39	22.43	23.39	22.76	52.99

Figure 79: Summary of DGE fuel consumption and L/100km conversion by propulsion type. Source: [13] [20] [50] [54] [55] [177] [180] [183] [184] [185] [186] [187] [188].

Under optimized conditions zero-emission buses are more efficient than diesel buses, with battery-electric buses being approximately four times more efficient and fuel cell battery-electric buses being approximately two times more efficient. Energy consumption of a zero-emission bus is more significantly impacted by external factors such as ambient temperature, road conditions, passenger load, driver training, and duty cycle than a diesel bus.

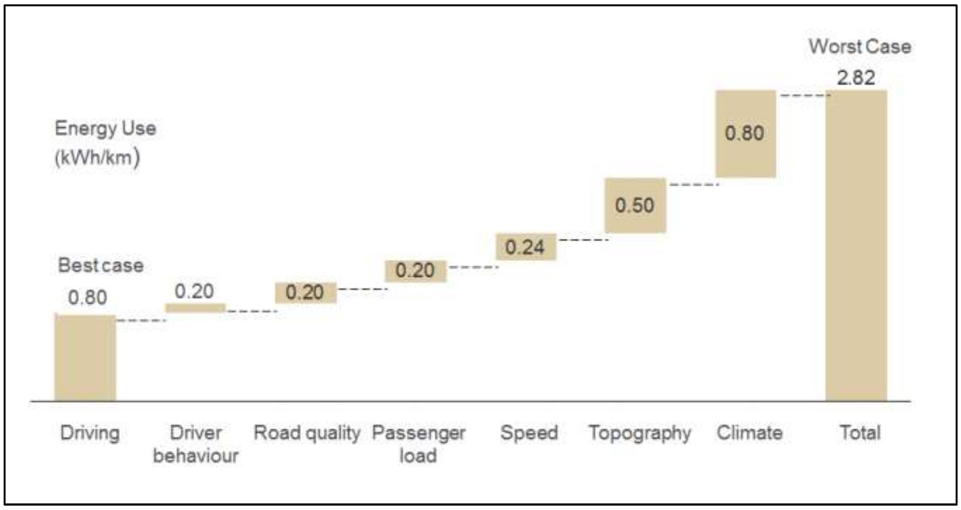


Figure 80: Energy consumption influences of zero-emission buses. Source: [203]

While a factor such as topography is likely to have minimal impact in a flat prairie city such as Winnipeg, seasonal variations in HVAC loads and road conditions will significantly influence energy consumption here. Training operators to utilize regenerative braking safely and effectively is the largest controllable factor to improve fuel economy.

Despite significantly larger battery capacity, energy consumption of a mid-capacity long-range bus is expected to be similar to the on-route charged buses previously tested by Transit [50] [177]. Energy consumption of a heavier maximum capacity long-range BEB is approximately 20% higher [188].

Winnipeg Transit collected a significant amount of energy consumption data while operating four buses on Route 20 over a period of 4-years. Route 20 is a fairly typical inner-city route with a similar duty cycle to Altoona's CBD duty cycle, which allows the data collected to serve as a good baseline for evaluating current technology.

7.5.1 Range

Energy consumption and energy storage capacity information were compiled from Federal Transit Administration (FTA) and real-life testing. CBD duty was used for comparison as this most closely resembles Transit's duty cycle. Results from these tests were assumed to be beginning-of-life (BOL) performance, while end-of-life (EOL) performance was calculated from BOL performance based on battery and fuel cell warranties; EOL performance is assumed to be 70% BOL performance for battery-electric and 75% BOL performance for fuel cell battery-electric. Diesel buses are assumed to have no less than 95% capacity at end of life.

Max Daily Range is a theoretical value calculated based on the number of drive/re-fueling cycles that could be completed in one week if Transit optimized zero-emission bus deployments based on End of Life range limitations.

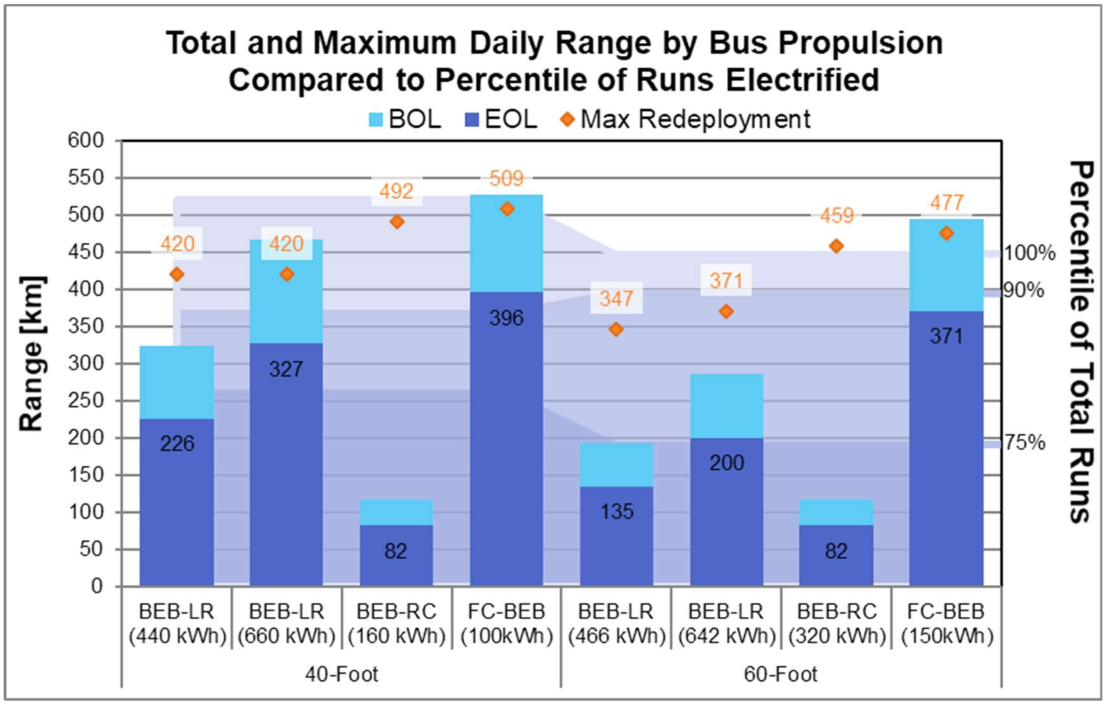


Figure 81: Estimated Range per drive cycle beginning and end of life no HVAC; Source: [13] [20] [50] [54] [55] [56] [177] [180] [183] [184] [185] [186] [187] [188] [204].

All technologies are capable of meeting the minimum daily range of 173 km for 30/40-foot buses and 138 km for 60-foot buses necessary to maintain weekly service levels at Winnipeg Transit. However, based on an expectation of 50,000 to 70,000 km/year and 90% availability, Transit buses would be required to travel between 152-213 km/day.

To make up for range deficiency, buses could be fueled more than once per day. This adds complexity, but allows zero-emission buses to complete more single-day in-service mileage. All technologies, with the exception of fuel cell buses, would require some amount of mid-day refueling to meet this minimum range requirement, 365 days per year.

Because no technology matches the range of diesel buses, new zero-emission specific schedules will need to be developed considering their range limitations. Runs that exceed the single deployment range of zero-emission buses would need to be split. More runs mean more annual fleet mileage and likely more buses and more operators.

Based on end-of-life range, the following percentage of current runs could be electrified based on a single daily deployment strategy:

Table 25: Percentage of 35-40-foot Transit runs that can be electrified based on single daily deployment by day of week

	Weekday	Saturday	Sunday	Total
FC-BEB	98.38%	82.95%	85.98%	94.63%
BEB – Rapid-charge*	99.73%	98.28%	98.13%	99.32%
BEB – Long-range Mid Capacity	80.22%	16.48%	32.71%	64.65%
BEB – Long-range Max Capacity	92.87%	55.68%	58.89%	83.11%

*On-route charging is considered a single deployment strategy. Assumes 100% charger availability and unlimited charge window. Actual range may be lower.

Table 26: Percentage of 60-foot Transit runs that can be electrified based on single daily deployment by day of week

	Weekday	Weekend	Total
FC-BEB	95.51%	23.07%	86.27%
BEB – Rapid-charge	100%	100%	100%
BEB – Long-range Mid Capacity	79.78%	0%	69.61%
BEB – Long-range Max Capacity	86.51%	0%	75.49%

*On-route charging is considered a single deployment strategy. Assumes 100% charger availability and unlimited charge window. Actual range may be lower.

On-route charged options such as rapid-charge battery-electric and fuel cell battery-electric buses are able to complete the largest percentage of runs without splitting. Long-range battery-electric buses, including those with maximum battery capacity, struggle with single deployment range particularly in 60-foot lengths.

Rather than splitting runs, initially it may make more sense to deploy zero-emission buses on shorter runs, while continuing to utilize diesel buses for longer runs. This strategy may not work for weekend deployments of 60-foot buses as all runs currently exceed the range of long-range BEBs, and only three can be operated with FC-BEBs. Even with the recent extension of the Southwest Transitway and the creation of the BLUE rapid transit line, there are still fewer than 24 weekend runs designed for 60-foot buses. Creating a few additional weekend runs to accommodate 60-foot zero-emission buses may be manageable.

While range restrictions may be manageable with a small test fleet size, they will become increasingly difficult to manage as diesel buses are phased out. Range and charging/refueling restrictions will need to be considered and designed into future schedules to avoid managing a fleet within a fleet during the transition from diesel to zero-emission.

7.5.2 Impact of HVAC Loads on Range

Running all-electric HVAC accessories runs down batteries and reduces range both in hot and cold ambient conditions, but larger HVAC heating loads result in a greater range reduction in winter. Winter road conditions, including snow and ice cover, limit the effectiveness of regenerative braking which in turn reduces the amount of energy returned while driving, and further reduces range [49].

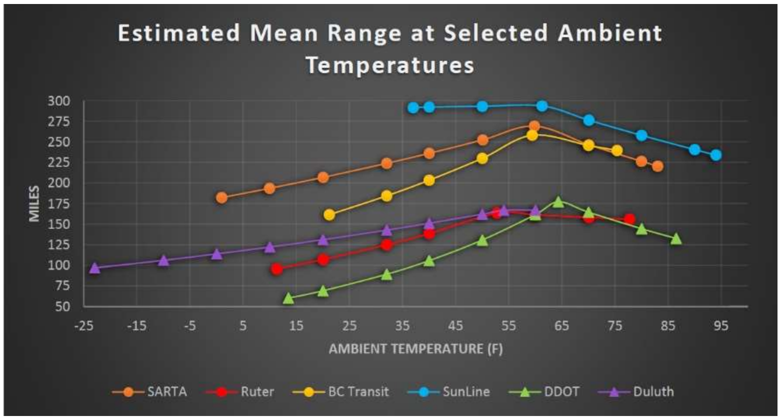


Figure 82: Estimated Mean Range of ZEB at select ambient temperatures. Source: [49]
***BEBs (Ruter, DDOT, Duluth); FC-BEB (Sunline); FCEB (SARTA, BC Transit)**

The range loss observed in Winnipeg during the battery-electric bus demonstration were slightly better in winter and worse in the summer than losses reported by other cities. There was no clear relationship between temperature and range in winter, but when the temperature was above freezing both heat and air conditioning impacted range.

Day	Temperature, [°C] climate.weather.gc.ca			Weather conditions climate.weather.gc.ca	Average Energy consumption	
	Average	Min	Max		kWh/km	kWh/mile
January 9, 2017	-19.7	-23.4	-15.5	Snow/Ice Crystals	1.3	2.09
January 10, 2017	-20.3	-18.3	-16.1	Snow/Blowing Snow	1.39	2.24
January 13, 2017	-25.4	-32.1	-19.8	Blowing Snow	1.27	2.04
February 14, 2017	-11.7	-6.5	-1.6	Mainly Clear	1.31	2.11
February 16, 2017	-0.7	-3	2.1	Mostly Cloudy	1.26	2.03
March 20, 2017	1.5	-3.9	5	Clear	1.29	2.08
May 16, 2017	14.6	8.9	17	Cloudy/Rain Showers	1.27	2.04
July 3, 2017	20.8	14.3	25.2	Mainly Clear	1.10	1.77
July 28, 2017	25.6	15.8	28.8	Clear	1.43	2.30

Figure 83: Typical winter energy consumption in Winnipeg; Low -23.3°C, Average -19.6°C. Source: Adapted from [205]

Winnipeg Transit requires 35 kW of heat to maintain cabin temperatures in extreme cold outdoor temperatures and 10 kW of air conditioning to maintain cabin temperatures in extreme outdoor hot temperatures. For zero-emission buses, heating is supplied by either a diesel or electric auxiliary heater, while air conditioning is supplied by all-electric HVAC accessories. Batteries do not produce significant heat under normal operating conditions, while fuel cells produce enough heat to supplement at least 15 kW of heating.

During Winnipeg's battery-electric bus demonstration, a large diesel auxiliary heater was used in combination with a small electric auxiliary heater. Electric heat was only operated if the outside ambient temperatures were above freezing. If the electric heater was unable to maintain cabin temperature at the set point, or if the outside ambient temperature approached freezing, the diesel auxiliary heater would take over. The use of varying amounts of electric heat in warmer ambient conditions explains why range fluctuates only when temperatures are above freezing. If Transit had instead utilized only electric heating, energy consumption increases could have resulted in as much as 60% reduction in range on cold days.

New Flyer's FC-BEBs are equipped with a heat exchanger which captures waste heat from the fuel cell for cabin heating, reducing the load from the electric auxiliary heater. It is unlikely that the additional heat from the electric auxiliary heater would be necessary except on extremely cold days. This should result in only minimal, if any, range reduction when operating in moderate conditions. However, these buses utilize the same air conditioning systems as battery-electric buses, so range reductions when the average daily temperature exceeds 20°C should still be expected.

Fuel cell buses equipped with heat exchangers have only been operating in regular service in California, and as such there is insufficient cold weather data to definitively predict range loss at temperatures below freezing. The buses were tested in Winnipeg during winter, but not in normal service with doors opening and closing for passenger boarding.

The ENC fuel cell buses operated by SARTA were not designed to capture waste heat from the fuel cell, and were instead equipped with only a Seico 70 kW electric heater. As a result, they lost approximately 28% of their range at -23.3°C [185] [49]. Assuming at least 42% of losses could have been avoided based on capturing waste heat, the expected losses of a FC-BEB with a heat exchanger would have been around 16%, similar to the losses during the battery-electric bus demonstration. Some additional cold weather performance tuning may be required to optimize fuel cell battery-electric buses for operating in Winnipeg's extreme winter conditions.

60-foot zero-emission buses have only recently been introduced to North America, and there has been no data published publicly about their HVAC performance. Energy consumption in summer and winter is expected to be considerably higher than that of a 40-foot bus due to increased heat loss through the articulated joint. The use of diesel auxiliary heaters will likely minimize some energy consumption increases in winter, but higher passenger loads and changes to the frequency and duration of door openings may result in more significant increases on hot days. For the sake of comparison losses of 20% have been assumed. The seasonal performance of 60-foot buses and the impact to operating cost will need to be investigated further.

Transit planners must consider vehicle range limitations when developing schedules. To account for performance variations due to temperatures planners should assume a 16% range reduction for 40-foot buses, and a 20% range reduction for 60-foot buses, in addition to capacity fade and usable capacity considerations.

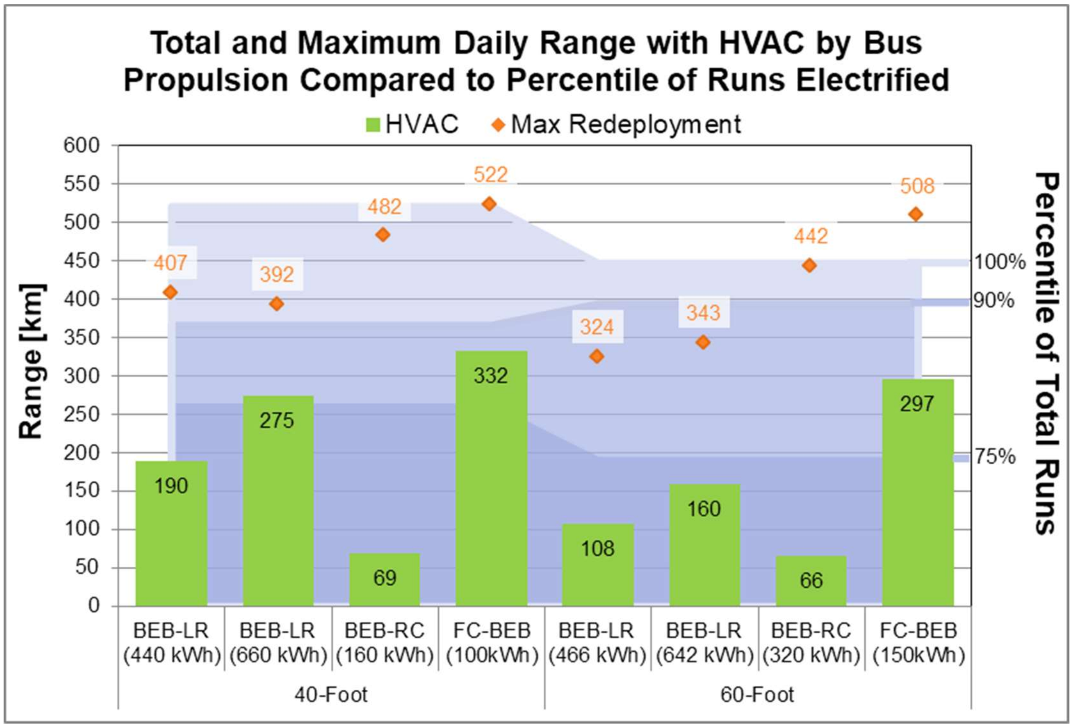


Figure 84: Estimated Range end of life with HVAC single deployment vs max daily

When range with HVAC is considered the number of runs that can be completed under a single deployment strategy decreases. Max redeployment range also decreases, but not as severely. In the case of fuel cell buses, maximum deployment range actually increases slightly.

Figure 85: Percentage of 35-40-foot Transit runs that can be electrified based on single daily deployment with max HVAC by day of week

	Weekday	Saturday	Sunday	Total
FC-BEB	93.54%	58.05%	58.88%	83.89%
BEB – Rapid-charge*	99.73%	97.13%	98.13%	99.12%
BEB – Long-range Mid Capacity	72.27%	8.09%	20.56%	56.05%
BEB – Long-range Max Capacity	88.69%	38.15%	44.86%	75.49%

*On-route charging is considered a single deployment strategy. Assumes 100% charger availability and unlimited charge window. Actual range will be lower.

Figure 86: Percentage of 60-foot Transit runs that can be electrified based on single daily deployment with max HVAC by day of week

	Weekday	Weekend	Total
FC-BEB	95.51%	23.07%	86.27%
BEB – Rapid-charge	100%	92.31%	99.02%
BEB – Long-range Mid Capacity	79.78%	0%	69.61%
BEB – Long-range Max Capacity	82.02%	0%	71.57%

*On-route charging is considered a single deployment strategy. Assumes 100% charger availability and unlimited charge window. Actual range will be lower.

Monitoring range with regards to seasonal temperature variations will be important for developing future schedules. Minimum range expectations during peak high and low temperatures in any given schedule will need to be considered. For zero-emission buses shortened range will mean adjusting run lengths, potentially increasing layover time for charging or dispatching more buses more frequently.

7.6 Safety by Design

The safety of buses is evaluated as part of the Altoona test. A Class 1: Physical Safety failure is any “failure that could directly lead to injury, a crash and/or physical damage” [177]. Prior to August 2016 it was possible to complete an Altoona testing and report a Class 1 failure. After this date Altoona implemented pass/fail criteria, of which a Class 1 failure resulted in an immediate Fail. To date, no heavy duty zero-emission bus tested at Altoona has reported a Class 1 failure. By industry accepted standards, zero-emission buses are considered to be equally as safe as diesel or CNG buses under normal operating conditions.

Because electric vehicle standards are still evolving, it is likely that manufacturers utilize slightly different strategies for detection, prevention, or response to failures. While it is difficult to evaluate and compare the effectiveness of vehicle safety architecture between makes and models of zero-emission buses based on available information, there are a few obvious design decisions that can be evaluated and discussed.

Table 27: Zero-emission Bus Design Considerations

		Battery	Battery Location	Fuel Storage	Fuel Cell Location	Propulsion Controls	Structure
40-Foot	**BYD K9**	LFP	Roof/Underbody/ Interior	Underbody	N/A	Engine	Steel
	Gillig	NMC	Roof/Engine	Underbody	N/A	Engine	Steel/ Stainless
	New Flyer XE40	NMC	Roof/Engine	Underbody	N/A	Roof	Steel/ Stainless
	Nova Bus LFSe	NMC	Roof/Engine	Underbody	N/A	Engine	Steel/ Stainless
	Proterra ZX5	NMC	Under body	Underbody	N/A	Engine	Composite
	New Flyer XHE40	NMC	Roof	Roof	Engine	Roof	Steel/ Stainless
	ENC Axess FCBD	NMC	Roof	Underbody/ Roof	Engine	Engine	Steel/ Stainless
60-Foot	**BYD K11**	NMC	Roof/Engine/ Interior	Underbody	N/A	Engine	Steel
	New Flyer XE60	NMC	Roof/Engine	Underbody	N/A	Roof	Steel/ Stainless
	New Flyer XHE60	NMC	Interior	Roof	Engine	Roof	Steel/ Stainless

7.6.1 Battery Chemistry

Both NMC and LFP batteries are considered safe, but LFP batteries are considered to have better thermal stability and are more tolerant to abuse. Thermal run-away of NMC cells starts at a lower temperature than LFP cells [206]. If a thermal runaway event does occur, LFP batteries have a very slow rate of temperature rise compared to NMC batteries, which helps slow the spread and increases the window of opportunity for safety systems to respond. Because the potential for thermal run-away is greater, buses equipped with NMC batteries require a more robust thermal management system than those with LFP batteries.

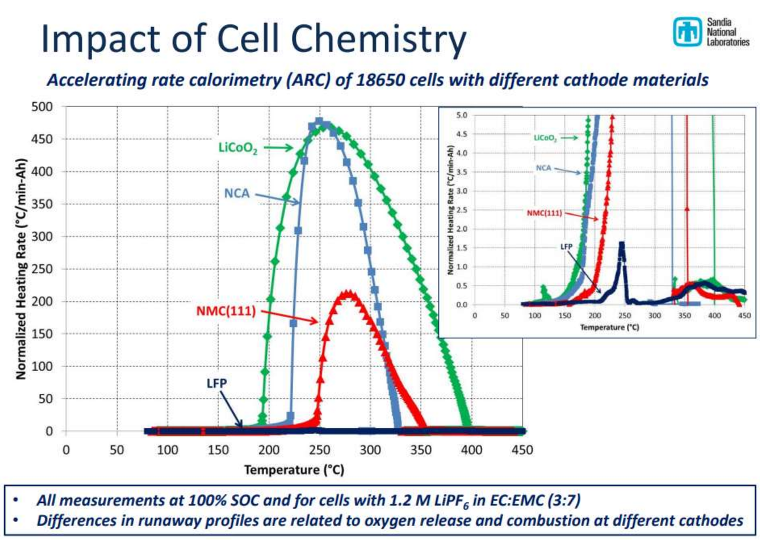


Figure 87: Thermal Run-away energy potential by cell chemistry. Source: [206]

7.6.2 Battery Location

Bus batteries are for the most part located outside of the passenger compartment, either on the roof, in the engine compartment, or under the bus. Some models from BYD and New Flyer contain interior batteries. New Flyer eliminated interior batteries from their battery-electric models when they switched from LFP to NMC batteries, but they still utilize interior NMC batteries with their 60-foot fuel-cell battery-electric model. BYD has recently announced their new Blade Battery which includes higher energy density and new packaging. It is unclear at this time whether Blade Batteries will be packaged any differently on their bus.

Batteries that are located on the roof are more protected from collisions, but the added weight in this area raises a vehicles centre of gravity, which could increase the risk of roll-over. All models except Proterra's mid-capacity BEB and New Flyer's 60-foot FC-BEB store at least a portion of their batteries on the roof. To test vehicle stability, Altoona testing includes a double-lane change obstacle avoidance test. This test involves weaving through pylons at speeds up to 72.42 km/h (45 mph). All zero-emission buses have passed the double-lane change test with no reported issues. Available battery capacities have increased from what was originally tested, therefore it is recommended that Transit confirm that the current models are compliant.

With roof mounted batteries, there is potential for toxic gases or molten metal to leak into the passenger compartment. This is because the gases vented from batteries are heavier than air, and the temperature of a lithium-ion battery fire is hot enough to melt metal. Sealed enclosures with vent paths pointed away from the roof and firewalls will help slow the spread, but cannot completely eliminate this risk. Transit will need to verify whether the manufacturer's mitigation strategy for rooftop pack safety is adequate, before determining if rooftop batteries are acceptable.

Batteries that are under the bus are better protected from rear end collisions, but are still susceptible to damage from side impacts and road debris. Proterra, BYD, and Nova Bus currently package batteries under the bus. Proterra's batteries are located between the axles and are contained in metal reinforced enclosures which have been drop tested, been subjected to thermal abuse testing, and under gone ballistic penetration testing to ensure safe performance in the application. BYD and Nova Bus both package batteries in the rear overhang area. Both manufacturers place their batteries inside an enclosure, but neither appear to provide additional reinforcements beyond what is provided by the vehicle frame and body. Nova Bus has completed extensive side impact testing to validate safety of batteries in this location, while BYD does not provide any specific details of validation testing of their design. Transit will need to verify whether the manufacturer's mitigation strategy for underbody pack safety is adequate before determining if underbody batteries are acceptable.

Batteries that are in the engine compartment are most vulnerable during a rear end collision. Engine compartment batteries in New Flyer and Gillig buses are currently stored above the rear bumper. This keeps them out of the impact zone from a collision with a light duty car or truck, but they are still susceptible to damage from collisions with larger commercial trucks or other buses. Both manufacturers provide either a barrier or a reinforced frame around their batteries for added protection. Neither manufacturer provides any specific details on rear impact testing performed to validate the safety of the packs in this area. Transit will need to verify whether the manufacturer's provisions for rear collision protection are adequate before determining if rear engine compartment batteries are acceptable.

Interior batteries are subject to the same protection as passengers, and are therefore well protected from all but the most severe collisions. However, adding high voltage batteries and cables to the passenger compartment does add some inherent risk. If batteries are damaged, either through collision or a thermal event, there is increased risk of passengers and the operator being exposed to toxic gases or high voltage electricity. Sealing enclosures and supplying a pathway for gases to vent to the exterior of the bus will help reduce the risk of gases mixing with cabin air. Enclosures around batteries should be made of touch safe materials to prevent risk of electrical shock. Transit will need to verify whether the manufacturer's mitigation strategy for interior pack safety is adequate before determining if interior batteries are acceptable.

7.6.3 Fuel Cell location

Up until recently fuel cells were designed to fit in approximately the same location as engines. As such, both New Flyer and ENC mount their fuel cells in the rear engine compartment. While the fuel cell itself may be vulnerable to damage in a rear collision, it is no more vulnerable than a diesel engine. There are no obvious hydrogen lines routed in high impact areas with either manufacturers design, but this should be confirmed. Regardless, following a crash there is potential for hydrogen fuel leakage either from the fuel cell or from damaged lines. While excess flow sensors should prevent major leaks, Transit should ensure that manufacturers have adequately sealed the engine compartment from the passenger area, and that a pathway to atmosphere is available to prevent a build-up of gas in the engine compartment. Hydrogen leak detectors should also be installed above the fuel cell, and in areas along fuel lines, to ensure any leaks are addressed as soon as they occur.

Ballard's 8th generation of fuel cell, FC Move, has been redesigned specifically for the transit bus market. It incorporates a new lower profile which enables it to be installed either in the engine compartment or on the roof [207]. While moving the fuel cell to the roof would further protect it during a collision, it is unclear whether manufacturers would need to move other roof mounted components such as batteries or propulsion controls to the engine compartment to accommodate this change. As of the end of 2020, neither New Flyer nor ENC have announced plans to offer Ballard's FC Move module, nor has this unit completed Altoona durability testing.

7.6.4 Fuel Storage Location

Both New Flyer and ENC store hydrogen in roof mounted tanks. There is little risk of damage to tanks in a collision. Unlike batteries, both hydrogen tanks and compressed hydrogen fuel are relatively light and therefore do not significantly increase the vehicle's centre of gravity or roll-over risk. Roof mounted tanks are considered the safest location for storing hydrogen as it is lighter than air, and as such there is no risk of any leaked fuel entering the passenger compartment below, and any ignited fuel would vent safely upwards.

Diesel fuel may need to be supplied for auxiliary heating in the winter. All models except New Flyer's fuel cell battery-electric bus are currently available with diesel auxiliary fuel tanks. Similar tanks are supplied on diesel buses and as such diesel fuel tanks supplied on battery-electric buses are not considered to be any less safe, assuming similar firewalls and engine compartment fire suppression systems are utilized. For models that store batteries in the engine compartment or under the floor in the rear overhang area, there may be some increased risk of fuel ignition during a thermal run-away event, but firewalls would similarly protect passengers regardless of the source of ignition.

7.6.5 Propulsion Control Equipment Location

Most manufacturers locate propulsion control components in the engine compartment for improved serviceability; New Flyer is the lone exception that places propulsion control components on the roof.

As with battery locations, propulsion controls contained on the roof are less vulnerable to vehicle impact damage than controls placed in the engine compartment. Similarly, controls that are located higher in the engine compartment are more protected from rear-end collisions than controls located lower in the compartment. Damage to propulsion controls are likely to result in a bus shutting down or being unable to restart. Buses with roof mounted controls may have a higher probability of drivability following minor collisions. Propulsion control systems do not have moving components, but there is potential for wiring to be damaged in an accident. In addition to the possibility of shutting down the bus, loose or damaged wires have the potential to create short circuits or arcs. Risk of accidental exposure may also be lower with roof mounted controls.

7.6.6 Structure

All manufacturers utilize monocoque or semi-monocoque construction. Everyone except Proterra utilizes carbon steel or stainless steel frames with aluminum or composite body panels, while Proterra utilizes composite unibody construction. While there is no bus collision data available comparing steel vs composite unibody construction, there is evidence that composites are capable of absorbing more energy in a collision [208]. It's unclear whether this actually improves passenger safety or just reduces body damage in a collision.

8 FINANCIAL IMPLICATION OF FLEET ELECTRIFICATION

The financial impact of integrating a small test fleet of zero-emission buses was evaluated based on expected capital, operational and indirect costs such as training and public engagement. Discussion on optional items such as depot management software and microgrids is also included in this section.

Some assumptions regarding the test fleet mix are required to estimate costs. The target for the test fleet size is 12-20 buses. As Transit's fleet includes both heavy-duty 40 and 60-foot buses, it makes sense to consider both lengths of buses in any cost evaluation. In order to collect statistically significant data from a zero-emission bus trial, CUTRIC recommends including a minimum of eight buses. Therefore, a 16-bus fleet with a 50/50 split of eight 40-foot and eight 60-foot buses will be used as a baseline for this analysis. This will skew operating costs per kilometer higher for the test fleet than it would normally be in the general fleet.

Alternative costing based on full fleet adoption of zero-emission buses, with a more realistic fleet mix of 92% 40-foot and 8% 60-foot buses, is also provided for comparison.

All costs discussed in the section are included for the purpose of comparing technologies. The true operating costs of zero-emission buses will need to be evaluated as the buses are operated in regular service over several years.

The data used in support of this evaluation was based on the current state of Winnipeg Transit's fleet and operations in the Fall of 2019. The COVID-19 pandemic has had a significant impact on Transit's overall operations in 2020, with public health orders and reduced ridership levels necessitating reductions to service, and changes to operations. Operational data from pre-COVID levels of service is used throughout the report nonetheless, as it is expected that transit service will return to these levels in the future, and that using levels of service from during the COVID-19 pandemic would result in incorrect assumptions, and an underestimation of necessary resources

8.1 Capital Costs

Capital costs include up-front one-time costs such as: buses, fueling equipment, fueling infrastructure installation, facility upgrades, utility upgrades, as well as any necessary land purchases.

8.1.1 Bus Purchase Price

Manufacturers were contacted directly for updated pricing. All bus prices were provided in US dollars and have been converted to Canadian dollars using a 1.35 exchange rate. Pricing excludes applicable taxes. Actual price at time of purchase may vary based on inflation or innovation. While both battery and fuel cell prices have been dropping in recent years, the cost of a zero-emission bus remains up to 262% higher than a diesel bus.

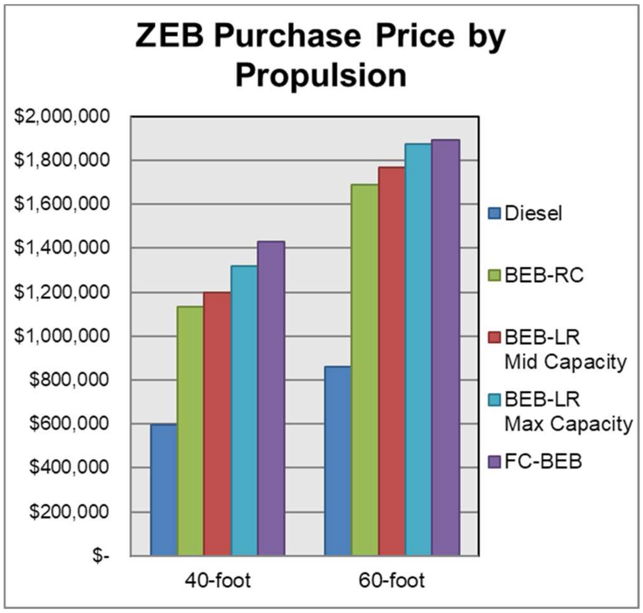


Figure 88: Summary of bus purchase price by propulsion type.

Purchase price alone does not clearly show the variation in value between each technology, as even after adjusting for efficiency differences, FC-BEBs carry significantly more stored energy on-board than even the largest capacity BEBs. When considering the amount of beginning-of-life usable on-board stored energy versus vehicle purchase price, the graph shifts considerably.

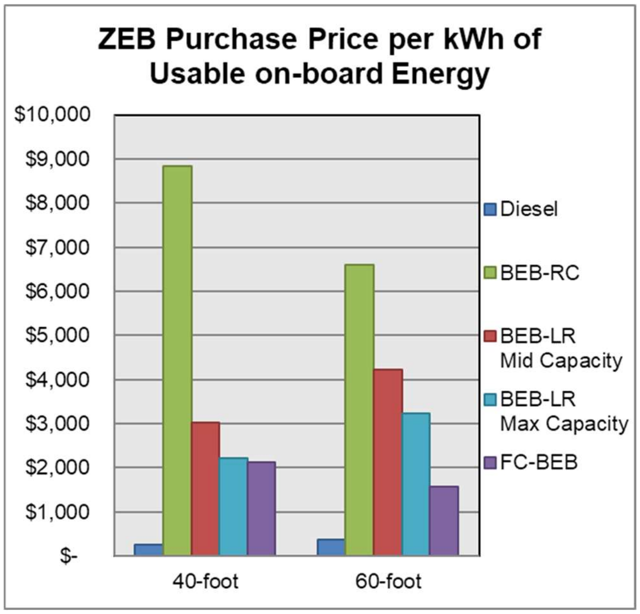


Figure 89: Summary of bus purchase price per kWh of usable on-board energy

This again does not provide the whole picture, as on-route charged buses are intentionally designed to carry less energy and charge more frequently throughout the day.

Looking to further equalize for efficiency and operational variations between BEBs and FC-BEBs, purchase price should instead be compared against expected operating range. While it is possible to extend range using mid-day charging, for a small zero-emission bus deployment it is unlikely that long-range buses will need to be charged more than once per day on a regular basis. To compare the true costs of the buses in the context of a small fleet operation purchase price should be compared to the expected range based on a single daily charging/refueling strategy, or single deployment strategy in the case of on-route rapid charge BEBs.

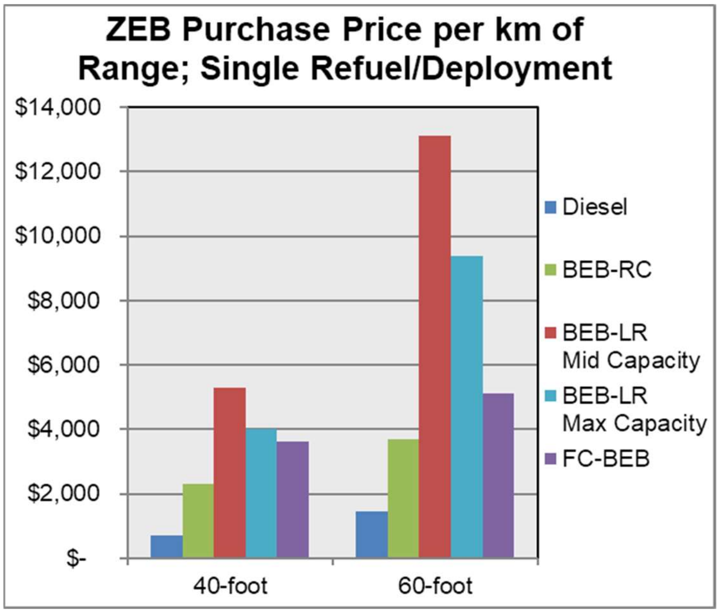


Figure 90: Summary of bus purchase price per kilometer of range based on single daily deployment strategy

Now the data more clearly shows the cost variations between BEB and FC-BEB based on range capabilities. While on-route rapid-charge BEBs are still the best value based on range, FC-BEBs are actually less expensive per kilometer of travel, when compared to long-range BEBs. This gap widens further when considering the cost of 60-foot buses.

Purchase price is constantly changing. Historically the cost of a diesel bus has risen continually based on inflation, while the cost of battery-electric and fuel cell battery-electric buses have decreased based on economies of scale, improved manufacturability, supply chain diversification, and increased competition in the market [209]. The difference between the cost of a battery-electric bus and a diesel bus is mainly the cost of the batteries, while the cost of the fuel cell as well as the batteries make up the price gap with fuel cell battery-electric buses. The volume of battery-electric buses produced is significantly higher than fuel cell battery-electric buses, therefore they have achieved a greater benefit from economies of scale, and as such their purchase price is expected to fall at a slower rate than a fuel cell battery-electric bus.

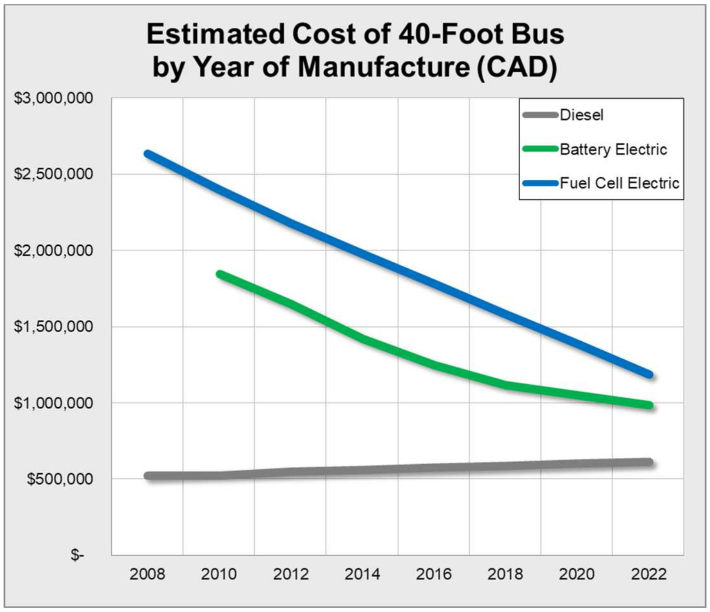


Figure 91: Cost of Zero-Emission 40-foot bus by year of manufacture

It is unclear at this time whether zero-emission buses will reach parity with diesel buses, or if they will plateau above this before pricing starts to rise with inflation. Manufacturers are not predicting bus prices to fluctuate considerably from current estimates prior to 2022.

Based on current pricing, the estimated cost to purchase 16 zero-emission buses equally composed of 40-foot and 60-foot lengths is as follows:

Table 28: Purchase price estimates for a 16-bus test fleet

	16 Bus Fleet	Lifetime Savings
BEB-RC	$ 22,559,400	-$ 12,988,680
BEB-LR Mid	$ 23,748,000	-$ 14,177,280
BEB-LR Max	$ 25,524,000	-$ 15,953,280
FC-BEB	$ 26,568,000	-$ 16,997,280

8.1.2 Charging/Fueling Infrastructure Purchase Price

Data from recent charging and fueling installations in the US have been compiled and presented for review. Where applicable manufacturers have been contacted for updated pricing. Any infrastructure prices not quoted in Canadian dollars have been converted from US dollars using a 1.35 exchange rate. Pricing excludes applicable taxes.

It is currently recommended that battery-electric buses utilize no more than 63% of name plate capacity to ensure similar range capabilities from beginning-of-life to end-of-life. With today's battery technology, the average charge rate of long-range batteries is C/3 which translate into a maximum depot charge rate of 220 kW for maximum-capacity buses, and 146 kW for mid-capacity buses.

Based on a review of Transit's fall 2019 schedule, a charging window of 2, 3, or 4 hours could be accommodated for either mid and maximum-capacity buses by varying the number of chargers and charger output. When the ratio of buses to chargers is scaled for a fleet of 16 buses, the recommended number of chargers by available charge time is as follows:

Table 29: Number of chargers recommended by charging window

	Number of Chargers
4-Hour Plug-in Depot Charging	4
3-Hour Plug-in Depot Charging	4
2-Hour Overhead Depot Charging	3
15-Minute On-Route Inductive Charging	2
10-Minute On-Route Conductive Charging	2

For a partial fleet of battery-electric buses, garage layout and power restrictions, rather than schedule determines the minimum number of chargers. An assessment of Brandon Garage determined that restricting charging capacity to only certain locations along a track could create significant deployment challenges. Each track at Brandon Garage accommodates seventeen 40-foot buses or twelve 60-foot buses. Installing charging points at all 34 locations along two tracks would be necessary to accommodate a mixed fleet of sixteen battery-electric as well as other non-battery-electric buses. A minimum of six plug-in chargers, or twelve overhead chargers, would be necessary to support this number of charging points rather than the number initially recommended.

Another factor to consider is life expectancy of refueling infrastructure. Hydrogen fueling stations are expected to have a useful life of at least 20 years, while hydrogen production equipment and chargers have a useful life of only 10-15 years. In both cases, some amount of mid-life overhaul will be required to align the life of the refueling equipment with that of the bus. Manufacturers have advised that units can be refurbished rather than replaced to extend life to 18 years, and as such infrastructure maintenance and overhaul costs will be considered under operating costs rather than capital costs.

Based on the above recommendations for charger quantities, the estimated infrastructure capital costs to operate a fleet of 16 zero-emission buses is as follows:

Table 30: Estimated infrastructure cost for a test fleet of 16 buses. Source: [210]

	Infrastructure Cost
Plug-in Depot Charging	$ 2,843,000
Overhead Depot Charging	$ 8,100,000
On-Route Inductive Charging	$ 1,491,301
On-Route Conductive Charging	$ 1,893,301
On-Site Hydrogen Production, Storage & Dispensing	$ 5,562,000

8.1.3 Facility Upgrades

Beyond electrical upgrades to accommodate charging or refueling equipment, other facility upgrades may be required to service electric vehicles. They may include adding or increasing capacity of overhead cranes, lighting upgrades around charging refueling equipment, upgrades to fire detection or suppression systems, additional gas detection equipment, and possibly ventilation system updates. The costs associated with these updates will vary based on technology and deployment strategy.

For a small test fleet, it is unlikely that any major overhaul to parking garage configuration would be considered. Certain items may need to be updated based on building and fire codes at both the parking garage and maintenance garage.

Facility upgrades associated with charging infrastructure are included in the cost estimates for the installation of the chargers, and will continue with each charger purchased.

In the case of fuel cell battery-electric buses, some upgrades to maintenance facilities will be unavoidable. There are, however, strategies that can be implementing to help to minimize facility costs, such as isolating or depressurizing fuel tanks and operating the buses only on battery power while inside the maintenance garage. With these restrictions in place, facility upgrades associated with the introduction of a fuel cell battery-electric deployment are likely to generate a one-time cost of up to $1,350,000 [126]. A detailed assessment of Transit's maintenance garage would be required to confirm this cost.

Some additional upgrades would be necessary if fueling equipment were to be located indoors rather than outdoors. Transit has determined that outdoor fueling is acceptable for operating a test fleet. Cost associated with indoor fueling will only be considered in future phases of transit electrification.

8.1.4 Back-Up Redundancy

Both battery-electric and fuel cell battery-electric buses require some amount of electricity to refuel. That electricity can come directly from the grid, via a microgrid, or indirectly from a back-up generator. For a small fleet, diesel or CNG back-up generators are likely the most cost-effective option for backup resiliency.

A fleet of sixteen battery-electric buses would require between 3,300-6,600 kWh of electricity. Considering the size of the fleet, fast charging would not be essential, but even assuming a generous 12-hour charge window, a 550 kW generator would be necessary to recharge the entire fleet. The power required to refuel a fleet of sixteen fuel cell battery-electric buses is dependent on the pressure of the fuel rather than the amount of fuel dispensed. Assuming that there is a sufficient amount of stored fuel to dispense, only a small 20 kW generator would be required to power the compressor and dispenser. If hydrogen production equipment needed to be powered as well, back-up generation power would need to increase to 500 kW to maintain minimum service levels.

With a small fleet there is built in resiliency, as a large number of diesel buses would be available to deploy during a power outage. As such, back-up generation is not a requirement. If Transit decides to install additional back-up power generation the estimated cost to purchase and install equipment based on a fleet of 16 buses is as follows:

Table 31: Cost estimation of back-up generation equipment. Source: [211] [212] [213]

	Cost Back-up Generation
Charging	$ 284,500
Hydrogen dispensing	$ 17,010
Hydrogen production & dispensing	$ 243,000

8.1.5 Land

For the next phase of electrification, Transit is only considering installing charging or fueling equipment on Transit owned land. No land purchases are anticipated at this time.

8.1.6 Tooling & Equipment

Transit reached out to zero-emission bus manufacturers to obtain a list of recommended tooling. Some of the tooling was unique to the manufacturer, while some equipment was standard across multiple platforms. Transit previously purchased some of the recommended tooling during the battery-electric bus demonstration. Item such as PPE has expired and would need to be replaced, but others such as test equipment, insulated tools, and hot sticks would be reusable.

New technology has been developed since Transit's battery-electric bus demonstration. This includes portable maintenance chargers, which are now recommended for maintenance garages to ensure that buses remain charged when under-going service [214]. Buses do not require significant amounts of power to maintain hotel loads (any non-propulsion based electrical load), but both low voltage and high voltage batteries will eventually drain. Battery-electric buses can only be charged using a J1772 compliant charger. Portable J1772 chargers are available but can be expensive, as what is on the market is typically oversized for bus maintenance purposes. More and more light-duty manufacturers are transitioning from 300 V to 880 V batteries, so there may be more options available in the future as the market expands to meet the needs of automotive garages. Fuel Cell battery-electric buses are not designed to be charged, but they are equipped with a maintenance charge port which can be used for emergency charging if the fuel cell can't or won't turn on. Charging via this method requires only a "dumb charger". A properly sized DC power supply with an adequate power cable and connector is all that is needed.

The estimated cost to purchase new tooling & equipment to support a fleet of sixteen zero-emission buses is as follows:

Table 32: Cost estimation of tooling & equipment

	BEB	FC-BEB
Laptop	$ 4,000	$ 4,000
Diagnostic Equipment	$ 13,500	$ 13,000
Test Equipment	$ 8,500	$ 8,500
PPE	$ 8,000	$ 8,000
Specialized Tools	$ 3,000	$ 6,500
Barriers & Signage	$ 3,000	$ 3,000
Maintenance Charger	$ 27,000	$ 8,000
Grand Total	**$ 67,000**	**$ 51,000**

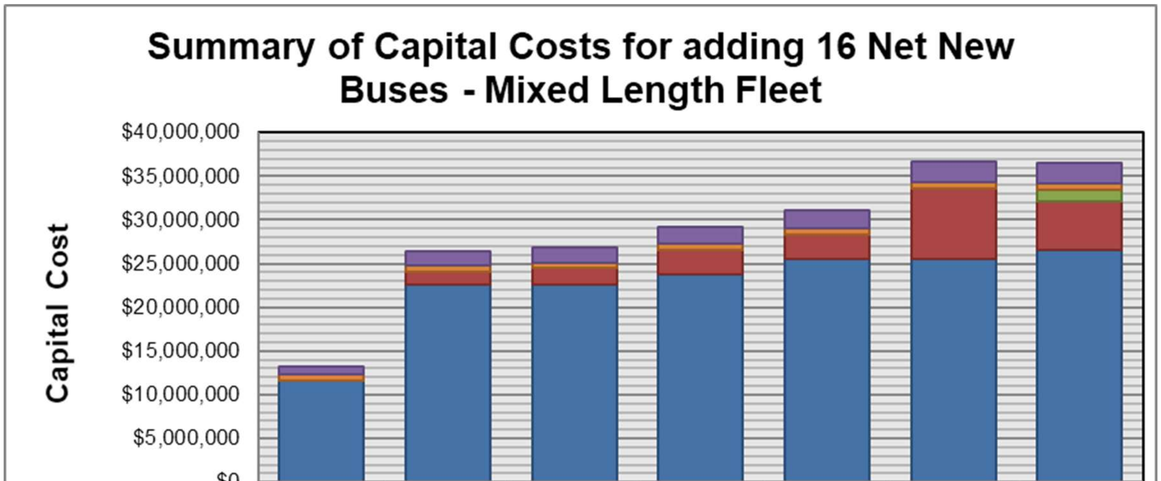
In addition to electric-bus specific tooling & equipment, there are some standard items that must be installed on all buses such as automated passenger counters (APC), automatic vehicle location (AVL) systems, and fareboxes. If buses are purchased to replace retiring diesel buses, then some equipment could be reused. In the case of a zero-emission test fleet, all buses will be considered net new buses, and as such the following items should be added:

Table 33:Cost of standard bus equipment for net new bus purchases

	Standard Equipment
AVL System	$ 229,907
Fareboxes	$ 299,065
APC System for 40-ft Bus	$ 24,184
APC System for 60-ft Bus	$ 35,267
Grand Total	**$ 588,423**

8.1.7 Summary of Estimated Capital Costs for a Small Test Fleet

When all capital costs relating to the introduction of zero-emission buses are considered, on-route rapid-charge battery-electric buses with inductive chargers are the least expensive zero-emission option, while long-range battery-electric buses with overhead depot chargers are the most expensive.



	Diesel	BEB-RC Ind.	BEB-RC Cond.	BEB-LR Mid Plug-In Depot	BEB-LR Max Plug-In Depot	BEB-LR Max Overhead Depot	FC-BEB
PST (7%)	$860,357	$1,732,021	$1,760,371	$1,909,842	$2,034,162	$2,402,152	$2,390,952
Land Purchase	$-	$-	$-	$-	$-	$-	$-
Back-up Power	$-	$-	$-	$-	$-	$-	$-
Tooling & Equipment	$625,454	$692,454	$692,454	$692,454	$692,454	$692,454	$676,454
Facility Upgrades	$-	$-	$-	$-	$-	$-	$1,350,000
Refueling Infrastructure	$-	$1,491,301	$1,896,301	$2,843,000	$2,843,000	$8,100,000	$5,562,000
Purchase Price	$11,665,360	$22,559,400	$22,559,400	$23,748,000	$25,524,000	$25,524,000	$26,568,000
Grand Total	$13,151,171	$26,475,176	$26,908,526	$29,193,296	$31,093,616	$36,718,606	$36,547,406

Figure 92: Summary of capital costs for a zero-emission test fleet compared to diesel replacement

8.2 Operating Costs

Operating costs include ongoing costs associated with buses and refueling equipment such as: scheduled and unscheduled bus maintenance, mid-life overhauls, fuel/electricity costs, refueling equipment maintenance, and refueling equipment refurbishment.

8.2.1 Maintenance

Maintenance costs include all labour and materials associated with scheduled preventative maintenance, unscheduled maintenance, major repairs, and mid-life overhaul activities of both buses and infrastructure. Transit maintains records on all bus related maintenance and compiles the data into annual reports. Currently, inspection, testing, and preventative maintenance of fueling equipment is contracted out for a fixed annual fee, with the contract being re-awarded every three to five years.

8.2.1.1 <u>Scheduled and Unscheduled Maintenance</u>

Winnipeg Transit maintenance reports for the years 2016 to 2020 were reviewed. Sixty-foot buses operated by Transit prior to 2019 were purchased used, and incurred higher than normal maintenance and overhaul costs during this time period. Data compiled by the Center for Urban Transportation Research indicates that on average, maintenance costs of a 60-foot bus should be approximately 43%

higher than a 40-foot bus [215]. To avoid artificially inflating the maintenance costs of 60-foot buses based on Transit's data, 40-foot data will instead be used to calculate this cost.

The cost of scheduled and unscheduled maintenance per 1,000 kilometers for 40-foot Xcelsior Diesel and Xcelsior Charge buses during this period was as follows:

Table 34: Maintenance costs per 1,000 kilometers of Transit's Xcelsior fleet 2016 to 2018 [53]

System	40-ft Diesel Fleet	40-ft Electric Demo Fleet
Body	$ 37.97	$ 39.86
Electrical	$ 34.11	$ 70.50
Engine	$ 65.43	$ 3.05
Brakes	$ 67.20	$ 14.01
Steering, Suspension & Axles	$ 34.52	$ 18.35
Fuel & Exhaust	$ 41.57	$ 2.21
HVAC	$ 25.59	$ 9.97
Air	$ 13.44	$ 20.77
Transmission	$ 28.81	$ 0.08
Oil	$ 7.50	$ 0.00
Other	$ 53.92	$ 39.50
Mid-Life Overhaul	$ 67.16	$ -
Total	**$ 477.21**	**$ 218.30**

Between 2016 and 2018, battery-electric buses accumulated between 30-50% of the mileage of a typical diesel bus. Due to the demonstrative nature of this program and the use of prototype components, some costs such as air and electrical maintenance may have been artificially high, while costs such as body work, axles, brakes, and suspension may have been artificially low because of mileage. Due to these discrepancies, the data collected during the battery-electric bus demonstration may not accurately depict the full maintenance cost per 1,000 km of an 18-year life bus. To refine the estimate for zero-emission bus maintenance, results from Transit's battery-electric bus demonstration were compared against data from other zero-emission bus trials.

It is widely assumed that regenerative braking will reduce the cost of mechanical brake maintenance, but to what extent has still not been well established. Much of the data used to establish zero-emission bus baselines is extrapolate from zero-emission bus trials in California. This data cannot not easily be used to predict the impact that inclement weather and icy roads have on brake life. Based on experience working with both diesel and battery-electric buses, the Vehicle Maintenance & Overhaul branch within Transit's Plant & Equipment division predicts that an 18-year life zero-emission bus would require 25% less brake maintenance than a typical diesel bus.

The motor, motor inverter, and inductors utilized in zero-emission buses are heavy-duty commercial components with predicted life expectancies of 20 years. While these components are expected to last the life of the buses, they only come with a 5-year warranty. There is limited data available for Transit to utilize to predict 18-year defect rates, as most zero-emission buses have been operating for less than 5 years, and very few transit agencies outside of Canada operate buses beyond 12 years. New Flyer, who leased the demonstration buses to Transit, was contacted to provide estimates for the replacement value of motors, inverters, and inductors. For estimation purposes a 5% defect rate will be assumed, but there is risk that fleet wide defects outside of the warranty period could significantly increase this cost.

Fuel cell battery-electric buses have identical propulsion and accessory systems to battery-electric buses, but they also include a fuel cell, fuel cell accessories, and a hydrogen fuel system, all of which require some additional maintenance. Ballard Power Systems, who has significant industry experience with multiple bus manufacturers, was contacted to provide estimates on the maintenance on these sub-systems.

Table 35: Predicted maintenance costs of a 40-foot zero-emission test fleet per 1,000 kilometers

System	40-ft Diesel Fleet	40-ft BEB	40-ft FC-BEB
Body	$ 37.97	$ 31.01	$ 31.01
Electrical	$ 34.11	$ 70.50	$ 70.50
Engine	$ 65.43	$ 8.05	$ 8.52
Brakes	$ 67.20	$ 50.40	$ 50.40
Steering, Suspension & Axles	$ 34.52	$ 27.50	$ 27.50
Fuel & Exhaust	$ 41.57	$ 2.21	$ 75.94
HVAC	$ 25.59	$ 9.97	$ 9.97
Air	$ 13.44	$ 13.44	$ 13.44
Transmission	$ 28.81	$ -	$ -
Oil	$ 7.50	$ -	$ -
Other	$ 53.92	$ 53.92	$ 53.92
Total	**$ 401.19**	**$ 267.00**	**$ 341.20**

In most the cases maintenance costs associated with 60-foot buses would be expected to be 43% higher than 40-foot buses, however engine maintenance will be greater if a centre driven axle is selected. This axle has two additional serviceable motors and requires two additional motor inverters to provide power.

Table 36: Predicted maintenance costs of a 60-foot zero-emission test fleet per 1,000 kilometers

System	60-ft Diesel Fleet	60-ft BEB	60-ft FC-BEB
Body	$ 44.35	$ 44.35	$ 44.35
Electrical	$ 48.78	$ 100.82	$ 100.82
Engine	$ 90.83	$ 17.85	$ 18.31
Brakes	$ 96.10	$ 72.07	$ 72.07
Steering, Suspension & Axles	$ 49.36	$ 39.33	$ 39.33
Fuel & Exhaust	$ 59.45	$ 3.16	$ 108.59
HVAC	$ 36.59	$ 14.26	$ 14.26
Air	$ 19.22	$ 19.22	$ 19.22
Transmission	$ 41.20	$ -	$ -
Oil	$ 10.73	$ -	$ -
Other	$ 77.11	$ 77.11	$ 77.11
Total	**$ 573.70**	**$ 388.15**	**$ 494.04**

There is still a lot of uncertainty regarding the reliability of zero-emission buses. The majority of issues reported by transit agencies are not related to the propulsion system or batteries, indicating that build quality or design flaws may be contributing to higher maintenance costs. Based on conversations that Winnipeg Transit has had with other transit agencies, these issues are not specific to one manufacturer either. While Transit's long-term target for bus availability is 90%, 65-85% is likely more realistic during the first 2 years of operation. In addition to overall reliability concerns, these buses feature parts and equipment that are not standard to diesel buses. Parts availability and bus downtime has been a major issue with battery-electric bus demonstrations across North America, including the one at Winnipeg Transit. While this does not necessarily have a direct cost impact, any downtime will potentially impact the annual fleet mileage, increase the need for spare buses, and reduce the amount of data collected during the testing period. To minimize this impact, zero-emission bus contract language around a "coach down" for repairs should be revised to include stronger financial penalties for unavailable parts or delayed repair procedures.

8.2.1.2 Mid-Life Overhaul

While mid-life overhaul costs associated with the zero-emission test fleet are shown under operating costs in this analysis, Transit could choose forecast these costs into the capital budget sometime between years nine and 12. In the case of diesel buses, some portion of the fleet is overhauled each year, and as such mid-life overhaul costs are included in Transit's operating budget. In order to properly compare the operating costs of diesel and zero-emission buses in this analysis, the mid-life overhaul costs of the zero-emission fleet were applied in a similar manner as the diesel fleet by averaging costs over their useful lives and estimated per 1000 km of travel, making them operating costs rather than capital costs.

Winnipeg Transit buses typically accumulate a total of 1,060,000 km before being retired between the ages of 18 to 22-years. Transit overhauls buses between 400,000 & 800,000 km in order to extend the life of the buses beyond the 12-year manufacturer validated life. All overhaul work is completed in-house. The average cost of overhauling a 40-foot bus between 2018 and 2020 was $80,586. Body work made up $63,186 while $17,400 was related to engine overhaul.

Zero-emission buses with the same steel unibody construction as diesel buses are expected to require similar body work at mid-life, but engine overhaul will be replaced with battery and fuel cell stack replacement. Based on manufacturer's warranties for batteries and fuel cells, it is assumed that zero-emission buses will be able to operate for 18-years and accumulate 930,700 km before retirement.

The replacement schedule is based on the following major component warranties:

Diesel Engine – 6-year/400,000 km;
Long-range Batteries – 9-year/4,000 cycles;
Rapid-charge Batteries – 6-year/5,000 cycles;
Fuel Cell Stacks – 6-year/unlimited km;

The purchase price of bus batteries and fuel cells are continually falling, and it is likely that replacement costs will be lower than 2020 pricing, but it is not likely that pricing with match the targets set for the light duty automotive sector. This is due to the smaller production volumes, the higher performance requirements and the longer life expectations of heavy-duty transit buses. Using 2020 pricing for battery packs and stack refurbishment as a baseline, it has been assumed that battery costs will fall at the same rate as automotive batteries, and that targeted reductions in fuel cell pricing will be met, resulting in the following end-of-life replacement costs:

Estimated Battery Costing 2028 – $275/585 per KW; long-range/rapid-charge [216].
Estimated Battery Costing 2034 – $200/427 per KW; long-range/rapid-charge [216].
Estimated Fuel Cell Stack Costing 2028 – $16,500 per stack [217].
Estimated Fuel Cell Stack Costing 2034 - $9,450 per stack [217].

Regulations require that end-of-life batteries be repurposed or recycled when they are replaced. At this time, it is unclear if there will be market demand for second-life batteries, and therefore some consideration for recycling costs should be included with a mid-life overhaul. Current estimates for battery recycling are as follows:

Estimated Battery Recycling 2028 $4,000 per tonne [162].
Estimated Battery Recycling 2034 – $2,500 per tonne [162] [218].

Currently propulsion motors, motor inverters, and inductors are predicted to last the life of the buses, and as such Transit does not anticipate replacing them at mid-life. Replacement of components due to defect may occur, and costs associated with this have been included under regular maintenance.

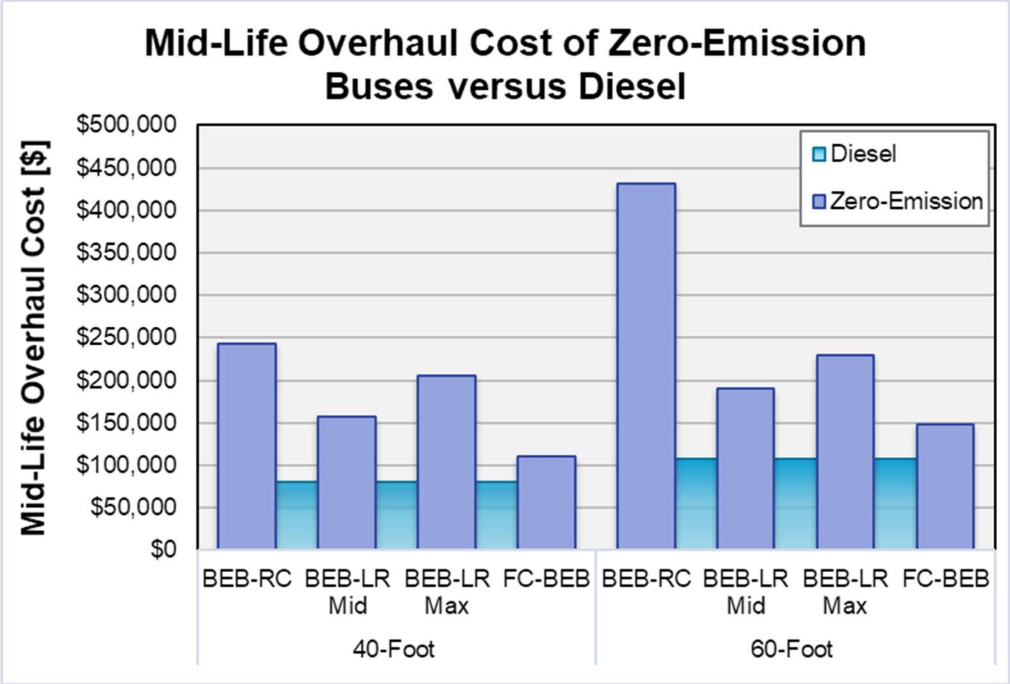


Figure 93: Mid-life overhaul cost of zero-emission buses versus diesel

8.2.1.3 Composite Body Maintenance and Overhaul

Proterra buses utilize composite unibody construction which has different requirements for body work repair and overhaul. The only other manufacturer with a composite body bus was North American Bus Industries (NABI), who produced a 45-foot “CompoBus” between 2002 and 2013. Los Angeles County Metropolitan Transportation Authority (LA Metro) operated the largest fleet of CompoBuses and reported that the buses had lower maintenance and repair costs, but greater mid-life overhaul costs compared to their NABI steel construction fleet [219].

Applying the same maintenance savings and increased overhaul cost to Winnipeg Transit’s operations, it is estimated that maintenance costs of a composite structure bus would be 2.14-2.39% higher than a steel structure bus.

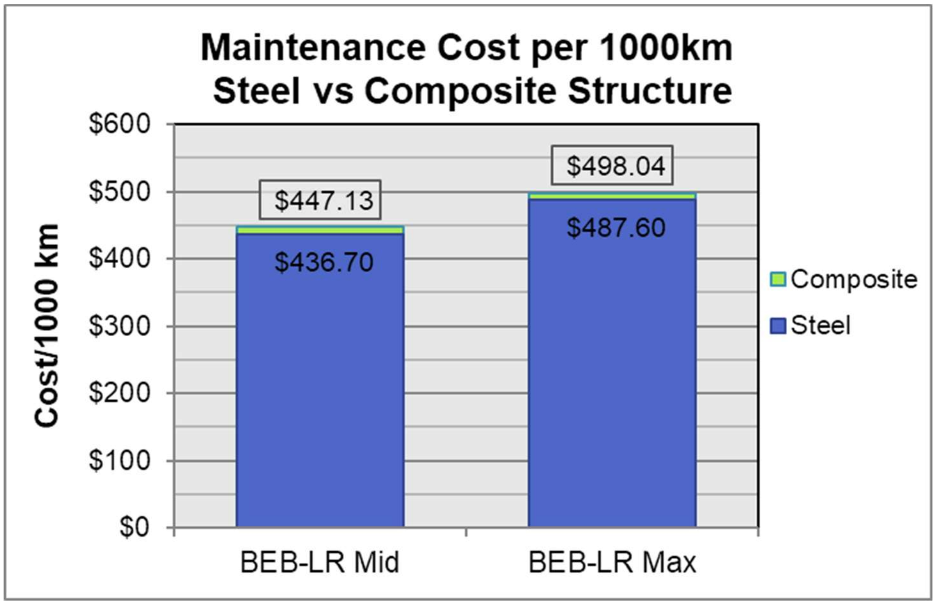


Figure 94: Maintenance cost per 1,000 kilometers - steel vs composite structure bus

8.2.1.4 Summary of Maintenance Costs:

Based on compiled information, estimates for combined maintenance and overhaul costs of zero-emission buses per 1,000 kilometers of travel are as follows:

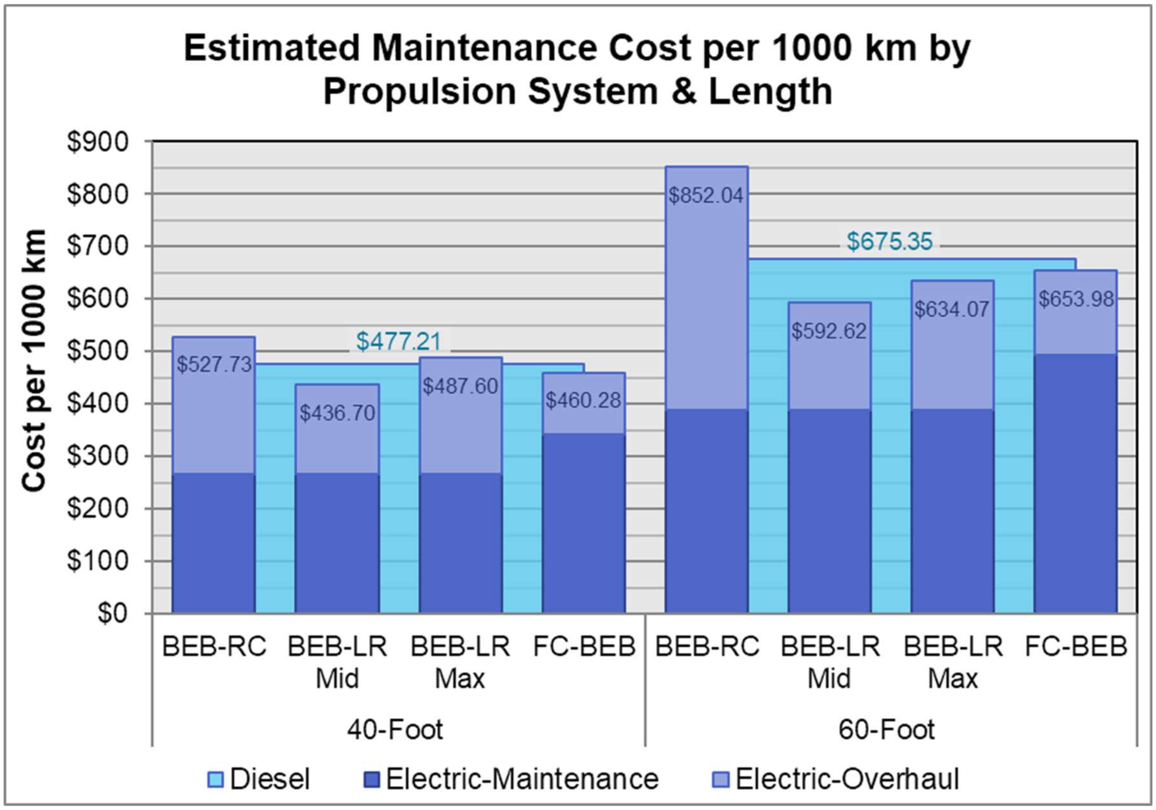


Figure 95: Estimated maintenance and overhaul cost of Zero-Emission buses per 1,000 kilometers [65].

Based on an 18-year, 930,700 km life the annual and total estimated combined maintenance savings from operating a sixteen bus zero-emission test fleet based on currently available capacity is estimated to be as follows:

Table 37: Estimated Maintenance Savings zero-emission vs diesel

	Annual Savings	Lifetime Savings
BEB-LR Mid*	$ 50,976	$ 917,568
FC-BEB	$ 15,844	$ 285,199
BEB-LR Max**	$ 12,776	$ 229,968
BEB-RC	-$ 93,984	-$ 1,691,712

*Saving for 40-foot BEB-LR Mid buses with composite structures would be reduced by 2.39%

**Saving for 40-foot BEB-LR Max buses with composite structures would be reduced by 2.14%

While annual maintenance costs are expected to be lower with all propulsion systems, high mid-life overhaul costs offset much of these savings. Despite this, rapid-charge battery-electric buses are the only zero-emission technology that does not produce some amount of lifetime maintenance savings when compared to diesel buses. In the case of a small test fleet, these costs will not be incurred until years 6 to 12 and be more appropriately managed through the capital budgeting process. Eliminating this would result in significantly lower annual operating costs.

8.2.2 Fueling Costs

Fueling costs are calculated as a combination of vehicle energy consumption, fuel/energy pricing, and fueling equipment expenses. Some assumptions regarding the test fleet mix and operation are necessary to estimate fueling costs.

As established previously, energy consumption for the test fleet will be based on a 50/50 split of eight 40-foot and eight 60-foot buses. While the actual annual mileage is likely to vary over the life of the bus, annual mileage will be assumed to be more aligned with a typical Transit bus, which accumulates 51,705 kilometers per year.

8.2.2.1 Fuel pricing

Diesel fuel pricing varies with each delivery. In 2019 Transit paid an average of $1.037/Litre for diesel and contracted out fueling equipment maintenance for $90,000 per year.

In the case of battery-electric buses the fuel will be electricity which is billed monthly based partially on peak demand and partially on actual usage. The number of buses, the operating duty cycle and charger efficiency will determine the monthly electricity usage, while the number of chargers and the peak combined charger power used in a month will determine the demand charges. Conductive chargers are assumed to be 99% efficient while inductive chargers are assumed to be only 90% efficient.

The electricity rate Transit receives depends on whether or not transformation and switching equipment is owned by Transit or by Manitoba Hydro. The expectation is that peak demand from centralized depot charging will necessitate Transit to purchase transformation and switching equipment. The cost for charging long-range BEBs at Brandon Garage is therefore being priced using Manitoba Hydro’s General Service Large – exceeding 750 V but not exceeding 30 kV commercial rate. With on-route chargers distributed across the city, it is likely that Transit can source power directly from the grid using Hydro’s equipment. The cost for charging on-route rapid-charge BEBs is therefore based on Manitoba Hydro’s General Service Medium rate.

General service medium

Charge	Cost
Basic monthly charge	$31.58
First 11,000 kWh	9.012¢/kWh
Next 8,500 kWh	6.662¢/kWh
Balance of kWh	4.211¢/kWh
First 50 kVA of monthly recorded demand	No charge
Balance of recorded demand	$10.78/kVA

Minimum monthly bill is the basic charge plus demand charge.

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General service large – exceeding 750 V but not exceeding 30 kV

Charge	Cost
Energy charge	3.955¢/kWh
Demand charge	$9.14/kVA

Minimum monthly bill is the demand charge.

Figure 96: Manitoba Hydro Commercial Rates [64]

Peak power draw from individual chargers has been estimated based on a usable capacity of 63% of nameplate capacity, and the ability to recharge buses to full in two, three, and four-hour windows. To evaluate facility peak demand, it will be assumed that the maximum number of chargers capable of operating simultaneously is aligned with the optimized number of chargers stated in **Table 38**, rather than the total number of chargers required based on the garage layout.

While actual charger power varies by manufacture, based on the available charge window and battery limitations, the maximum charge power is assumed to be as follows:

Table 39: Maximum peak power demand based on charging window

	Charger Power	Facility Demand
Mid Capacity 4-Hour Plug-in Depot Charging	70 kW	280 kW
Max Capacity 4-Hour Plug-in Depot Charging	105 kW	420 kW
Mid Capacity 3-Hour Plug-in Depot Charging	95 kW	380 kW
Max Capacity 3-Hour Plug-in Depot Charging	140 kW	560 kW
Max Capacity 2-Hour Overhead Depot Charging	220 kW	660 kW
15-Minute On-Route Inductive Charging	300 kW	600 kW
10-Minute On-Route Conductive Charging	450 kW	900 kW

In the case of fuel cell battery-electric buses, current industry targets are around USD $5/kg (CAD$6.75) at the dispenser [93]. Hydrogen costs may be higher for a small fleet, particularly if gaseous delivered fuel is utilized, due to lower total volume and inconsistent demand. Based on Manitoba's low hydro-electricity rates, the expectation is that Transit can produce and dispense fuel for a small test fleet on site for between CAD$4.00-$6.00 per kilogram, with costs fluctuating based on monthly fuel usage [65]. Transit may be able to source lower cost delivered liquid hydrogen from industrial production or by-product sources. Current expectation is that the cost of fuel dispensed will be

$2.00-6.00/kg [79]. The cost of hydrogen is likely to vary over the life of the bus so for comparison costing of $2, $4 and $6 per kilogram will be evaluated.

The following chart summarizes predicted fuel/energy consumption based on Winnipeg Transit's current and expected fleet operations:

Table 40: Summary of energy consumption by propulsion system, duty cycle and length

		Current	Master Plan	Energy Consumption
40-Foot	**Diesel**	60.890	60.890	L/100km
	BEB-RC	1.303	1.303	kWh/km
	BEB-LR Mid	1.377	1.377	kWh/km
	BEB-LR Max	1.453	1.453	kWh/km
	FC-BEB	12.314	12.314	km/kg
60-Foot	**Diesel**	88.46	77.69	L/100km
	BEB-RC	2.355	2.713	kWh/km
	BEB-LR Mid	2.289	2.674	kWh/km
	BEB-LR Max	2.409	2.788	kWh/km
	FC-BEB	6.433	4.450	km/kg

Altoona performance adjusted for HVAC load based on battery-electric bus demonstration. Actual result will vary.
[5] [55] [53] [56] [177] [180] [183] [20]

Based on an average month where;

- the fleet accumulates 68,941 kilometers,
- all power come from the grid,
- no load balancing software utilized,
- refueling infrastructure is metered separately,

Transit could expect the following fuel costs when operating a small fleet of 16 buses:

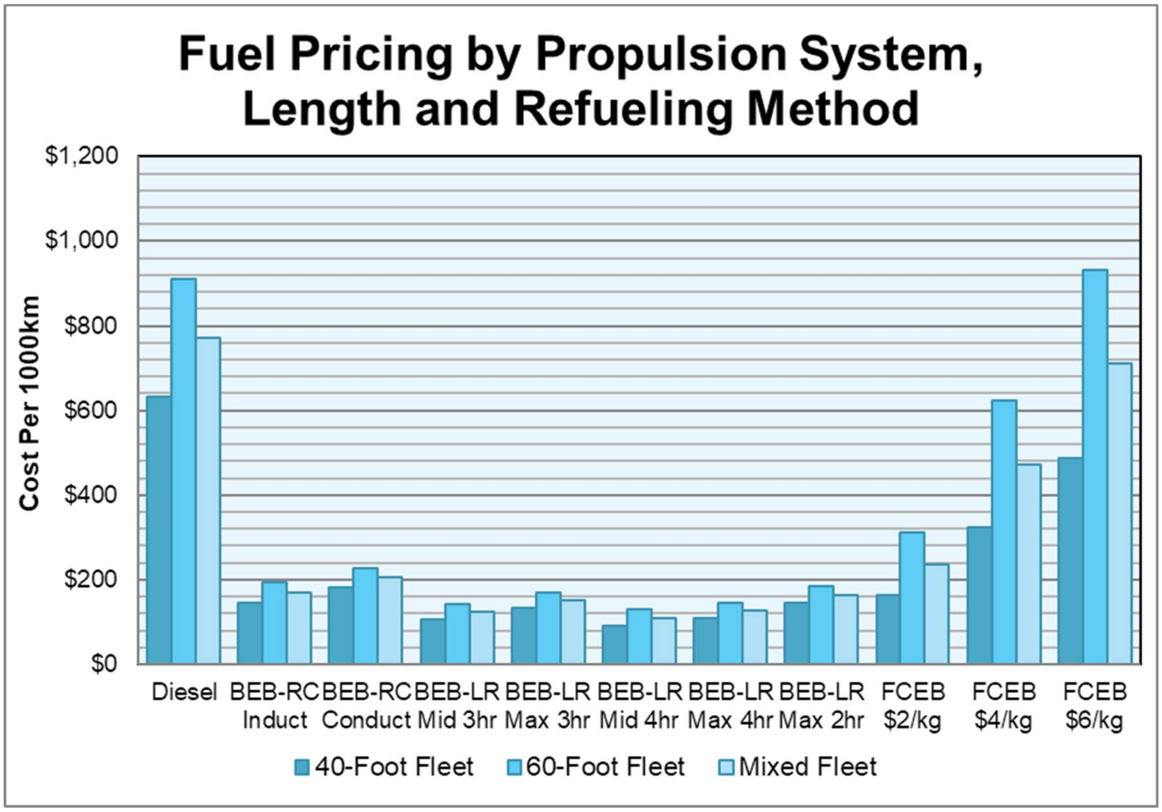


Figure 97: Fueling pricing by propulsion system, length and refueling method

The percentage of 60-foot buses in the fleet has a direct impact on the operating costs of fuel cell battery-electric buses, but has only marginal impact on the operating cost of battery-electric buses. Fuel costs are linear. Larger buses consume more fuel therefore fueling costs go up. Electricity costs however are based on both demand and usage. Since demand charges are mostly the result of the number of chargers installed, this portion of a utility bill is not impacted by fleet mix. The usage portion of the bill will fluctuate based on fleet energy consumption, but as Manitoba has very low energy pricing the extra energy consumed by the larger bus has minimal cost impact.

The cost of operating zero-emission buses may fluctuate monthly. If spikes in energy demand are observed, fleet management software or energy storage systems could be implemented to balance loads and stabilize costs of charging or hydrogen production.

8.2.2.2 Fueling Operations

Buses need to be fueled or charged before they are deployed. Currently diesel buses are washed, cleaned, serviced and fueled in the same track before being parked. Fueling takes place concurrently with other activities. This process will need to be modified for zero-emission buses.

Rapid-charge battery-electric buses primarily charged on-route, and do not necessarily require any charging when they are returned to the garage at the end of a run. If the buses are returned with sufficient energy to return to the charger before their next deployment, they do not need to be parked in a track equipped with chargers. This means they can follow the same process as the diesel buses. In-service time is lost while charging but no additional staff need to be hired or repurposed for refueling.

Long-range battery-electric buses need to charge for several hours. For the test fleet the intention is to locate chargers along two tracks in the parking garage. The buses can follow the same process as the diesel buses, but must be parked in a track equipped with chargers. As the buses would normally be parked in this area regardless, charging while parking adds no extra time to the process.

Fuel cell battery-electric buses need to be fueled with hydrogen at an outdoor fueling station. Indoor fueling would be possible, but is cost prohibitive for a small fleet and will only be considered in the future as part of fleet-wide electrification. Depending on the location of the fill station, fueling will take place either before entering, or after exiting, the service track. All other operations would remain the same and the buses could be parked in any track. Because fueling is outdoors it cannot reasonably be completed concurrently with other service activities. Additional labour associated with fueling outdoors should be considered lost time.

Based on the expected fuel consumption of a fleet of sixteen 40 and 60-foot buses, it can be assumed that fueling would require resource allocation of approximately 2.57 person-hours per day, or just over $24,600 based on 2020 salary levels.

8.2.2.3 Infrastructure maintenance & overhaul

Fueling equipment requires different levels of maintenance based on power and the number of moving parts to service. Transit currently contracts out the maintenance of diesel fueling equipment, and will likely do the same with hydrogen fueling equipment and potentially chargers as well.

With proper maintenance, all chargers are expected to last 15 years without major repair or replacement, and would only require minimal overhaul to extend the life to 18-20 years. Pantographs are only expected to last 12 years or 600,000 cycles, and would need to be replaced at least once during an 18-year period. Similarly, hydrogen fueling equipment is expected to last at least 20 years with proper maintenance, but if Transit is producing fuel on site, electrolyzer stacks would need to be replaced every 9-10 years.

While Transit may get more competitive offers through an open bid opportunity, based on information provided by charger manufacturers and a similarly sized transit agency with hydrogen fueling equipment, Transit should expect to pay the following if charging and fueling maintenance were contracted out:

Table 41: Annual fueling infrastructure maintenance for 16-bus test fleet [220]

Refueling	Annual Maintenance per unit	Mid-life Overhaul Per unit
Diesel	$ 90,000	$ -
Depot Plug-in	$ 10,000	$ 30,000
Depot Overhead	$ 20,000	$ 145,000
On-Route Inductive	$ 15,000	$ 30,000
On-Route Conductive	$ 20,000	$ 145,000
Fuel Dispensing	$ 73,000	$ -
Fuel Dispensing & Production	$ 146,000	$ 150,000

When the capacity of the buses and the available fueling window is considered, each refueling technology is capable of supporting a different number of buses. Based on a 16 bus test fleet, the total estimated cost to maintain fueling equipment over 18 years based on the physical number of chargers and fueling equipment installed can be estimated as follows:

Table 42: Refueling infrastructure maintenance per 1,000 kilometers of travel; 16-bus test fleet

Refueling	Lifetime Maintenance & Overhaul
Diesel	$ 2.76
Depot Plug-in	$ 126.92
Depot Overhead	$ 406.95
On-Route Inductive	$ 40.29
On-Route Conductive	$ 67.83
Fuel Dispensing	$ 88.24
Fuel Dispensing & Production	$ 186.55

8.2.2.4 Summary of fueling Costs

Based on compiled information on vehicle energy consumption, fuel/energy pricing, and fueling equipment, expenses associated with fueling a mixed fleet of zero-emission buses per 1,000 kilometer travel are estimated as follows:

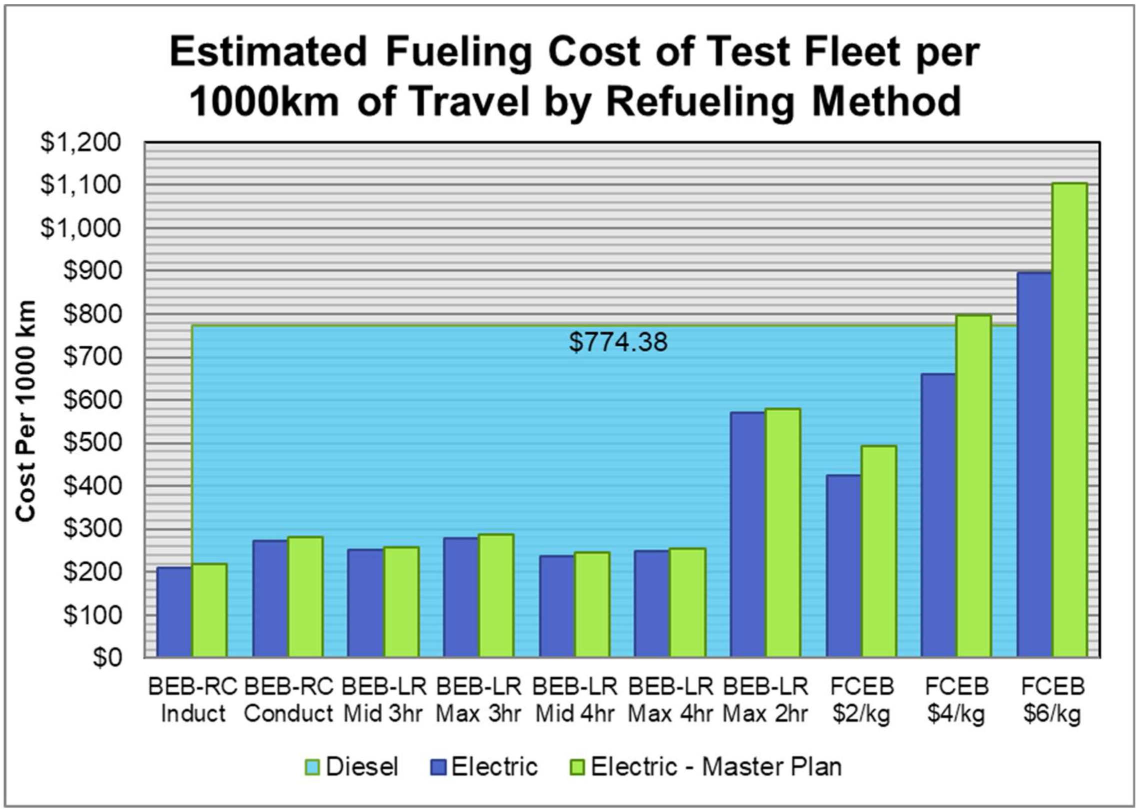


Figure 98: Estimated fueling cost of Zero-Emission buses per 1,000 kilometers

Despite only small differences in energy consumption between models of battery-electric buses, there are significant fueling cost variations based on which charging strategy is utilized. The number of buses and chargers are fixed so there is little variation for bus or charger performance differences. Monthly operating costs can be reduced by simply by lowering charge rates either by limiting power output or implementing load balancing software.

For on-route charging, lowering the charge rate will lower cost but it also negatively impacts service, as longer layovers mean less passenger miles per day. For depot charging, when only a small percentage of the fleet is battery-electric, a larger than normal charging window can be used to lower operating costs without impacting service.

In the case of fuel cell battery-electric buses where operating costs are greatly influenced by fuel pricing, obtaining the lowest price of fuel possible will be critical to managing monthly operating expenses.

Energy consumption increases associated with operating 60-foot buses on rapid transit corridors will result in increased monthly operating expenses for all zero-emission technologies. A fuel cell battery-electric test fleet would be the most impacted by the transition, with an expected increase in operating cost of between 16.1-23.0% depending on the price of hydrogen. To match the operating cost of diesel, Transit would initially need to dispense hydrogen at a price of $4.91/kg, but that price would need to decrease by around $1.10 per kilogram to remain competitive as BRT service increases.

8.2.3 Summary of Annual Operating Costs

Based on an 18 year, 930,700 km life and Transit's current duty cycle, the annual operating costs a 16 bus zero-emission test fleet is estimated to be as follows:

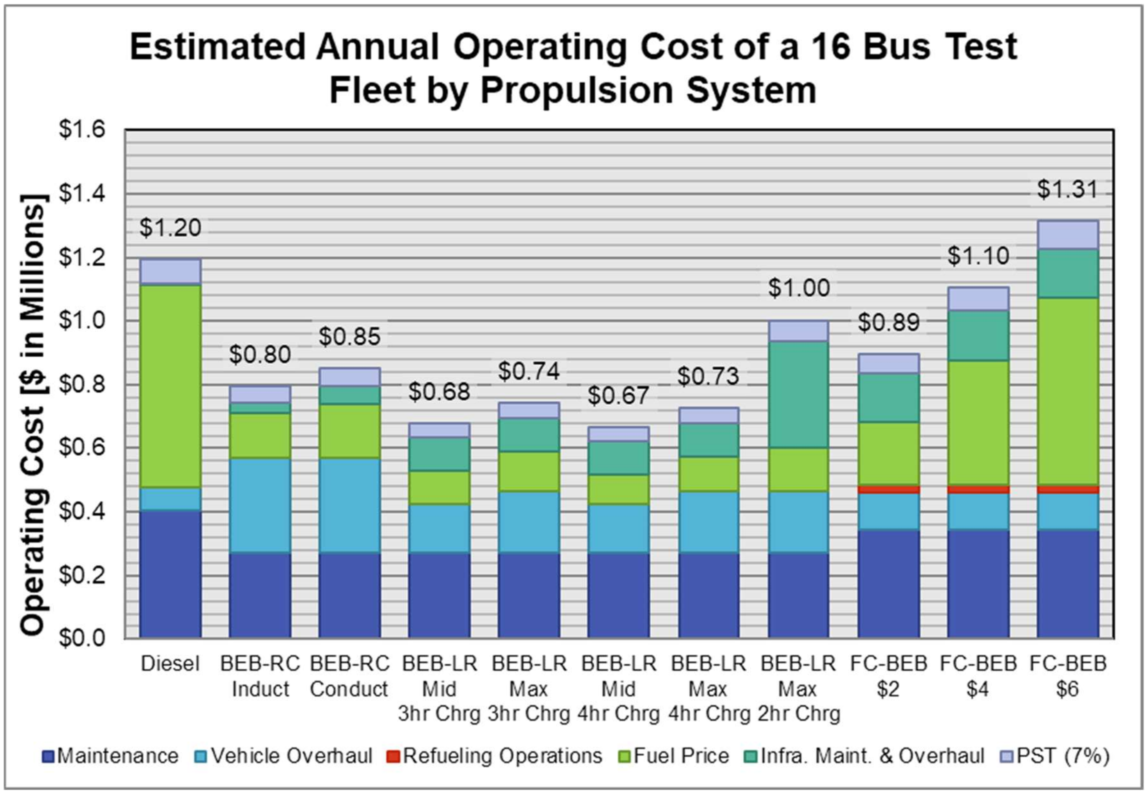


Figure 99: Estimated annual operating cost of zero-emission test fleet vs diesel; current duty cycle

Based on an 18 year, 930,700 km life and Transit's current duty cycle, the estimated annual operational savings from a 16 bus zero-emission test fleet is as follows:

Figure 100: Estimated annual operational savings zero-emission vs diesel; 16-bus test fleet

	Annual Savings	Average Savings per Bus
BEB-LR Mid 4hr Charging	$ 529,810	$ 33,113
BEB-LR Mid 3hr Charging	$ 518,075	$ 32,380
BEB-LR Max 4hr Charging	$ 469,041	$ 29,315
BEB-LR Max 3hr Charging	$ 452,611	$ 28,288
BEB-RC Conductive	$ 399,782	$ 24,986
BEB-RC Inductive	$ 343,541	$ 21,471
FCEB $2/kg	$ 301,288	$ 18,830
BEB-LR Max 2hr Charging	$ 192,992	$ 12,062
FCEB $4/kg	$ 91,799	$ 5,737
FCEB $6/kg	-$ 117,689	-$ 7,356

All zero-emission bus options could potentially have lower operating costs than diesel buses. In the case of fuel cell buses, the average cost of fuel over 18-years will determine whether or not the technology reaches parity with diesel. The cost of hydrogen, infrastructure maintenance, and overhaul spread out over just sixteen buses is the largest reason that the technology does not produce operating savings over 18-years.

The cost of battery replacement has the most significant impact on the overall savings between battery-electric models. Battery life improvements may eliminate or reduce the number battery replacements required over an 18-year period and further improve savings.

In all cases, annual savings should be expected to decrease as BRT service expands.

8.3 Other Cost Considerations

Beyond direct costs relating to purchasing, installing, and operating zero-emission buses, there are a number of indirect costs associated with rolling out this new technology. Some items such as workforce training will be required, while others are optional items that could improve operational efficiency and reduce costs.

8.3.1 Workforce Training

The introduction of zero-emission buses brings with it the need to train, or retrain, employees to safely interact with buses and fueling infrastructure, as well as how to effectively diagnose, service, and repair the vehicles.

Under the Manitoba Workplace Safety and Health Act 2018 s.4(2)(c), Transit must ensure that all employees are *"acquainted with any safety or health hazards which may be encountered by the workers in the course of their service, and that workers are familiar with the use of all devices or equipment provided for their protection."*

Transit should take a multi-level approach to training to ensure all staff receive adequate information to safety perform their duties. Employee training can be obtained through a combination of formal education, manufacturer specific training, and in-house programs. A five-level approach to employee safety training is recommended.

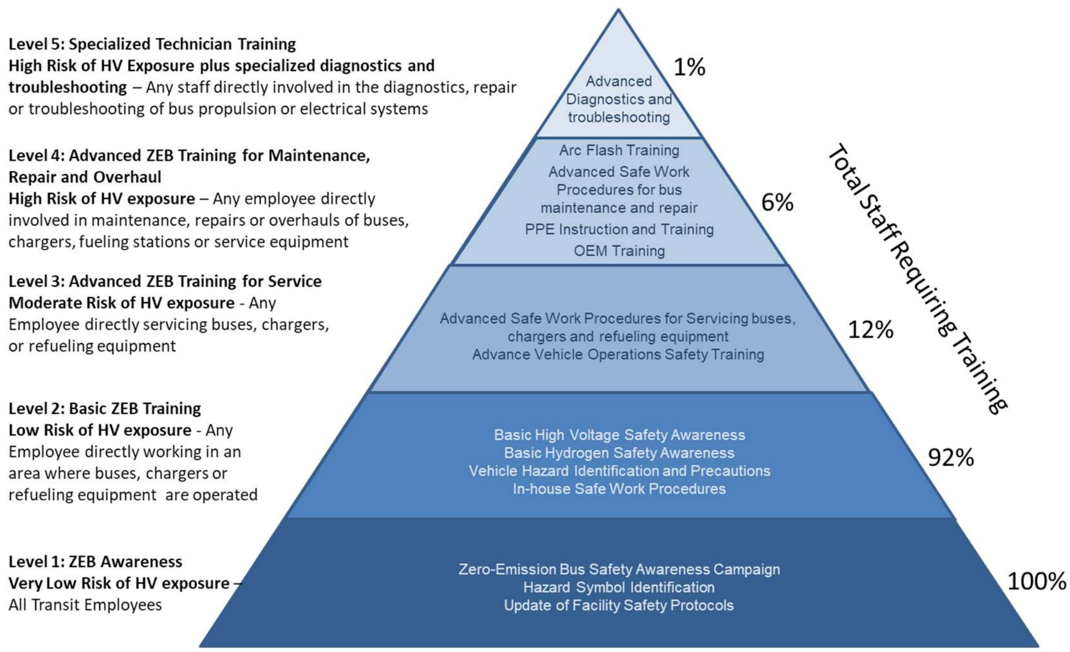


Figure 101: Five-level approach to employee safety training

8.3.1.1 Basic Training

Level 1 and 2 meet the needs of most Transit employees. Transit has previously developed learning modules during the battery-electric bus demonstration. These modules likely require only minimal updates to align with current technology.

Level 1: ZEB Awareness – Very Low Risk of HV exposure – All Transit Employees

It is recommended that Transit develop a zero-emission bus awareness campaign to alert all staff of the introduction of a new technology, and update them on any new policies and procedures being implemented for employee safety.

Affected Divisions:

- Operations: Administration, Inspectors, Instructors, Operators, Control Centre
- Plant & Equipment: Administration, Vehicle Maintenance and Overhaul, Bus Servicing, Facilities Maintenance
- Service Development
- Asset Management Office
- Finance and Administration
- Communications
- Information Services
- Human Resources

Scope of Training:

- Zero-emission bus safety awareness campaign
- Hazard symbol identification
- Refresh of facility safety protocols

Estimated Training Duration: 1 hour

Recommended training group: 1721 employees
Minimum required training group for test fleet: 1721 employees

Level 2: Basic ZEB Training – Low Risk of HV exposure - Any Employee directly working in an area where buses, chargers, or fueling equipment are operated, or those directly responsible for related training and development.

Employees that interact directly with buses, chargers, or fueling equipment should receive additional training to familiarize themselves with buses, chargers and fueling equipment layouts as well as built in safety features. Training should include basic high-voltage and hydrogen safety, with a focus on safe work procedures.

Electrical safety training is readily available through many occupational safety training providers. Transit could also develop an in-house program.

Affected Divisions:

- Operations: Administration, Inspectors, Instructors, Operators, Control Centre
- Plant & Equipment: Administration, Vehicle Maintenance and Overhaul, Bus Servicing, Facilities Maintenance
- Service Development
- City of Winnipeg, Innovation – Communications Systems Branch

Scope of Training:

- Level 1
- Bus familiarization
- Basic high voltage safety awareness
- Basic hydrogen safety awareness
- Vehicle hazard identification and precautions
- Operations safety training
- In-house safe work procedures

Estimate Training Duration: 4 hours

Recommended training group: 1585 employees
Minimum required training group for test fleet: 97 employees

8.3.1.2 Advanced Training

Levels 3 and 4 should be developed for employees with increased risk of high voltage exposure through service or maintenance, while Level 5 training would be reserved for specialized technicians only. During Transit's battery-electric bus demonstration, service and maintenance of the vehicle's propulsion system was performed by New Flyer, therefore Transit has very few existing in-house safe work procedures to draw upon. New in-house learning modules will need to be developed, while some advanced training will need to be supplemented with formal education.

The following levels are recommended for advanced training, however, exact training should be refined and applied as roles and responsibilities of each area are established.

Level 3: Advanced ZEB Training for Service – Moderate Risk of HV exposure - Any employee directly responsible for servicing buses, chargers or fueling equipment, or those directly responsible for related training and development.

Employees that service buses, chargers, or fueling equipment should receive additional training to familiarize themselves with safe work procedures for servicing buses, chargers, and fueling equipment. This training should include instruction on service procedures, as well as tools and personal protective equipment required to perform service.

Affected Divisions:

- Operations: Instructors
- Plant & Equipment: Vehicle Maintenance and Overhaul, Bus Servicing, Facilities Maintenance

Scope of Training:

- Levels 1 & 2
- Advanced safe work procedures for servicing buses, chargers, and fueling equipment
- Advanced vehicle service safety training
- Fueling infrastructure safety training
- Facility emergency response procedures for service and parking garage
- Tools and equipment for zero-emission bus service
- Basic PPE Instruction and Training
- Vendor and OEM service training

Estimated Training Duration: 16 hours In-House or OEM training

Recommended training group: 205 employees
Minimum required training group for test fleet: 36 employees

Level 4: Advanced ZEB Training for Maintenance – High Risk of HV exposure – Any employee directly responsible for repair and overhaul of buses, chargers, fueling equipment, or service equipment.

Employees that repair or overhaul buses, chargers, or fueling equipment should receive additional training to familiarize themselves with safe work procedures for maintaining, repairing, or overhauling buses, chargers, and fueling equipment. This training should include instruction on service procedures, as well as tools and personal protective equipment required to preform repairs. Employees at this level should also receive formal arc flash training.

Affected Divisions:

- Operations: Instructors
- Plant & Equipment: Vehicle Maintenance and Overhaul, Facilities Maintenance

Scope of Training:

- Levels 1-3
- Arc Flash training
- Advanced safe work procedures for bus maintenance and repair
- Advanced vehicle maintenance safety training
- Advanced PPE instruction and training
- Tools and equipment for zero-emission bus maintenance
- Facilities emergency response procedures for maintenance garage

- Vendor and OEM maintenance training

Estimated Training Duration:

- 16 hours In-house training or OEM training
- Completion of RRC Introduction to Electric Vehicles Program Modules 1 & 2
- Arc Flash Training
- First Aid Training

Recommended training group: 110 employees
Minimum required training group for test fleet: 16 employees

Level 5: Specialized Technician Training – High Risk of HV Exposure plus specialized diagnostics and troubleshooting – Any staff directly involved in the diagnostics, repair, or troubleshooting of bus propulsion and electrical systems, or charging and fueling infrastructure.

This training would be required only for a few specialized mechanics & supervisors, as well as facility electricians who support charging or fueling infrastructure. This training should include theory and hands on training in electrical schematics, J1939 communication protocol, vehicle multiplexing systems, ladder logic, and any vehicle specific software required for advanced diagnostics and troubleshooting.

Affected Divisions:

- Plant & Equipment: Vehicle Maintenance and Overhaul, Facilities Maintenance

Scope of Training:

- Levels 1-4
- Advanced diagnostics and troubleshooting of vehicles
- Advanced diagnostics and troubleshooting of facilities and equipment

Estimated Training Duration:

- 16 hours In-House training or OEM training
- Completion of RRC Introduction to Electric Vehicles Program Modules 1-3

Recommended training group: 15 employees
Minimum required training group for test fleet: 4 employees

A more detailed breakdown of department training requirements for full fleet electrification is outlined below:

Table 43: Summary of employee training requirements at full fleet

Department	Level 1	Level 2	Level 3	Level 4	Level 5
Plant & Equipment - Vehicle overhaul/Maintenance	186	186	130	90	10
Plant & Equipment - Bus Servicing	59	59	40	0	0
Plant & Equipment - Facilities Maintenance	44	44	30	20	5
Plant & Equipment - Admin	30	30	0	0	0
Operations - Bus Operators	1158	1158	0	0	0
Operations - Inspectors	63	63	0	0	0
Operations - Instructor	19	19	5	0	0
Operations - Admins	16	16	0	0	0
Information Systems	18	2	0	0	0
Service Development	12	3	0	0	0
AMO	6	0	0	0	0
Business Centre	19	0	0	0	0
Communications	7	0	0	0	0
Customer Service	18	0	0	0	0
Finance & Admin	14	0	0	0	0
HR	11	0	0	0	0
Transit Plus	41	0	0	0	0
City of Winnipeg Innovation - Communications Systems	0	5	0	0	0
Total	**1721**	**1585**	**205**	**110**	**15**

8.3.1.3 Training Cost for Test Fleet

Based on internal discussions, Transit expects to train the following number of employees to support a test fleet of up to 16 zero-emission buses:

Table 44: Summary of employee training requirements for test fleet

Department	Level 1	Level 2	Level 3	Level 4	Level 5
Plant & Equipment - Vehicle overhaul/Maintenance	186	30	20	12	4
Plant & Equipment - Bus Servicing	59	10	7	0	0
Plant & Equipment - Facilities Maintenance	44	4	4	4	2
Plant & Equipment - Admin	30	2	0	0	0
Operations - Bus Operators	1158	32	0	0	0
Operations - Inspectors	63	2	0	0	0
Operations - Instructor	19	5	5	0	0
Operations - Admins	16	2	0	0	0
Information Systems	18	2	0	0	0
Service Development	12	3	0	0	0
AMO	6	0	0	0	0
Business Centre	19	0	0	0	0
Communications	7	0	0	0	0
Customer Service	18	0	0	0	0
Finance & Admin	14	0	0	0	0
HR	11	0	0	0	0
Transit Plus	41	0	0	0	0
City of Winnipeg Innovation - Communications Systems	0	5	0	0	0
Total	**1721**	**97**	**30**	**16**	**6**

Initially, Transit will be heavily reliant on training modules provided by bus and infrastructure original equipment manufacturers (OEM). Bus OEMs typically include some training with each new bus contract, as well as offering additional training for purchase. A typical offering includes:

1. Vehicle Introduction & Safety
2. Operator Training
3. Vehicle Maintenance Training
4. Vendor Training
5. First Responder Training for local emergency first responders

Class sizes are usually limited with the included training, so a “train-the-trainer” approach is recommended to strategically train lead technicians and supervisors in the operations and plant and equipment divisions. The information gained through OEM and vendor training should be utilized to develop a robust in-house training program to roll out to future training cohorts.

It is expected that training for one group of six, up to Level 4, would be included in any contract to purchase buses, and that additional 16-hour training modules could be purchased at a cost of $8,100 each. It is likely that a single train-the-trainer session would be adequate for the establishment of in-house training for Levels 1 and 2. Because of the complex nature of bus service and maintenance, it is recommended that Transit plan to purchase additional OEM training modules for all employees requiring Level 3 or higher.

Transit has previously utilized Safety Services Manitoba (SSM) for Arc Flash training, as well as Basic First Aid and CPR training. Continuing to utilize occupational safety training centres will ensure that employees receive consistent and up-to-date information in this area. Transit should expect a higher number of employees to require arc flash and first aid training as the zero-emission bus fleet grows.

There are currently no provincial licensing requirements for electric vehicle mechanics. Red River College is currently working with Transit to develop an “Intro to Electric Vehicle Technology” course, which will provide technicians the training and expertise required to work on zero-emission buses. This program contains advanced safe work practices and procedures, and provides hands on experience with the tools and equipment required for zero-emission bus maintenance. This course will likely be integrated into their Automotive Technician Certificate program and could be utilized to pilot new Red Seal certifications of electric vehicle mechanics, similar to what is being launched in British Columbia [221].

Red River College has indicated that six Transit employees could pilot a proposed Level 5 training program free of charge, in order to test the curriculum. Once the program is officially launched, it would be offered based on a fixed cost per person. As Transit’s zero-emission bus fleet increases, current employees could receive training through this program. Future graduates of the Automotive Technician Certificate program would likely be equipped with the skills necessary to service or repair zero-emission buses, eliminating the need for Transit to retrain.

Based on these assumptions, the estimated training cost associated with launching a test fleet of 16 zero-emission buses would be as follows:

Table 45: Estimated cost of training with New Flyer buses

	Cost
Level 1	$ 0
Level 2	$ 0
Level 3	$ 32,500
Level 4	$ 20,000
Level 5	$ 0
Total	**$ 52,500**

If Transit purchases buses from anyone other than New Flyer, significantly more training would be required, as mechanics would need to be trained on all systems, rather than just BEB specific systems. This is further complicated if Transit splits a procurement between multiple manufacturers. New Flyer is currently the only manufacturer with both 40-foot and 60-foot fuel cell battery-electric buses, therefore it is likely that a split procurement involving both battery-electric and fuel cell battery-electric buses would require New Flyer training, as well as additional training from a second OEM.

While New Flyer has trainers based in Winnipeg, all other manufacturers would require additional travel expenses to bring trainers to Winnipeg.

Table 46: Estimated cost of training with mixed fleet of New Flyer and another manufacturer with structure steel body

	Cost
Level 1	$ 0
Level 2	$ 0
Level 3	$ 73,000
Level 4	$ 39,500
Level 5	$ 10,000
Total	**$ 122,500**

If Transit purchases Proterra buses a further $20,250 would need to be added to account for additional Structural Composite training.

Table 47: Estimated cost of training with mixed fleet of New Flyer and Proterra composite body buses

	Cost
Level 1	$ 0
Level 2	$ 0
Level 3	$ 73,000
Level 4	$ 59,500
Level 5	$ 10,000
Total	**$ 142,500**

Transit should also consider including annual refresher courses for operators, mechanics, and technicians, as information may be forgotten if people are infrequently working on, or with zero-emission buses.

8.3.2 Public Engagement

The City of Winnipeg encourages public engagement on major projects to inform, involve, and collect feedback from residents to ensure that projects are aligned with community values.

In the case of a zero-emission bus test fleet, Transit likely does not require consultation or collaboration from residents, but should consider a public information engagement.

To adequately inform the public, Transit should budget for the creation of promotional material such as advertising and information handouts for open houses, as well as website updates.

It is estimated that Transit should budget no more than $35,000 for an engagement of this size.

8.4 Annual Operating Increases

Continual improvement initiatives at Winnipeg Transit, including additions to the fleet and service changes, generally results in annual maintenance costs increasing at a rate greater than inflation. Between 2015 and 2019, vehicle maintenance costs relating to diesel buses increased by an average of 4% annually. The introduction of zero-emission buses would require significantly more planning and preparation than a typical continual improvement initiative. Therefore, Transit should expect some operating costs related to zero-emission buses to increase annually at a higher percentage.

To account for additional administration, hiring, training and development, and salary realignments associated with the introduction of zero-emission buses, 1% will be added, making the annual increase 5% rather than 4%. This should better reflect incremental costs resulting from transitioning Winnipeg Transit’s workforce to support zero-emission buses.

The cost of electricity used to charge buses and produce hydrogen is not affected by labour. Manitoba Hydro rates have increased by an average of 3% between 2016 and 2020, and as such, fuel pricing for zero-emission buses is assumed to also increase by 3% annually. Diesel prices are more volatile, but is assumed to increase at the City of Winnipeg’s recommended operation and maintenance inflation rate of 2% annually.

Table 48: Rate table for annual inflation

	Rate of Inflation Diesel Operations	Rate of Inflation ZEB Operations
Maintenance	4%	5%
Vehicle Overhaul	4%	5%
Fuel Price	2%	3%
Refueling Operations	4%	5%
Infrastructure Maintenance & Operations	4%	5%

8.5 Cost to Purchase, Operate, and Maintain a Fleet of Sixteen Zero-Emission Buses and Associated Infrastructure

Based on an 18-year, 930,700 km life, Transit's current duty cycle, operations starting in 2022, and adjusted for annual inflation up to 2030, the lifetime capital and operating costs of a small test fleet of zero-emission buses is estimated to be as follows:

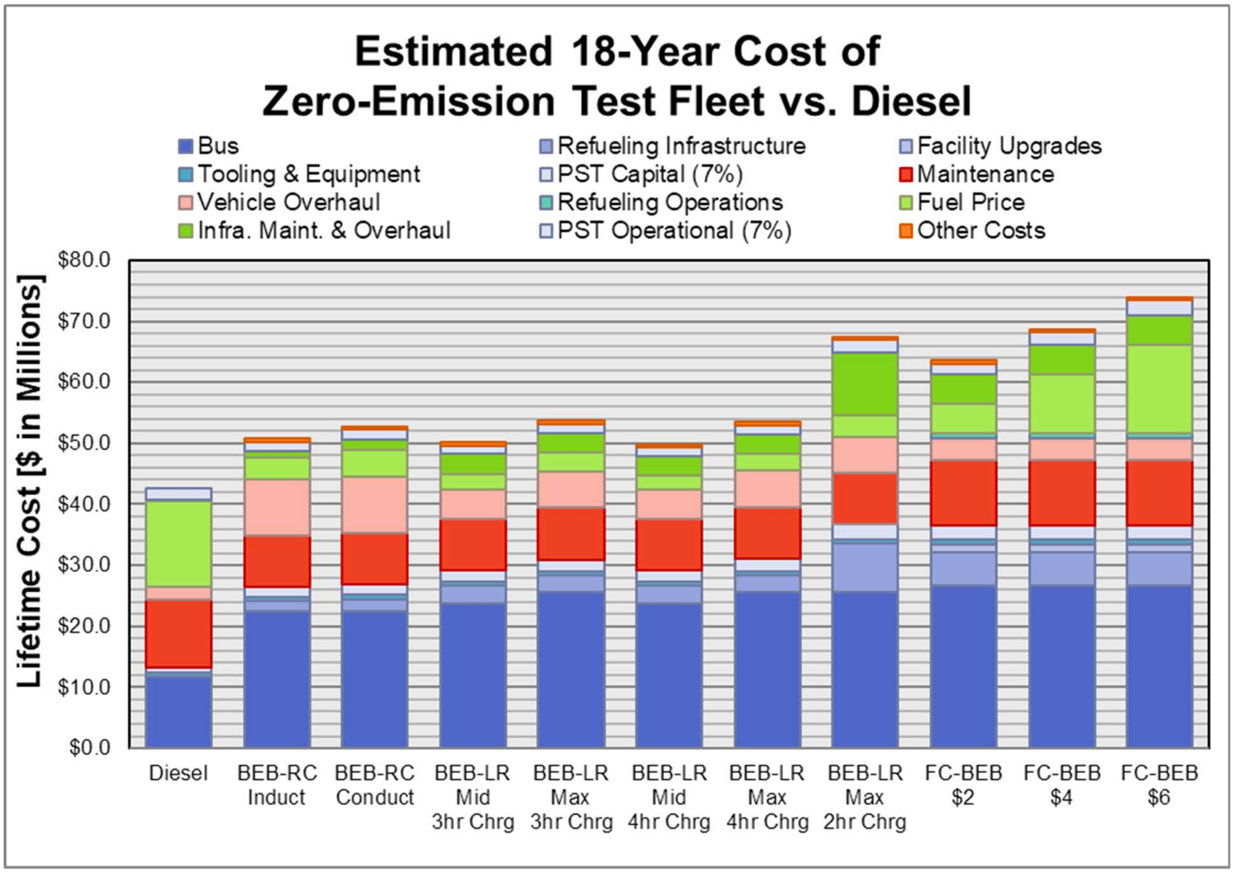


Figure 102: 18-year lifecycle costs of a zero-emission test fleet compared to diesel replacement

Despite significant operational savings, the initial purchase price of zero-emission buses plus additional supporting infrastructure remains a barrier to the technology reaching parity with diesel bus costs over an 18-year useful life. Without receiving any funding to offset the incremental capital expenses, the lifecycle costs to purchase and operate a zero-emission test fleet will not break even with diesel buses over their 18-year useful life.

There are various federal programs available to supplement the capital costs associated with zero-emission vehicles and infrastructure. Investing in Canada Infrastructure Program (ICIP) - Public Transit Infrastructure Stream (PTIS) is a program commonly used by Transit, but there are other programs which could also be utilized.

Regardless of which funding model is selected, Federal funding is available up to a maximum of 50%, with the total funding from provincial and federal funds not to exceed 75%.

Under ICIP-PTIS the federal contribution would be capped at 40% and the provincial contribution at 33.3% of eligible expenses. Based on an 18-year, 930,700 km life and Transit's current duty cycle, the lifetime capital and operating costs with a PTIS eligible project are estimated to be as follows:

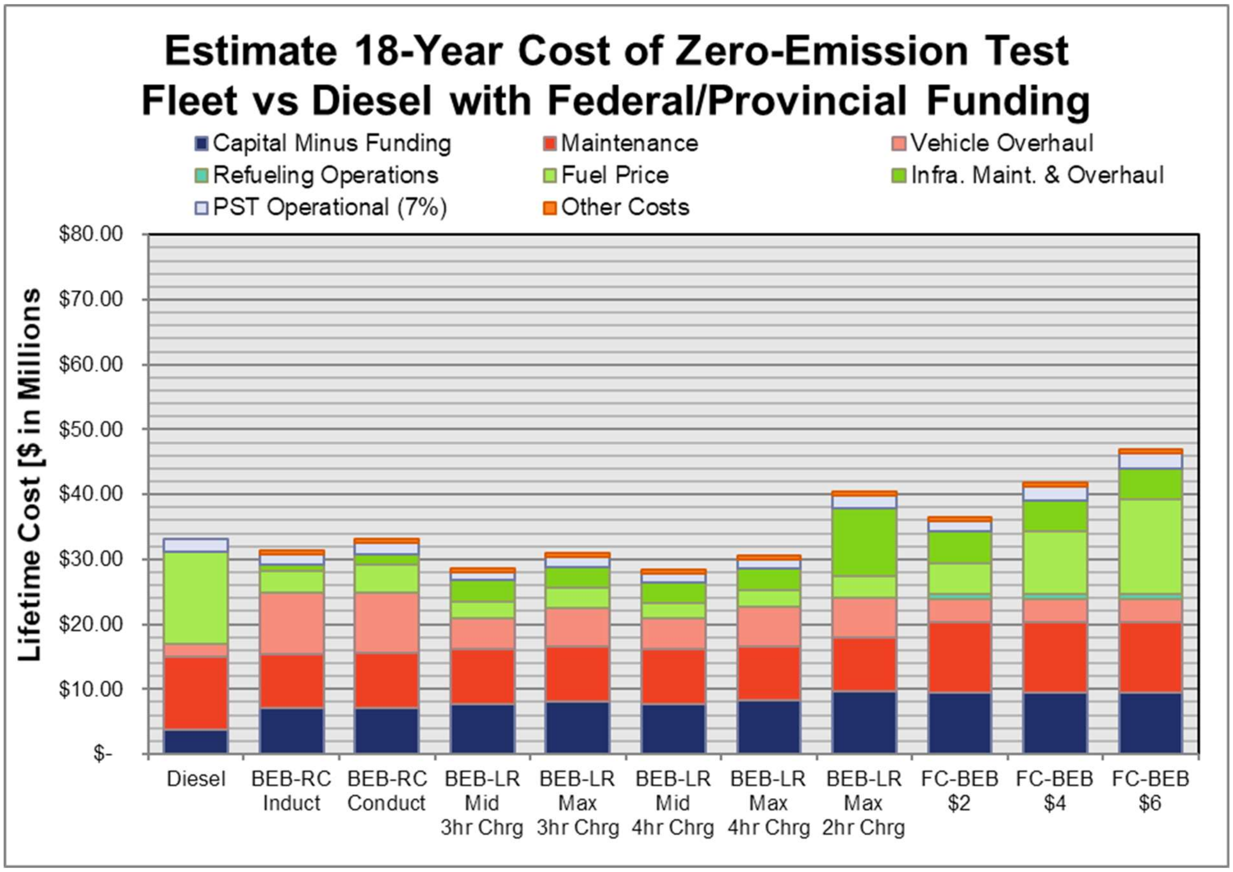


Figure 103: 18-year lifecycle costs of an ICIP-PTIS funding zero-emission test fleet compared to diesel replacement

With initial capital investment reduced through the support of the Federal and Provincial Governments, the case for zero-emission buses is significantly stronger. Procurements which include long-range zero-emission buses will have a higher amount of eligible expenses, and therefore will benefit from the greatest cost reduction with funding.

Table 49: Return on Investment of a zero-emission bus test fleet

	ROI	
	No Funding	**ICIP**
BEB-LR Mid 3hr Charging	>25-years	8-years
BEB-LR Mid 4hr Charging	>25-years	8-years
BEB-LR Max 3hr Charging	>25-years	10-years
BEB-LR Max 4hr Charging	>25-years	10-years
BEB-RC Inductive	>25-years	10-years
BEB-RC Conductive	>25-years	13-years
FC-BEB $2/kg	>25-years	>25-years
BEB-LR Max 2hr Charging	>25-years	>25-years
FC-BEB $4/kg	>25-years	>25-years
FC-BEB $6/kg	>25-years	>25-years

The use of operational savings to offset capital costs is possible with all technologies, but in the case of FC-BEBs, a source of extremely low-cost hydrogen would be required to do so. Based on current hydrogen pricing, it is likely that a small fleet of FC-BEBs will result in higher operating costs than diesel buses, and 18-year lifecycle parity will not be possible. It will however, be possible for a small fleet of BEBs to produce lifetime savings over diesel if an appropriate charging strategy is selected.

Table 50: Estimated Lifetime savings of a small electric test fleet by technology and refueling strategy compared to diesel

	Lifetime Savings	Avg. Lifetime Savings/Bus	Avg. Annual Operating Savings/Bus
BEB-LR Mid 4hr Charging	$ 5,380,937	$ 336,309	$ 32,599
BEB-LR Mid 3hr Charging	$ 5,089,417	$ 318,089	$ 31,587
BEB-LR Max 4hr Charging	$ 3,150,644	$ 196,915	$ 26,481
BEB-LR Max 3hr Charging	$ 2,866,835	$ 179,177	$ 25,064
BEB-RC Inductive	$ 2,336,560	$ 146,035	$ 19,702
BEB-RC Conductive	$ 682,179	$ 42,636	$ 14,329
FCEB $2/kg	-$ 2,815,937	-$ 175,996	$ 10,386
BEB-LR 2hr Charging	-$ 6,623,614	-$ 413,976	-$ 2,644
FCEB $4/kg	-$ 8,019,708	-$ 501,232	-$ 7,683
FCEB $6/kg	-$ 13,223,479	-$ 826,467	-$ 25,751

8.6 Future Cost Considerations

The following additional costs are not essential to the deployment of a zero-emission test fleet, but operational savings would likely be increased with their implementation. Investing in this technology would result in changes to both capital and operational costs. Return on investment would need to be evaluated in greater detail to determine whether or not these items should be included with a test fleet.

8.6.1 Depot Management Software

There are two different types of software that are recommended to be implemented in conjunction with the launch of zero-emission buses, Charger Management Software and Yard Management Software.

8.6.1.1 Charger Management Software

Chargers are able to operate independently, but they can also be integrated into a charger network. Charger management software is utilized to monitor, report, optimize, and control networked charging infrastructure to improve efficiencies and lower energy costs.

When the number of zero-emission buses in a fleet are small, Transit will have more flexibility relating to charge time and charge power. Operating a small number of chargers at maximum power simultaneously will result in high monthly demand charges, but the costs are still manageable when compared against diesel fuel pricing. Transit can manually control demand charges as the fleet grows by limiting the number of chargers purchased. This, however, may un-necessarily complicate operations, particularly during the transition from conventional diesel to electric.

Entry-level charger management software collects data on charging events and reports key performance indicators such as energy usage and charger efficiency. It will also report errors and operations outside of normal parameters. Transit agencies will still need to manually review the data and develop appropriate responses, but the quantity and quality of data available to support decisions will be improved.

Smart charging is offered at the next level up. Smart charging introduces load balancing and load shifting, where power distribution to the chargers is automatically adjusted based on parameters set by the transit agency. These parameters can include fixed power limits, bus schedules, and energy pricing. The software develops a charging schedule based on those parameters to lower energy costs.

Development in this area is expanding, and further review of available packages and interoperability may be required closer to the time of purchase. Transit should ensure that any software selected is OCPP (Open Charge Point Protocol) compliant to allow for maximum flexibility relating to charger vendors.

Software pricing varies widely. Some vendors are currently offering software on a long-term contract based on the chargers purchased, while others offer their software with a renewable annual licence. Some charger management software packages include yard management modules while others are charging specific. There may be cost savings from selecting a vendor who provides both. It is recommended that Transit further refine their zero-emission bus deployment strategy before deciding to implement charger management software. There is no requirement to have software in place prior to the launch of the test fleet.

8.6.1.2 Yard Management Software

Yard Management Software focuses on scheduling, dispatching and depot management. While Transit currently utilizes software to manage these functions, new modules are now available to address the unique depot management challenges associated with battery-electric buses and charging, although the same software can also be utilized for managing other types of buses.

Scheduling software will need additional inputs such as onboard energy, energy consumption, state of charge limitations, charger locations and charge rates to adequately develop zero-emission bus schedules. Energy consumption might also need to vary through the day based on expected passenger and HVAC loads. All of these factors will need to be considered when developing zero-emission specific runs. Utilizing scheduling software with integrated electric bus modules will greatly simplify this process and allow Schedulers to test various different scenarios to optimize bus and charger utilization.

Beyond the need to develop unique schedules zero-emission buses management is further complicated by charging restrictions. When zero-emission buses return to the depot at the end of a run they cannot be assigned to a random parking location, their parking assignment must be targeted based on their next assignment. If the buses need to be charged they need to be assigned to a location with a charger. If the bus does not require charging, they still have to be strategically located such that they can be dispatched to the appropriate run at the appropriate time and are not blocked by a bus on a charger.

Automatic depot management software can be used to evaluate these restrictions and develop parking assignments to minimize unnecessary bus movement. Each bus configuration, including length, fuel time, and maximum charge rates, will need to be evaluated against the service, maintenance and dispatch schedules. Once developed, dispatch can then monitor the assignments and manually override if adjustments need to be made, such as when a bus arrives with a lower SOC than expected or if a charger is down for repair.

Dispatching software can monitor the schedule and parking assignments and provide location data to operators.

As with charger management software, there is no requirement to have any new yard management software in place prior to the launch of the test fleet. Feedback from the zero-emission bus trial may determine whether or not implementation of yard management software is necessary, or may become necessary, as the fleet grows. Further review from Transit’s Information Systems team is required to determine which packages best integrate with Transit’s current processes and software.

8.6.2 Microgrids

Both charging and on-site hydrogen generation require significant amounts of energy. Charging is very efficient, but charging multiple buses simultaneously results in spikes in demand. Spikes in demand will increase monthly electricity costs and affect the average fuel price cost per kilometer of travel. For a similarly sized fleet, production of hydrogen via electrolysis generally results in lower peak demand than charging, but the process is less efficient and utilizes nearly three times more energy than charging.

Many utilities have implemented time-of-use pricing for both demand and energy to encourage people to reduce electricity usage between 6am and 10pm. Manitoba Hydro has not yet implemented time-of-use rates, but it is possible that this may be implemented in the future. All of these items lead to potential uncertainty in fuel pricing for electric vehicles.

In addition, Manitoba Hydro has indicated that any service capacity expansion at Brandon Garage would be limited to a maximum of 2,500 kVA, and that there is no ability to further expand capacity at Fort Rouge Garage. It may be possible for Manitoba Hydro to support increases beyond this, but it would take 4-5 years for them to update their distribution system, and there would be a large cost associated with a project of that size.

To stabilize and potentially reduce fuel pricing or to expand electrical capacity, transit agencies are looking to implement microgrid energy systems (microgrids).

Microgrids are localized energy networks that utilize self-generated energy from sources such as solar or wind to supply power to buildings or equipment. Microgrids can be completely self-contained or partially grid tied. Transit currently has significant amounts of unutilized space on top of their transit and maintenance garages that could potentially be used for solar photovoltaic (PV) installations.

8.6.2.1 Brandon Garage Solar PV Feasibility Study

Winnipeg Transit hired Core Renewable Energy to assess the self-generation capabilities of a potential roof mounted solar PV installation on top of Brandon Garage [92]. The roof was determined to have sufficient space to configure 2,520 PV-panels. Based on current technology limitations, a configuration of this size would be capable of producing up to 1,109 kW of power under ideal conditions.

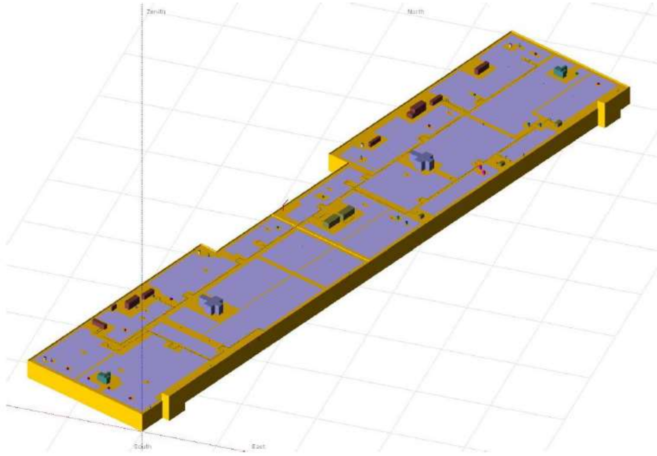


Figure 104: Winnipeg Transit Brandon Garage Microgrid, 1.1 MWdc Solar PV layout

Based on site limitations due to seasonal light variations, climate, weather, and shading as well as system losses it is estimated that a solar installation of this size could potentially produce 1,341 MWh of energy annually, with an approximate decline in output of 0.8% each year. This amount of self-generated energy could charge a fleet of nineteen 40-foot, or ten 60-foot BEBs, or to produce enough hydrogen for a fleet of six 40-foot, or three 60-foot FC-BEBs.

Daily and seasonal variations would necessitate a Winnipeg Transit based microgrid remaining grid tied, as ensuring consistent power for charging or hydrogen production would be essential.

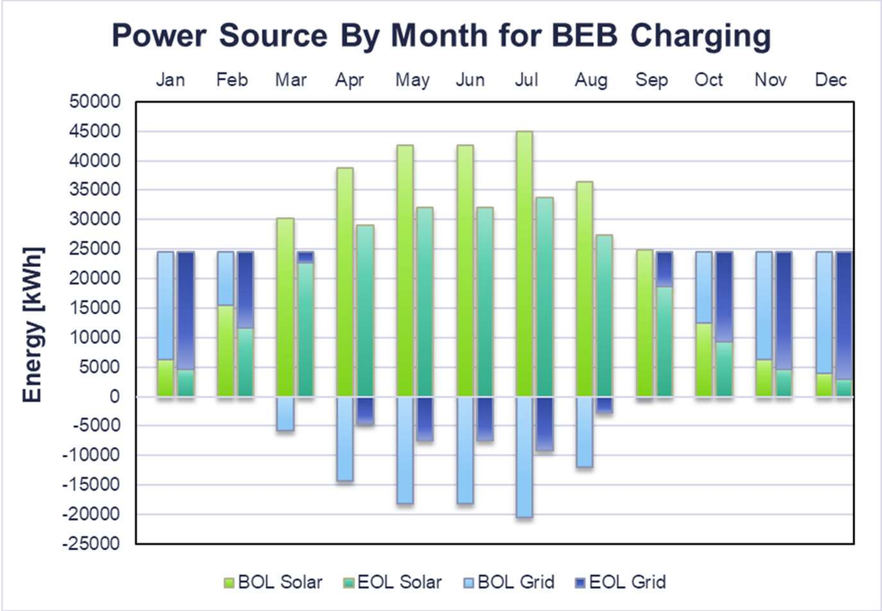


Figure 105: Power source for charging 16 BEB by month based on estimated PV System normalized production

A solar PV microgrid would be capable of self-generating approximately 6,400 kWh per day in July, but only 550 kWh per day in December. The average weekly energy consumption of a 16-bus electric fleet is estimated to be 24,570 kWh per week, with weekday usage peaking around 4,300 kWh. Other loads at the Brandon garage average around 4,000 kWh/day with slight variations month to month.

The amount of electricity being generated also varies throughout the day. If a microgrid is equipped with a battery based energy storage system, then excess energy not immediately being consumed can be stored for later use. If the system is not equipped with storage, excess energy is either lost or returned to the grid if the system is equipped with net-metering.

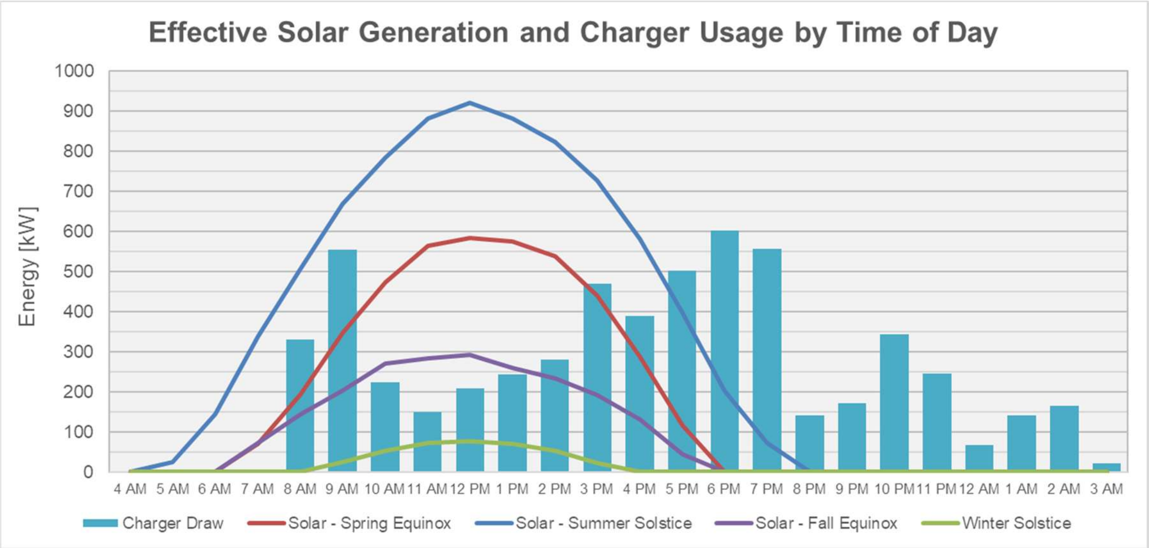


Figure 106: Effective solar power generation compared with estimated charger energy usage by time of day [92].

During the summer, a rooftop solar installation would typically be able to generate more total energy than a small fleet of zero-emission buses would typically require for charging; however, the electricity is not necessarily being generated when charging is occurring. To have better control over when and how self-generated electricity is being managed, a microgrid should be equipped with an energy storage system. This is particularly important if solar PV is to be used for peak-shaving periods of high power demand resulting from simultaneous charging loads, or to time-shift grid usage if Manitoba Hydro implements time-of-use rates.

Without energy storage any excess energy not being consumed by the building or chargers would be load shed. Manitoba Hydro does offer net-metering, which could allow Transit to sell excess energy back to the grid; however, the cost to sell is lower than the cost to purchase. Net-metering would effectively lower the kWh price of energy from $0.0395/kWh to $0.01/kWh for the equivalent number of electrons purchased from the grid [64] [92].

The total combined daily energy requirements of the building and the chargers is likely to exceed the daily energy output of a rooftop solar installation. Equipping the systems with energy storage would allow 100% of self-generated electricity to be captured and consumed at a later time. The system would still need to be grid tied to ensure stable power throughout the year.

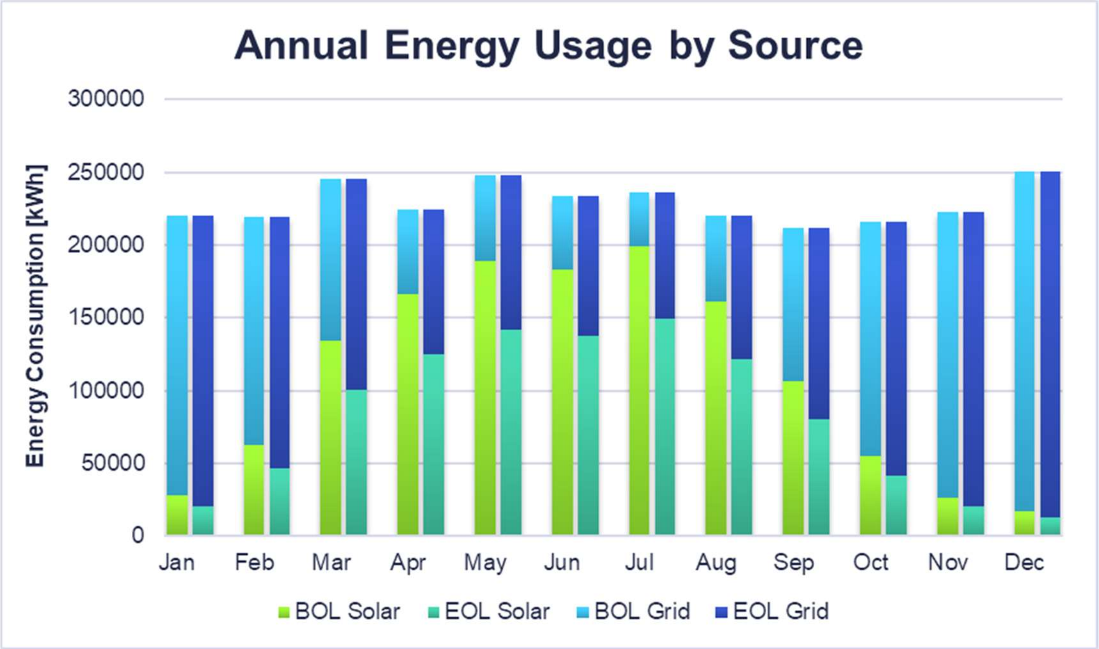


Figure 107: Annual estimated consumption building and chargers grid tied-solar

While a solar PV microgrid without energy storage does not work well for charging, it would potentially work effectively if Transit operates an electrolyzer for the purpose of generating hydrogen. A 1.0 MW or greater electrolyzer would be necessary to support a fleet of sixteen fuel cell battery-electric buses. When operated at 100% capacity, an electrolyzer of this size could utilize all power generated by solar PV, even in the summer. If operations do not necessitate running the electrolyzer at full 100% capacity 24 hours per day, 7 days a week, then production capacity could be scaled up during the day to take advantage of the availability of self power electricity, and reduced to a lower level in the evening to reduce grid loads. Based on the current predicted system performance, Transit could potentially produce up to 26,644 kg of hydrogen from solar annually. This would offset approximately 27% of the total hydrogen needed for a sixteen bus fleet.

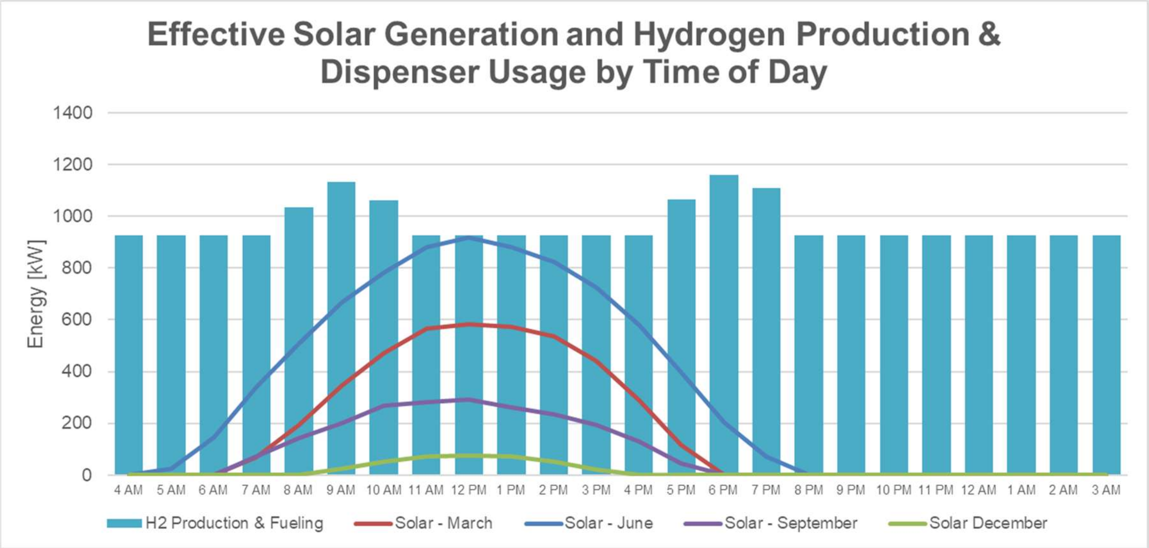


Figure 108: Effective solar power generation compared with hydrogen production and dispenser energy usage by time of day [92].

8.6.2.2 Microgrid Cost Considerations

Return on investment (ROI) of a solar PV microgrid is not easy to calculate. Monthly electricity costs are a combination of peak demand and energy usage. Microgrids have the potential not just to reduce energy usage through the use of self-generated electricity, but also the ability to reduce peak power through load balancing. Some savings, however, will be offset by additional maintenance costs.

Estimated cost of Solar PV installation: $1,894,301
Estimated cost of Energy Storage System installation: $5,800,000
Estimated cost of Solar PV installation with Energy Storage: $8,622,301

The following is a simplified example showing potential utility savings with various microgrid options:

Assumption:

- 20 battery-electric bus fleet;
- 5 chargers (140 kW output)
- Monthly consumption of 106,630 kWh
- Minimum solar output of 4,730 kWh daily
- Weekday Energy Consumption of 4,375 kWh
- Total Monthly output of 26,500 kWh
- Large customer commercial rates
- 20-hour charge window

Example 1: Grid Power versus Grid and Solar PV

In this scenario, solar electricity is used directly when it is generated, but high peak demand in the evening when solar is not being generated still occurs. This results in lower energy costs but similar monthly demand charges as a system without solar PV.

Table 51: Monthly electricity utility charges with grid-tied solar system

	Grid	Grid & Solar PV
Demand	$ 6,398.00	$ 6,398.00
Energy	$ 4,217.22	$ 3,169.14
Total	$ 10,615.22	$ 9,567.14

Total Monthly Savings: $1,048.08

Preliminary estimates indicated a ROI of 23 years. Utilizing this configuration with hydrogen generation would likely have a shorter payback period, as Transit would not initially need to produce hydrogen at 100% capacity which would potentially allow production, and thus peak demand, to be lowered when solar is not being generated.

Example 2: Grid Power versus Grid Power plus Load Balancing with Energy Storage;

In this scenario, grid power is used to charge a battery at a steady rate throughout the day. Chargers or electrolyzers would then pull energy from a battery based energy storage system rather than the grid directly. The total amount of energy consumed from the grid does not change, but the rate at which it is pulled from the grid is reduced. Peak power is lowered, resulting in a reduction in monthly demand charges.

Table 52: Monthly electricity utility charges with load balancing from energy storage

	Grid	Grid & Storage
Demand	$ 6,398.00	$ 4,596.66
Energy	$ 4,217.22	$ 4,217.22
Total	$ 10,615.22	$ 8,810.88

Total Monthly Savings: $1,804.34

The high initial cost of energy storage systems combined with an estimated 17% annual savings results in a payback period in excess of 30 years. The cost of energy storage systems needs to come down for this option to be cost effective. Utilizing government programs to offset the high upfront capital cost may be an option until technology prices reduce.

<u>Example 3: Grid Power versus Grid Power plus Load Balancing with Storage, plus Solar PV;</u>
In this scenario, a combination of solar PV and grid power charge a battery at a steady rate throughout the day. The total amount of energy consumed by the grid is reduced by the amount of solar energy generated. The rate at which energy is pulled from the grid will vary throughout the day, but will not exceed a levelized rate. This results in both a reduction in energy and demand charges.

Table 53: Monthly electricity utility charges with grid-tied solar system and load balancing from energy storage

	Grid	Grid, Solar PV & Storage
Demand	$ 6,398.00	$ 4,421.48
Energy	$ 4,217.22	$ 3,169.14
Total	$ 10,615.22	$ 7,590.62

Total Monthly Savings: $3,024.38

Some of the savings generated will be offset by the costs of maintaining the microgrid. With the variable nature of solar, and the way that demand charges are calculated, it may not always be possible to achieve maximum potential savings with solar PV. The introduction of energy storage systems, however, ensures a reduction of at least 17% regardless of how the utility company assesses monthly demand charges.

As with the previous scenario, the high cost of energy storage systems still results in a ROI in excess of 30 years even with additional savings from reduced demand charges. If Manitoba ever introduces time-of-use rates there may be additional cost benefits from implementing a solar PV microgrid with energy storage. Costs of both solar panels and the batteries used in energy storage systems are continually falling, so benefits from implementing a microgrid with solar PV may improve with time.

The algorithms needed to effectively manage utility costs with a microgrid are very complex, and integrating depot management software may be necessary to optimize system performance and maximize return on investment. Feedback from operating a zero-emission test fleet would provide data as to how a microgrid installation could be implemented to maximize operational savings.

8.7 Impact of Fleet size on Lifecycle Costs

Capital costs, including buses and refueling infrastructure, are directly affected by the fleet size, while operating costs are a function of the number of buses and annual mileage. Fleet size and annual operating hours are also used to establish staffing levels.

It has been theorized that the capital costs associated with fuel cell battery-electric buses decrease as the fleet grows, while battery-electric bus costs increase exponentially. If the capital savings are significant enough, the lifecycle cost of fuel-cell battery-electric buses may be competitive with a battery-electric fleet, regardless of hydrogen fuel pricing.

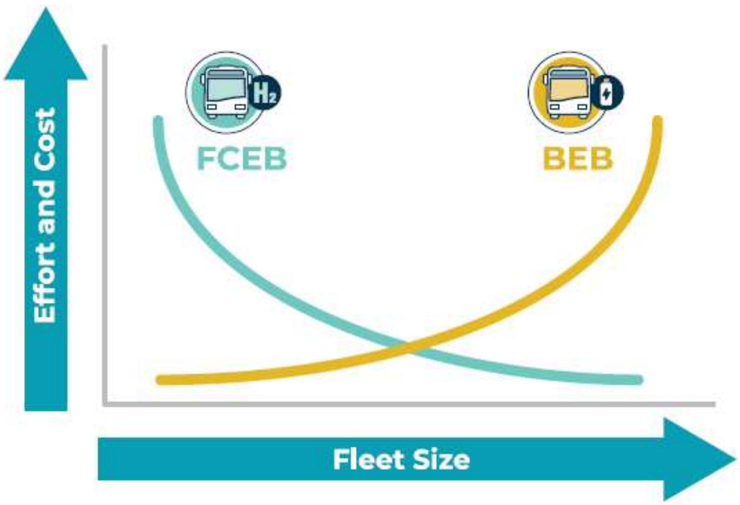


Figure 109: Relative cost of refueling infrastructure by fleet size. Source: [126]

The cost impact of large-scale electrification will be reviewed to determine how fleet size impacts the lifecycle of zero-emission buses compared to diesel.

8.7.1 Projected Fleet Size Required to Maintain Service Levels

Each technology has varying range and refueling limitations. These variations result in an increased number of zero-emission buses needing to be deployed to maintain the service levels of Transit's current diesel fleet.

Winnipeg Transit's weekday and weekend run list from the 2019 fall schedule were reviewed. The impact to fleet size has been estimated based on each technology's range and charging limitations.

Weekday peak levels are significantly higher than weekend peaks, therefore only weekday information was used to determine fleet size. The energy consumption for buses operating in Winnipeg was considered along with end-of-life performance for each technology.

Transit currently interlines routes into runs which vary in duration from 2 to 23 hours, and can be up to 600 kilometers in length. Zero-emission buses have significantly shorter range than the diesel buses they would be replacing. While it may be possible to initially place zero-emission buses on the shorter, less demanding runs, eventually runs that exceed the range of zero-emission buses will need to be split into multiple shorter runs. Run splitting results in the need for more buses and drivers, and increases non-service or deadhead kilometers on an annual basis.

The per kilometer operating cost of chargers is significantly lower than the per kilometer operating cost of buses, therefore, it is assumed that a strategy which includes the fewest number of buses possible, rather than the fewest number of chargers, would produce the lowest combined operating costs.

For evaluating long-range BEBs it was determined that runs designed for 40ft or smaller buses would be split at 200 km and 285 km for 440 kWh (Mid Capacity) and 660 kWh (Max Capacity) buses respectively, and runs designed for 60-foot buses would be split at 120 km and 170 km for 466 kWh (Mid Capacity) and 642 kWh (Max Capacity) buses respectively. For FC-BEBs, any runs designed for 40ft or smaller buses would be split at 330 km and runs designed for 60-foot buses would be split at 285 km. To stay within these length restrictions, some runs were split more than once. The maximum number of buses required to maintain service was determined based on spare ratios of 15% and 20%. The ratio of buses to chargers was adjusted to ensure that at no point during the day did the sum of buses driving, charging, or queuing to charge, exceed the maximum number of buses required during peak service.

For evaluating on-route rapid-charge BEBs, it was determined that both maximum range as well as the ratio of buses to chargers impacted fleet size. Any route under 64 km could be completed without on-route charging, while any route longer than 64 km would require the use of an on-route charger. Assuming a 10-minute charge window with a 450 kW charger, and a 15-minute window with a 300 kW charger, a maximum of 13 and 9 buses could utilize the same charger during a 2-hour window. This results in 8.33% more buses with a 450 kW charger, and 12.50% more buses with a 300 kW charger, being required to complete runs longer than 64 kilometers. The maximum number of buses required to maintain service was determined based on all buses driving (runs 64 km or under), or driving and charging (runs over 64 km) during the course of a weekday. As above, a 15% and 20% spares ratio was applied against this number.

With range limitations considered for all zero-emission technologies, the fleet size impact is as follows:

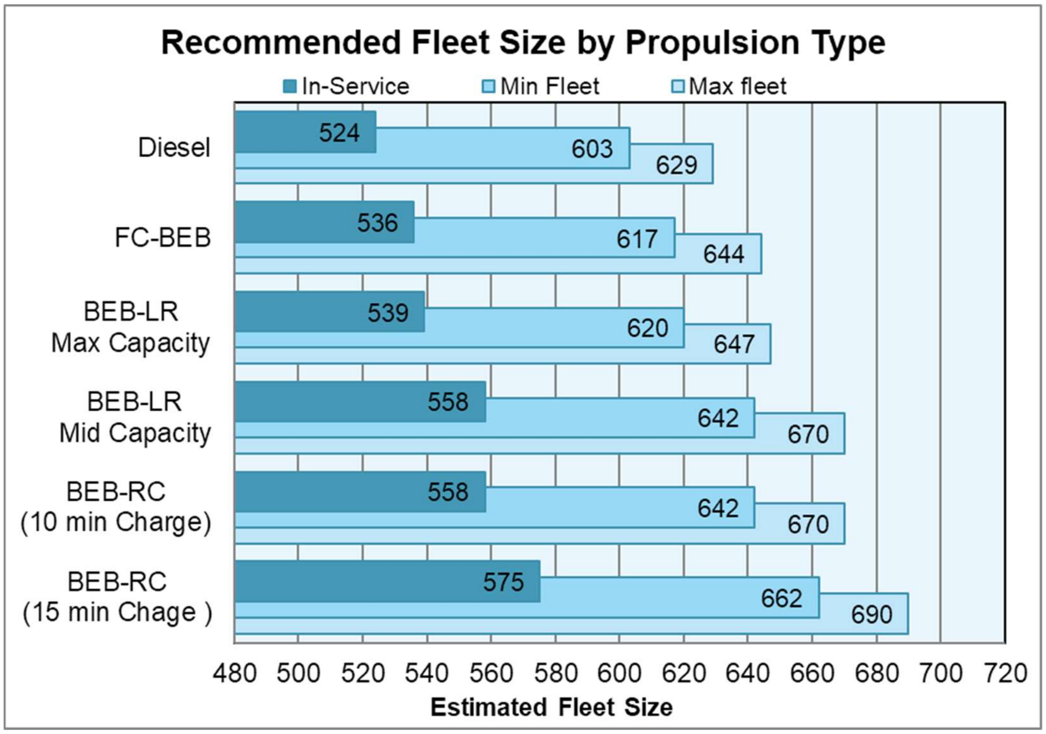


Figure 110: Estimated fleet size by propulsion system based on range and optimized charge ratio

All electric propulsion systems will require more buses to be driving during peak hours on weekdays to provide the same level of service as is currently provided with diesel buses. To maintain a 20% spares ratio, fleet size would need to be expanded between 2.39% to 9.70%. Only high capacity long-range BEBs (660/642 kWh) and FC-BEBs could replace diesel buses on a 1:1 basis, while maintaining at least a 15% spare ratio.

The above results represent a worst-case scenario. Schedules developed specifically around zero-emission bus limitations may help mitigate fleet size increases.

8.7.2 Projected Annual Range to Maintain Service Levels

Total operating hours are a combination of in-service hours and non-service hours. Non-service hours include any movement of the bus without passengers, including both pull into and out of the garage and deadhead travel between routes. In a typical year, this equates to 12.2% of total accumulated vehicle range being non-service hours.

In 2019 the average distance for non-service kilometers per run was as follows:

Table 54: Average length of non-service mileage per run in 2019

	Average Pull/Deadhead [km]
Weekday	15.151
Saturday	13.001
Sun/Holiday	14.675

Each run being split or on-route charged bus being added into rotation will result in additional non-service mileage. The estimated annual mileage by propulsion system based on the number of runs being split is as follows:

Table 55: Estimated annual travel distance by propulsion system

	In-Service [km]	Pull/Deadhead [km]	Total [km]
Diesel	26,818,899	3,485,896	30,304,795
BEB-RC (450 kW)	26,818,899	3,742,193	30,561,092
BEB-RC (300 kW)	26,818,899	3,861,316	30,680,215
BEB-LR Mid	26,818,899	4,409,000	31,227,899
BEB-LR Max	26,818,899	4,013,049	30,831,948
FC-BEB	26,818,899	3,770,227	30,589,126

8.7.3 Impact of Fleet size on Capital Costs

8.7.3.1 Impact of Fleet Size on Bus Purchase Price

It is expected that some volume discounts would apply with a large zero-emission bus procurement. The fuel cell industry is predicting a large price reduction once orders exceed 100 units, based on efficiency gains from large scale production of fuel cells and other fuel system components [97] [93]. Recent larger battery-electric bus procurements from King County Metro and LA Metro do not indicate any significant reduction in unit price based on volume. It is more likely that battery-electric buses will have modest price reductions based on battery pricing rather than opportunities of scale.

When both fleet size and opportunities of scale are considered, the capital costs associated with operating a fuel cell fleet becomes cost competitive with battery-electric options.

Assumptions:

- Fleet size based on range limitations and Transit's fall 2019 schedule.
- Fleet mix of 92% 40-foot buses and 8% 60-foot buses.
- 40-foot fuel cell battery-electric bus price of $850,000USD [97] [93].
- 60-foot fuel cell battery-electric bus price of $1,190,0000USD [97] [93].
- 33% reduction in battery per kWh pricing.

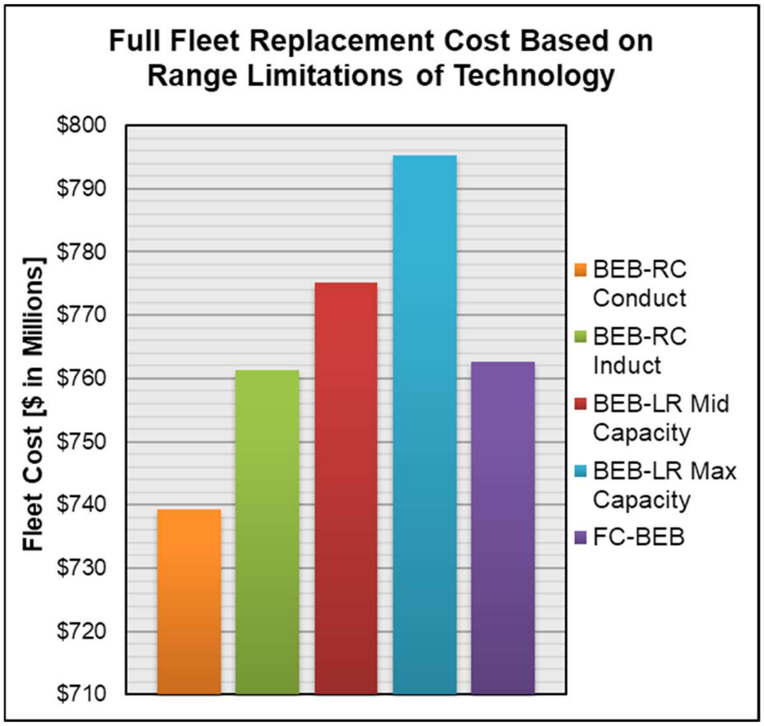


Figure 111: Full fleet replacement cost based on range limitation of technology and economies of scale

Bus purchase price is not the entire story as when larger fleet sizes are considered, infrastructure investment can greatly inflate costs on a per bus basis.

8.7.3.2 Impact of Fleet size on Refueling Infrastructure Cost

Charger availability has a significant impact on both on-route charged BEBs and depot charged BEBs. Capping charge power to reduce peak loads and lower operating costs results in longer charge times, and could create a charging backlog if there are not enough chargers available to meet demand. Failure to charge in the available window may result in a shortage of buses ready to deploy during peak service.

Fuel cell battery-electric buses fill relatively quickly, but fuel capacity limitations restrict the total mileage that can be completed. It is anticipated that Transit would require between 8,000-9,000 kg of hydrogen per day if they converted their entire fleet to fuel cell battery-electric buses. This volume of fuel is well suited for delivery of liquid hydrogen. The infrastructure costs of a fueling system designed around delivered fuel is significantly lower than one which integrates large-volume fuel production.

Transit's fall 2019 schedule can accommodate a charging window of 2, 3, or 4-hours for both mid and maximum capacity long-range BEBs, while a 10 or 15-minute window must be utilized every two hours for on-route rapid charge buses. The maximum fill rate of hydrogen is 3.6 kg/min which means a 40-foot fuel cell bus can fuel from empty to full in as few as 6.6 minutes, while a 60-foot can fuel in 11.8 minutes.

With full fleet electrification, operational systems design around diesel buses could be re-optimized for zero-emission buses. It is assumed that an optimal number of chargers or refueling equipment could be purchased, and that any current facility and refueling equipment limitations could be managed through operational changes. Based on these assumptions, the recommended number of buses per type of fueling equipment, and the per unit cost is as follows:

Table 56: Cost of refueling infrastructure and number of buses supported per unit. Source: [97] [99] [210] [126] [222]

	Unit Cost	Buses per Unit
Plug-in Depot Charger; 4-Hour	$ 283,250	2.23
Plug-in Depot Charger; 3-Hour	$ 325,250	4.275
Overhead Depot Charger; 2-Hour	$ 675,000	6.668
On-Route Inductive Charger; 15-Minute	$ 745,650	9
On-Route Conductive Charger; 10-Minute	$ 948,150	13
Fill Station (9,000 kg/day) - Delivered	$ 28,552,500	700
Fill Station (8,500 kg/day) - Production	$ 44,820,000	700

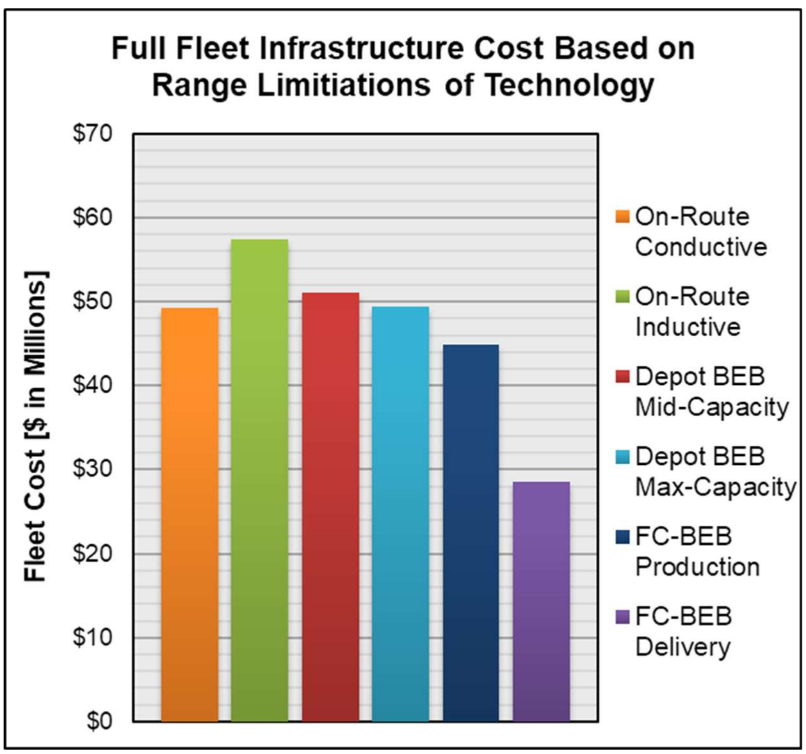


Figure 112: Full fleet infrastructure cost based on range limitation of technology and economies of scale. Source: [97] [99] [210] [126] [222]

8.7.3.3 Impact of Fleet Size on Facility Upgrades

If Transit's entire fleet were converted to zero-emission buses, all three of Transit's parking, service garages and maintenance garages would require new fueling infrastructure to support these buses.

As with the evaluation of the test fleet costing, anticipated facility upgrades associated with charging infrastructure are included in the cost estimates for the installation of the chargers, and will continue with each charger purchased.

In the case of fuel cell battery-electric buses, outdoor fueling would be acceptable for a small deployment, but the efficiency losses associated with outdoor fueling would make it impractical to manage at a large scale. Indoor fast fueling with hydrogen is permitted, but facility modifications would be required to bring the building into compliance with applicable codes and standards.

There are currently no transit facilities in North America fueling indoors with hydrogen, but there are, however, some operating facilities with indoor CNG fueling. CNG and hydrogen are both lighter than air gases which have similar code requirements for indoor fueling according to the NFPA. A National Renewable Energy Laboratory (NREL) report from 2015 identified that the facility modifications associated with converting Roaring Fork Transit Agency's indoor diesel fueling facility to an indoor CNG fueling facility cost USD$2,700,000 [223]. Adjusted for inflation, Transit could expect to spend approximately CAD$4.62 million per parking garage to support indoor fueling, plus $1.35 million for the maintenance garage ventilation and detection updates for a total of $15,202,000 [93].

For evaluation purposes costs associated with garage conversion will be utilized; however, it should be noted that in the case of a purpose-built garage, the costs of building a hydrogen ready facility may be lower than building a charger ready facility based on recent announcements from other Western Canadian cities. Calgary Transit recently completed a LEED Gold Certified maintenance and storage garage built to accommodate up to 424 CNG buses at a cost of $174 million, or approximately $410,000 per bus. Meanwhile, Edmonton Transit's new LEED Silver Certified Kathleen Andrews garage completed around the same time and designed to house 300 battery-electric buses cost approximately $210 million or $700,000 per bus [224] [225] [226]. While the two costs may not be directly comparable it is something that should be considered when evaluating electrification costs associated with replacing Transit's North Garage.

8.7.3.4 Impact Of Fleet Size on Back-Up Redundancy

As the number of zero-emission buses in the fleet grows, back-up resiliency during power outages will not be able to be maintained with diesel buses alone. While the exact amount of zero-emission buses that could be supported without generation will vary based on actual bus availability, it is expected that Transit would need to invest in some form of back-up generation equipment once the fleet exceeds 100 buses.

Both battery-electric and fuel cell battery-electric buses require some amount of electricity for fueling. That electricity can come directly from the grid, via a microgrid, or from a back-up generator. A fleet of 644 to 690 battery-electric buses would require up to 31 MW of power to maintain charging infrastructure at full capacity.

In the case of a fuel cell battery-electric fleet, fueling stations would include three to five days of stored fuel. Assuming there is stored fuel available to dispense, just 1.03 MW of power is needed for the hydrogen compression, cooling, and dispensing equipment required to maintain operations [91] [90] [227].

Chargers do not run at 100% capacity all day, and the actual amount of energy consumed by the fleet on a weekday would only be around 149,000 kWh. While it might be possible to install lower capacity generation equipment and extend charge time, the bus to charger ratio is so lean that doing so would result in the need to utilize spares to maintain service levels while the buses recharge. Adding chargers may be an option as well; however, it is likely more cost effective to add enough generation equipment to support the maximum required charger output, rather than buy and maintain more chargers for rare outage events. It might also be adequate to reduce the number of buses deployed if the event causing the prolonged power outage also results in reduced ridership, such as during a winter storm. This strategy would not be acceptable if the outage results in increased demand for buses, which may be the case if future transit operations include light rail. Power for light rail comes directly from overhead wires, so a prolonged power outage would result in the need to replace light rail service with off-wire buses. Based on the risks associated with operating on reduced backup power, it is recommended that Transit install sufficient backup generation to maintain charging operations at full capacity.

Energy storage and generators are two methods of providing backup power. Energy storage can be used for short duration charging, but backup generation would be necessary to provide resiliency during a prolonged power outage. A study from Toronto Transit Commission (TTC) noted that 5 MW of diesel back-up generation costs approximately $5 million, plus an additional $3 million for each 5 MW increase thereafter [228].

Assuming backup generation is spread out over three facilities with no change to the number of buses at each location, Transit should expect the following costs for back-up generation to support a zero-emission fleet of 644 to 690 buses:

Table 57: Cost estimation of back-up generation equipment in depot. Source: [211] [212] [213] [227] [91] [90]

	20 MW Charger Backup	25 MW Charger Backup	30 MW Charger Backup	2 MW H2 Fuel Backup
Fort Rouge Garage	$ 8,000,000	$ 11,000,000	$ 14,000,000	$ 567,000
Brandon Garage	$ 5,000,000	$ 5,000,000	$ 5,000,000	$ 243,000
North Garage	$ 5,000,000	$ 5,000,000	$ 5,000,000	$ 243,000
Total	**$ 18,000,000**	**$ 21,000,000**	**$ 24,000,000**	**$ 1,053,000**

Assuming each on-route charger has its own 300 kW or 500 kW back-up generator the cost for backup generation in support of on-route charging would be as follows:

Table 58: Cost estimation of back-up generation equipment for on-route charging. Source: [211] [212]

	On-Route Charger Backup
On-Route Conductive Charging	**$ 15,280,650**
On-Route Inductive Charging	**$ 12,636,000**

8.7.3.5 Impact of Fleet Size on Land

The charging infrastructure for long-range battery-electric buses and fuel cell battery-electric buses can easily be installed on Transit owned property regardless of fleet size. Some re-zoning may be required to accommodate hydrogen fueling or fuel production, but these costs would be built into the estimate for refueling infrastructure.

It is highly likely that some on-route chargers will need to be installed on land not currently owned or leased by Transit. Real property costs are exempt from government funding, and therefore the additional real property cost associated with this technology could significantly add to the overall cost of electrification. Information supplied by customers using on-route charging in the US indicate a space requirement of at least 200 ft^2 (18.58 m^2) to install charging equipment [229]. The City of Winnipeg estimates that the purchase price of land around a major artery would cost between $40 to $50 per square foot; however, costs could escalate if purchasing is not possible and land expropriation becomes necessary.

Assuming 40% of on-route chargers are located on non-Transit owned property, and purchase is possible at an average of $10,000 per station, Transit could expect to pay an additional $308,000 for 72 on-route inductive charging stations and $208,000 for 52 on-route conductive charging stations.

Transit parking garages are currently space limited, which necessitates parking buses nose-to-tail to maximize capacity. This layout is not well suited to charging, which requires a bus to stay in one place for up to four hours. If Transit ultimately purchases a large number of battery-electric buses, a new garage may create an opportunity to replace the first-in-first-out deployment strategy Transit current uses with something better suited to charging.

Figure 113: Configuration of Brandon Garage bus storage facility

Some transit agencies have deployed an angular parking configuration for battery-electric buses rather than nose-to-tail parking. This configuration improves vehicle accessibility, allowing buses which have completed charging to be deployed almost immediately, rather than having to wait for multiple buses ahead of them in line to complete charging.

Figure 114: Alternative parking layout with angled parking. Source: Adapted from [230]

Unfortunately, a parking garage which includes angular parking would require a larger footprint than one with nose-to-tail-parking in order to accommodate the same number of buses. It is possible that site specific constraints may prevent any parking layout other than first-in-first-out. If additional land is available, Transit may want to consider evaluating different parking configurations and its impact on both capital and operational costs in the design of a new zero-emission bus garage.

8.7.3.6 Impact of Fleet Size on Tooling & Equipment

Transit currently performs some service, maintenance, or repairs at all four garages. Work is performed in designated bays at all facilities.

Transit is expected to operate the following number of maintenance and repair bays in support of a zero-emission fleet:

Table 59: Transit maintenance and repair bay summary

Description	QTY
Minor Maintenance/Repair Bays	20
Major Maintenance/Repair Bays without Overhead Cranes	40
Major Maintenance/Repair Bays with Overhead Cranes	20
Specialty Repair Areas (Battery/Fuel Cell)	6

Each garage should be equipped with one set of specialized tooling for occasional maintenance. All maintenance and repair bays would need to be equipped with appropriate PPE. Minor repair bays would need to be equipped with tooling and test equipment necessary for diagnostics and minor repairs, while the major repair bays will also need to be equipped with additional specialized tooling and diagnostic equipment. Service of roof mounted equipment such as hydrogen tanks would be restricted to bays equipped with overhead cranes; therefore, specialized tooling relating to those components would only need to be supplied to those areas only. It is anticipated that major battery and fuel cell repairs would be completed out of station, in an area equipped for that purpose.

The estimated cost to purchase new tooling & equipment to support a full fleet of zero-emission buses is as follows:

Table 60: Cost estimate of tooling and equipment to support maintenance of a ZEB fleet

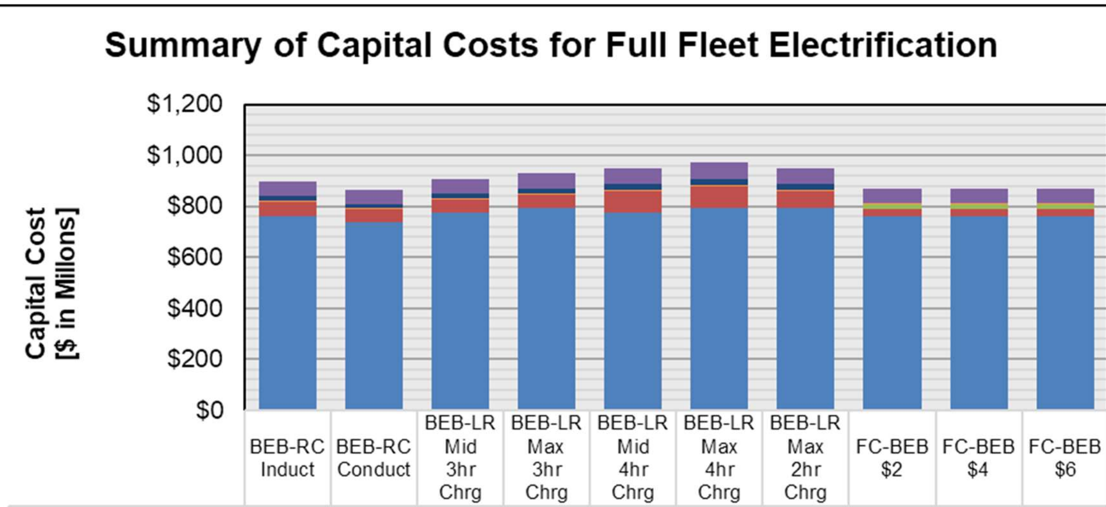
Description	BEB	FC-BEB
Laptops	$ 336,500	$ 336,500
Diagnostic Equipment	$ 541,500	$ 539,000
Test Equipment	$ 659,000	$ 659,000
PPE	$ 723,000	$ 723,000
Specialized Tools	$ 594,000	$ 614,500
Barriers & Signage	$ 196,000	$ 196,000
Grand Total	**$ 3,050,000**	**$ 3,068,000**

In the case of zero-emission fleet replacement, all new zero-emission buses will be considered replacement buses, and as such fareboxes and AVL systems from retiring buses can be reused and only the following costs should be added per bus:

Table 61: Cost estimate for standard bus equipment

Description	Standard Equipment
AVL System	$ -
Fareboxes	$ -
APC System for 40-ft Bus	$ 3,023
APC System for 60-ft Bus	$ 4,408

8.7.3.7 Overall Impact of fleet size on Capital Costs:



	BEB-RC Induct	BEB-RC Conduct	BEB-LR Mid 3hr Chrg	BEB-LR Max 3hr Chrg	BEB-LR Mid 4hr Chrg	BEB-LR Max 4hr Chrg	BEB-LR Max 2hr Chrg	FC-BEB $2	FC-BEB $4	FC-BEB $6
PST (7%)	$58.769	$56.460	$59.461	$60.961	$62.065	$63.480	$62.131	$56.877	$56.877	$56.877
Land Purchase	$0.308	$0.208	$-	$-	$-	$-	$-	$-	$-	$-
Back-up Power Cost	$15.281	$12.636	$18.000	$21.000	$21.000	$24.000	$21.000	$1.053	$1.053	$1.053
Tooling & Equipment	$5.212	$5.150	$5.150	$5.078	$5.150	$5.078	$5.078	$5.086	$5.086	$5.086
Facility Upgrades	$-	$-	$-	$-	$-	$-	$-	$15.202	$15.202	$15.202
Refueling Infrastructure	$57.415	$49.304	$51.064	$49.438	$85.258	$82.426	$66.150	$28.553	$28.553	$28.553
Bus Purchase Price	$761.340	$739.272	$775.233	$795.360	$775.233	$795.360	$795.360	$762.638	$762.638	$762.638
Grand Total Capital	$898.325	$863.029	$908.908	$931.837	$948.706	$970.343	$949.718	$869.409	$869.409	$869.409

Figure 115: Summary of capital costs for full fleet electrification

The large fleet analysis of capital costs associated with a zero-emission buses produces results that are very different from the small fleet analysis. Fuel cell battery-electric buses, which were the most expensive propulsion system from the small fleet analysis, become the lowest cost long-range option and the second most cost-effective solution overall next to on-route rapid-charge buses charged conductively. This shift occurs for a variety of reasons.

The purchase price of a fuel cell battery-electric bus in a large order is predicted to reduce more dramatically than that of a battery-electric bus. Pricing for both technologies has benefited from increased production volume of propulsion components, including batteries. Fuel cell buses however, have additional components unique to the fuel system which have not yet benefitted from pricing reductions due to economies of scale. The extra range of fuel cell battery-electric buses also results in a need to purchase fewer total buses compared to other propulsion systems.

Charging has a low entry point but the costs continue to grow linearly as the fleet grows. Hydrogen refueling infrastructure and storage requires a large one-time up-front investment, but no additional investment until the fleet outgrows the capacity of the filling station. Hydrogen refueling infrastructure also has more built in resiliency to power outages, resulting in significantly lower backup generation equipment requirements compared to charging.

Facility upgrades required at the maintenance garage to service a small fleet of fuel-cell buses had a large impact on overall capital cost. When these one-time costs are spread out over hundreds of buses, upgrading the maintenance facility and integrating indoor fueling at multiple facilities has only minimal impact to the overall capital costs.

8.7.4 Impact of Fleet Size on Operating Costs

8.7.4.1 Impact of Fleet Size on Maintenance Costs

Scheduled and unscheduled maintenance costs are not expected to be directly impacted by the size of the fleet, but rather indirectly based on the annual mileage of the fleet.

Mid-life overhaul costs, however, are directly impacted by the number of buses in the fleet, as the number of parts requiring replacement increases with fleet size.

The revised cost of maintenance and overhaul per 1,000 km per technology based on an expected fleet size of 644 to 690 zero-emission buses is as follows:

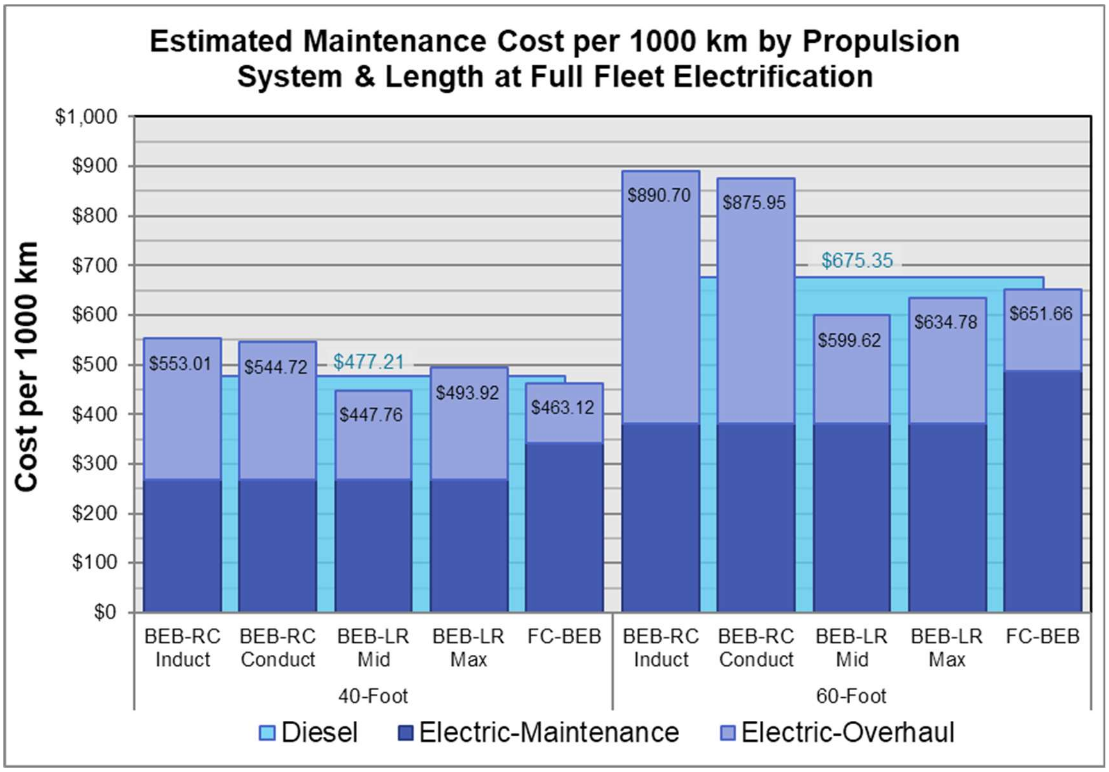


Figure 116: Estimated maintenance cost per 1,000 km by propulsion system and length at full fleet electrification

8.7.4.2 Impact of Fleet size on fueling costs

Fueling costs are calculated as a combination of vehicle energy consumption, fuel/energy pricing, and fueling equipment expenses. Fleet size and refueling strategy both impact fueling costs. Fleets requiring higher annual range will utilize more energy or fuel per year to provide the same level of service. The quantity and capacity of fueling infrastructure needed to support zero-emission buses is directly impacted by fleet size.

Based on the volume of fuel needed to support a large fleet of fuel cell battery-electric buses, it is expected that Transit would utilize delivered fuel rather than invest in large-scale on-site hydrogen production equipment. There are currently no expected mid-life overhaul costs associated with a delivery based fueling model.

Currently, Transit outsources the inspection, testing, and preventative maintenance of petroleum storage and handling systems. The contract includes servicing equipment all three transit garages. It is expected that Transit would similarly contract out costs related to inspection, testing, and preventative maintenance of hydrogen storage and handling systems. Based on the limited number of experienced vendors it is likely that annual fees will be higher than what Transit is currently paying for diesel, but it is reasonable to assume that Transit would be able to have hydrogen fueling equipment at multiple locations contracted out at a similar price to what is currently estimated for a single station [220].

Annual infrastructure maintenance and overhaul costs of charging is based on the total number of chargers. It is assumed that Transit would contract out the annual maintenance of the chargers rather than do this work in house. Through a competitive bid process, 50% savings over currently quoted prices are likely. The mid-life overhaul cost of chargers is not expected to decrease based on volume as it is unlikely that all chargers would need to be upfitted at the same time.

Table 62: Estimated infrastructure maintenance and overhaul cost per 1,000 km; Small fleet vs large fleet

Refueling	Small Fleet		Large Fleet	
	Annual Maintenance	Mid-life Overhaul	Annual Maintenance	Mid-life Overhaul
On-Route Inductive	$ 36.26	$ 4.03	$ 18.82	$ 3.52
On-Route Conductive	$ 48.35	$ 19.47	$ 17.02	$ 11.52
Plug-In 3-hour Mid	$ 48.35	$ 8.06	$ 25.14	$ 7.04
Plug-In 3-hour Max	$ 48.35	$ 8.06	$ 24.65	$ 6.91
Plug-In 4-hour Mid	$ 48.35	$ 8.06	$ 48.19	$ 13.50
Plug-In 4-hour Max	$ 48.35	$ 2.69	$ 47.19	$ 13.22
Plug-In 2-hour Max	$ 72.53	$ 29.21	$ 31.79	$ 21.52
Hydrogen Fuel Dispensing	$ 176.48	$ 10.07	$ 7.16	$ -
Diesel	$ 2.97	$ -	$ 2.97	$ -

Energy/fuel consumption is a combination of bus type, fleet mix and kilometers travelled. It is assumed that the mix of articulated and non-articulated buses in a zero-emission fleet would be similar to today's fleet mix which is currently 92% non-articulated and 8% articulated buses.

Based on fleet size, annual range, and estimate infrastructure maintenance and overhaul costs, the expected fueling cost per 1,000 kilometers of travel for a 644 to 690 zero-emission bus fleet is as follows:

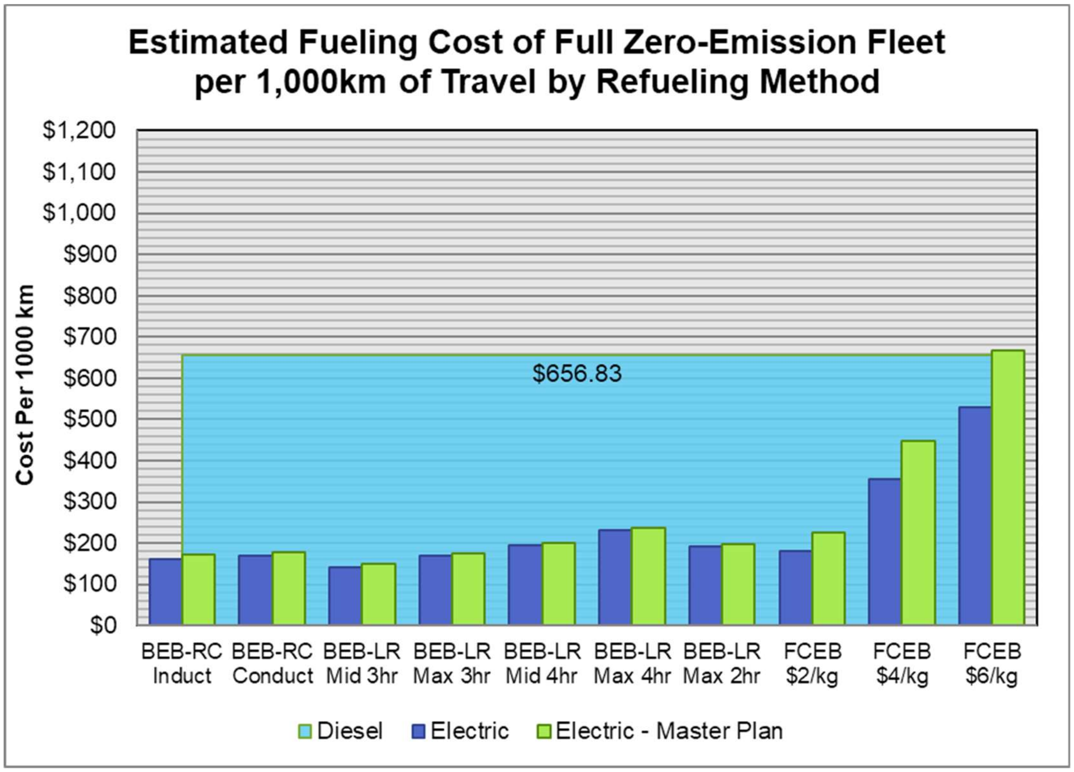


Figure 117: Estimated fueling cost of Zero-Emission buses per 1,000 kilometers at full fleet electrification

Overall, the per kilometer fueling costs of a large fleet are lower than the per kilometer fueling costs of a small test fleet. This is based on a combination of a larger fleet having a lower percentage of 60-foot buses than a small test fleet, as well as there being projected cost savings through competitive bidding of refueling infrastructure maintenance contracts. The one exception to this was slow charged long-range battery-electric buses. The large number of chargers required to support the fleet resulted in considerable infrastructure maintenance and overhaul costs which moved this combination from the least expensive, to the most expensive fueling method.

Overhead depot charging becomes cost competitive at large scale, mainly due to the low number of chargers required to support the fleet. It should be noted however that the strategy costed does not include charging points at every charging location. Transit would need to create designated charging areas and develop new processes to accommodate the movement of buses in and out of those areas. Expanding the number of electrified overhead charging locations would significantly increase both capital and operational costs.

The cost of hydrogen fueling was also significantly reduced based on fleet size. If low-cost hydrogen can be secured the fueling costs of fuel cell battery-electric buses are competitive with battery-electric charging. Even if the cost of hydrogen does not decrease as much with volume as industry predicts, a fuel cell battery-electric bus fleet is still likely to produce fuel savings when compared to a similarly sized diesel fleet.

8.7.4.3 Impact of Fleet Size on Fueling Operations

Regardless of fleet size, buses need to be fueled or charged before they are deployed.

Outdoor fueling is not practical for a large fleet of fuel cell battery-electric buses. Transit would need to upgrade their facilities to accommodate indoor fueling. With the introduction of indoor fueling, fuel cell battery-electric buses could be washed, cleaned, serviced and fueled in the same track before being parked. These activities could be completed concurrently, eliminating the wasted person hours associated with moving to and from the garage for outdoor fueling.

Fleet size has no impact on the process for storing or deploying buses that are primarily charged on-route. In-service time is lost while charging, but no additional staff needs to be directly hired or repurposed for fueling.

The complexity of managing depot-charged long-range battery-electric buses increases with fleet size, but it does not necessarily directly translate into increased operational costs. Today, sequential charging can be used to link up to 4 buses to the same charger. This eliminates the need to physically move buses to free up a charging space when charging is complete. Future development in charger management is likely to further expand the flexibility of charging. Charging schedules and bus assignments are likely to be managed dynamically using software and data from the bus to optimize bus redeployments and charger utilization.

Based on the utilization of charger management software and upgrading to indoor hydrogen fueling, there are not expected to be any additional person-hours generated by fueling of a large zero-emission fleet as compared to today’s diesel fueling process.

8.7.4.4 Overall Impact of Fleet size on Operating Costs

Based on an 18 year, 930,700 km life and Transit’s current duty cycle the annual operating costs of a 644 to 690 zero-emission bus fleet is estimated to be as follows:

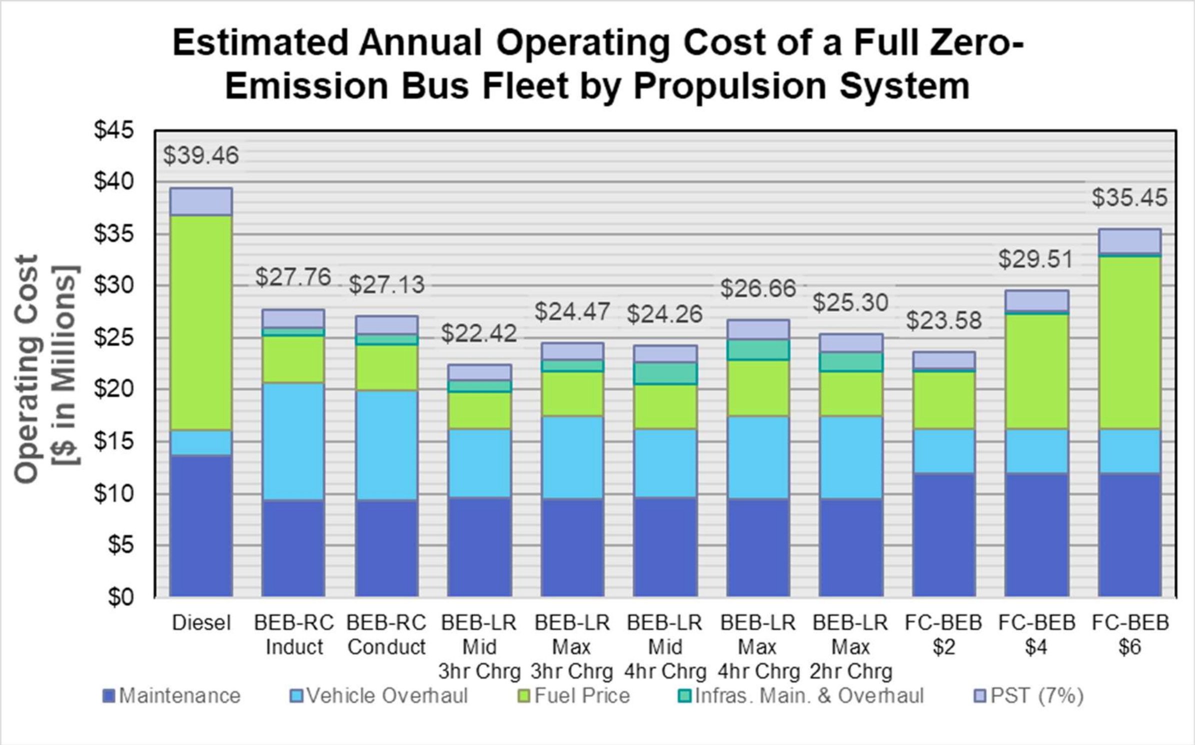


Figure 118: Estimated annual operating cost of a large zero-emission vs diesel fleet;

When costs associated with a large fleet of zero-emission buses are considered, all technologies are predicted to produce annual operational savings over today's diesel buses.

Based on an 18-year, 930,700 km life and Transit's current duty cycle, the estimated annual operational savings from a 644 to 690 zero-emission bus fleet is as follows:

Table 63: Estimated operational savings of a zero-emission fleet vs a diesel fleet; current duty cycle

	Annual Savings	Avg. Annual Savings/Bus
BEB-LR Mid 3hr Charging	$ 17,032,901	$ 25,422
FCEB $2/kg	$ 15,880,442	$ 24,659
BEB-LR Mid 4hr Charging	$ 15,194,014	$ 22,678
BEB-LR Max 3hr Charging	$ 14,981,162	$ 23,155
BEB-LR 2hr Charging	$ 14,155,796	$ 21,879
BEB-LR Max 4hr Charging	$ 12,799,082	$ 19,782
BEB-RC Conductive	$ 12,329,067	$ 18,402
BEB-RC Inductive	$ 11,698,011	$ 16,954
FCEB $4/kg	$ 9,945,226	$ 15,443
FCEB $6/kg	$ 4,010,009	$ 6,227

As with a small fleet of zero-emission buses, when the operating costs of a full zero-emission bus fleet are considered, all zero-emission technologies have the potential to produce annual operational savings over diesel. With the increase in the size of the zero-emission bus fleet, the annual savings from battery-electric buses decreased while the savings from operating fuel cell battery-electric buses increased. This swing was mainly the result of costs relating to fueling infrastructure at scale. Having to maintain and operate a large number of chargers negated some of the fuel savings from low cost electricity, while expanding from one hydrogen fill station to three had little impact. At scale it is likely that the inspection, testing and preventative maintenance of hydrogen storage and handling systems could be contracted for a similar price as the current petroleum systems.

Fuel cell battery-electric buses are potentially both the least expensive, and the most expensive, zero-emission bus technology to operate, depending on the price of fuel. Operational savings disappear as the price of fuel exceeds $6.60/kg, but at pricing under $4/kg these buses approach parity with most battery-electric options. If pricing drops below $2/kg, savings surpass that of all other technologies. Green hydrogen prices this low may be possible with the availability of by-product hydrogen, but there is no guarantee that Transit could secure stable fuel prices over the entire life of bus [79].

Despite having similar energy usage, there is a wide variation in electricity cost depending on charging strategies. Utilizing a strategy with fewer chargers and lower peak demand will minimize costs. It is recommended that Transit further investigate implementing charge management software to manage electricity demand.

8.8 Cost to Purchase, Operate, and Maintain a Full Fleet of Zero-Emission Buses and Associated Infrastructure

The data below represents estimated fleet costs if Transit's fleet was converted to 100% zero-emission today, based on the current vehicle and infrastructure pricing estimated above. Bus and infrastructure costs are expected to fall in the near term but may increase with inflation as the technology matures. Total required investment from Transit will vary depending on the transition rate from diesel to zero-emission.

Based on an 18-year, 930,700 km life, Transit's current duty cycle, operations starting in 2022, and adjusted for annual inflation up to 2030, the lifetime capital and operating costs of a 644 to 690 zero-emission bus fleet are estimated to be as follows:

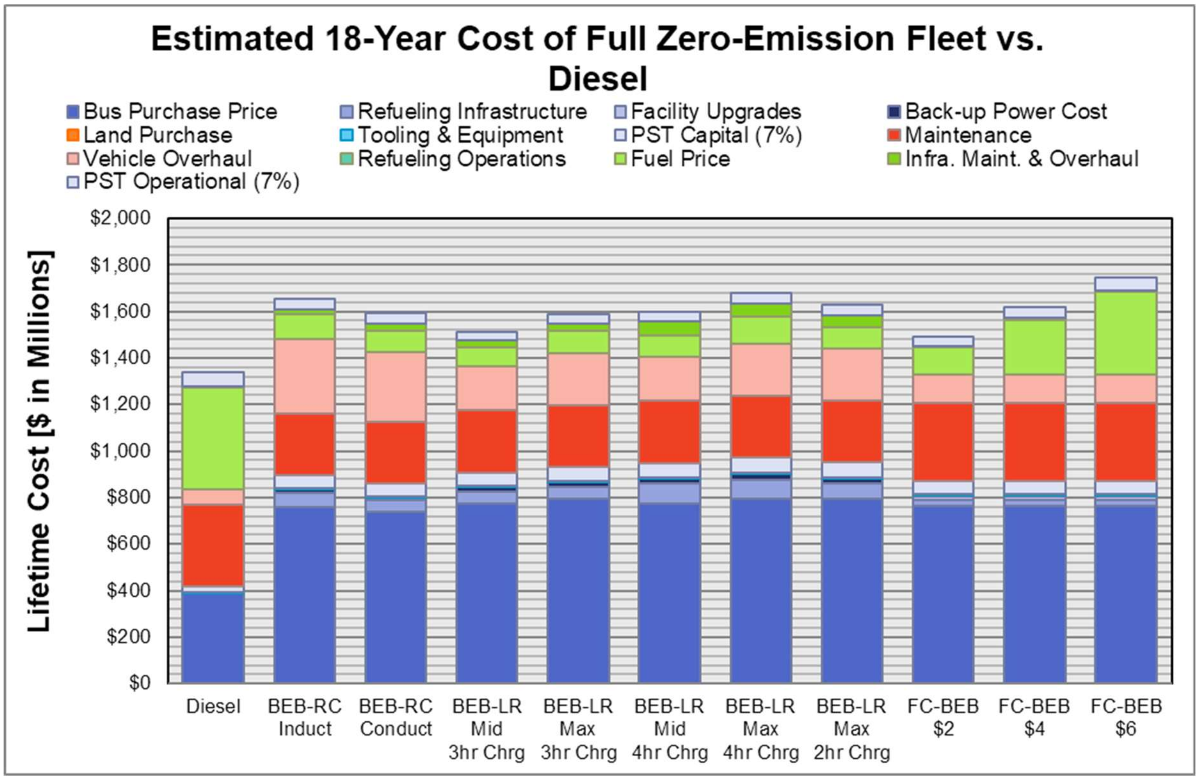


Figure 119: 18-year lifecycle costs of a full zero-emission fleet compared to diesel replacement

As with the evaluation for lifecycle cost of a small zero-emission fleet, the lifecycle cost of a large fleet of zero-emission buses is still higher than that of a similarly sized diesel fleet, even after economies of scale are applied to the purchase price of the buses and associated infrastructure. Fuel savings associated with slow charging a small fleet of buses are negated by higher bus-to-charger ratios and associated fueling cost increases. When all costs are considered, no zero-emission technology would be capable of breaking even with diesel buses.

Regardless of fleet size, it will be necessary to utilize federal and provincial funding programs to supplement the capital costs associated with zero-emission vehicles and infrastructure.

Assuming the continued availability of ICIP-PTIS or another similar program, and a similar 40/33/27 funding split between federal, provincial and municipal governments, the lifetime capital and operating costs based on an 18-year, 930,700 km life and Transit's current duty cycle are estimated to be as follows:

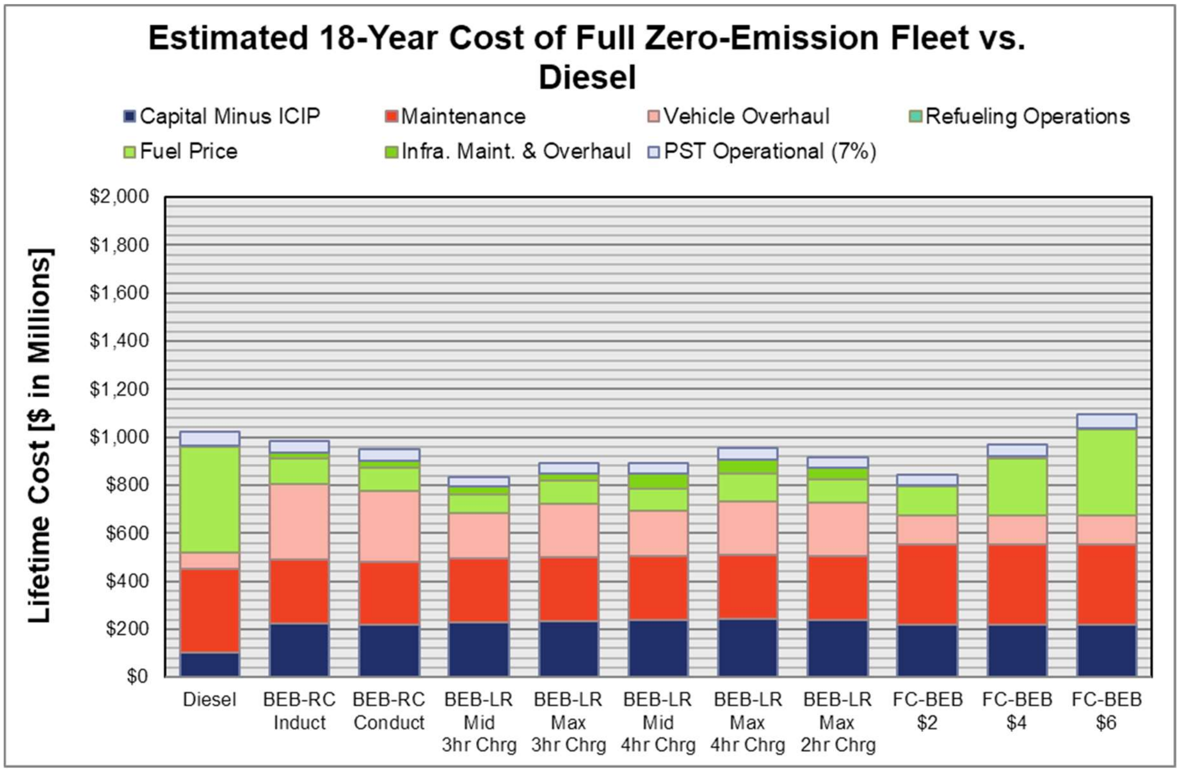


Figure 120: 18-year lifecycle costs of a full zero-emission fleet compared to diesel replacement with three-level government funding

With adjustments for fleet size and capital reduced through support from the Federal and Provincial government, all zero-emission technologies reviewed are predicted to have annual operational savings, and deliver lower total cost of ownership over an 18-year period when compared to today's diesel fleet.

Table 64: Return on Investment of full zero-emission fleet replacement

	ROI	
	No Funding	ICIP
FC-BEB $2/kg	>25-years	7-years
BEB-LR Mid 3hr Charging	>25-years	8-years
BEB-LR Mid 4hr Charging	>25-years	9-years
BEB-LR Max 3hr Charging	>25-years	9-years
BEB-RC Conductive	>25-years	10-years
BEB-LR Max 2hr Charging	>25-years	10-years
BEB-LR Max 4hr Charging	>25-years	12-years
BEB-RC Inductive	>25-years	12-years
FC-BEB $4/kg	>25-years	12-years
FC-BEB $6/kg	>25-years	>25-years

The use of operational savings to offset capital costs is possible with all technologies, and in the case of FC-BEBs, the dispensed price of hydrogen would only need to be around $4.70/kg to do so. If lower priced hydrogen could be sourced, the operational savings from fuel cell battery-electric buses approach those of battery-electric. The pay back period on fuel cell battery-electric buses is also significantly improved when larger scale is considered, mainly as a result of reductions in the per bus cost of refueling infrastructure.

Table 65: Estimated lifetime savings of a 644 to 690 zero-emission bus fleet by technology and refueling strategy compared to diesel

	Lifetime Savings	Avg. Lifetime Savings/Bus	Avg. Annual Operational Savings/Bus
BEB-LR Mid 3hr Charging	$ 190,093,417	$ 283,722	$ 25,990
FCEB $2/kg	$ 181,572,680	$ 281,945	$ 25,460
BEB-LR Mid 4hr Charging	$ 133,603,328	$ 199,408	$ 22,120
BEB-LR Max 3hr Charging	$ 132,564,245	$ 204,891	$ 22,455
BEB-LR 2hr Charging	$ 105,167,505	$ 162,546	$ 20,481
BEB-RC Conductive	$ 75,310,217	$ 112,403	$ 15,549
BEB-LR Max 4hr Charging	$ 69,297,420	$ 107,106	$ 17,837
FCEB $4/kg	$ 54,485,971	$ 84,606	$ 14,497
BEB-RC Inductive	$ 39,532,854	$ 57,294	$ 12,929
FCEB $6/kg	-$ 72,600,738	-$ 112,734	$ 3,534

Transitioning from a small to a large fleet of zero-emission buses changes the average operational savings per bus. Bus range limitations, as well as infrastructure capital, and infrastructure maintenance and operating costs, all contributed to variations.

Table 66: Estimated lifetime savings per bus based on fleet size

	Small Fleet Savings	Large Fleet Savings	Change
BEB-LR Mid 3hr Charging	$ 31,587	$ 25,990	-$ 5,596
BEB-LR Mid 4hr Charging	$ 32,599	$ 22,120	-$ 10,479
BEB-LR Max 4hr Charging	$ 26,481	$ 17,837	-$ 8,644
BEB-LR Max 3hr Charging	$ 25,064	$ 22,455	-$ 2,609
BEB-RC Inductive	$ 19,702	$ 12,929	-$ 6,774
BEB-RC Conductive	$ 14,329	$ 15,549	$ 1,220
FCEB $2/kg	$ 10,386	$ 25,460	$ 15,075
BEB-LR Max 2hr Charging	-$ 2,644	$ 20,481	$ 23,125
FCEB $4/kg	-$ 7,683	$ 14,497	$ 22,180
FCEB $6/kg	-$ 25,751	$ 3,534	$ 29,285

The cost advantages of battery-electric over fuel cell battery-electric appear to narrow as the number of zero-emission buses in the fleet grow. The five technologies and fueling strategies that produced the greatest amount of operational savings when a small fleet size was considered, had the greatest reduction in savings when a large fleet size was considered. A strategy that utilizes plug-in chargers at a lower power output was an inexpensive option for a test fleet, but become increasingly more expensive due to the high bus-to-charger ratio it would require at scale. Fuel cell battery-electric buses which were more expensive than diesel buses when a small fleet size was considered, could potentially have the largest amount of operational savings if lower-cost hydrogen was available.

9 FUNDING ZERO-EMISSION BUS AND CHARGING INFRASTRUCTURE

High capital costs have been identified as one of the major barriers to large scale adoption of zero-emission buses. Zero-emission buses are twice as expensive as the diesel buses they are replacing, and also require supporting refueling infrastructure which can add as much as $350,000 extra per bus. To help transit agencies mitigate this issue, bus manufacturers have developed new lease and finance options, while the federal and provincial governments have launched infrastructure funding programs targeted at transit and zero-emission buses specifically.

9.1 Battery Lease & Finance Options

Zero-emission buses have been shown to have lower annual operating and maintenance costs than diesel buses [53]. It is predicted that the annual savings will result in zero-emission buses having a similar total cost of ownership over a 12-year period as diesel buses. Despite the potential savings, the high upfront purchase cost of ZEBs is often a barrier to adoption for transit agencies considering the transition to zero-emission buses.

In an effort to align the initial purchase price of battery-electric buses with that of diesel buses, several manufacturers are now offering new lease and finance options. Options include financing the bus and the batteries separately, financing the bus while leasing the batteries, and leasing the bus for a fixed term. The additional cost of borrowing would be offset by predicted savings from fueling and maintenance. This brings the total cost of ownership more in line with that of a diesel bus while greatly reducing or eliminating the incremental capital cost difference between the two. Rather than increasing Transit's capital budget and reducing the operating budget, everything is kept the same as it is today. Savings from fuel and maintenance are simply used to make a battery lease payment.

Figure 121: Potential operating costs of BEB with leased batteries vs. a diesel bus in US Dollars. Source: [231]

9.1.1 Finance Options

Battery financing would allow Transit to extend the payback period for the batteries, but it does not come with any additional warranty or service. Battery financing is currently being offered by New Flyer. New Flyer sales representatives have stated that the maximum financing term currently being offered is 60 months. Transit would own the batteries outright at the end of the term. Other than warranty-related issues Transit would be responsible for all service and maintenance throughout the life of the pack, as well as managing repurposing, recycling, or disposal of the batteries at end of useful life.

9.1.2 Lease Options

Bus lease options are available from all manufacturers for short-term leases. This is generally used as a method of trialing or testing buses with no commitment to purchase at the end of the lease. Long-term leasing and battery leasing are relatively new options that are now being offered by some manufacturers.

9.1.2.1 Long-Term Bus Leasing

BYD has partnered with Generate Capital to create Green Transportation Leasing (GTL) which offers options for leasing battery-electric buses [232]. They offer options for transit agencies to own the vehicle outright at the end of a 12-year term, or structure shorter term residual value leases where BYD owns the bus at the end of the term. Interest rates vary between 3.5-8% [232].

9.1.2.2 Battery Leasing

Battery leasing allows transit agencies to extend the payback period for the batteries, but also can be configured to include service and maintenance over the lease term. Battery leasing is currently being offered by both BYD and Proterra. Transit would pay a monthly or yearly payment to the bus manufacturer over the life of the bus. The bus manufacturer owns the battery packs at the end of the term.

Proterra currently works with Mitsui & Co., LTD to offer battery financing options [233]. In this scenario transit agencies are responsible for paying for the cost of the bus minus batteries up front, while financing the purchase and maintenance cost of the batteries over the life of the bus. Total replacement of the batteries after six years regardless of state of health is included under the terms of the contract. This model has only been utilized in the USA where buses have a 12-year expected life, but it has been stated by Proterra sales representatives that this could be expanded to 18 years with an additional battery replacement factored into the contract. Proterra also agrees to manage the repurposing, recycling or disposal of end of useful life batteries.

9.1.3 Battery Leasing/Financing at Winnipeg Transit

The batteries utilized on the demonstration buses tested at Transit performed reliably during the trial, but after less than 4 years and completing only about 40% of the mileage of an average diesel bus, the batteries were obsolete and would have required replacement had the demonstration continued. Transit currently operates diesel buses for 18 to 20 years, and expects zero-emission buses to operate a minimum of 18 years.

Since Transit's initial battery-electric demonstration, battery technology has improved with respect to capacity, performance, and cycle life. Manufacturers now offer extended battery warranties of up to 6 years on rapid-charge batteries, and 12 years on long-range batteries. Since the oldest battery-electric buses currently in operation are only approaching six years of service with similar mileage shortfalls, and newer long-range battery-electric buses have been in operation for less than three years, there is significant uncertainty regarding battery life and long-term performance.

Based on the expectation of performance, extended battery warranties allow for sufficient energy throughput for Transit's needs, but rated end-of-life capacity covered by the warranty is typically less than 70% of the beginning-of-life capacity, which may not be sufficient to meet Transit's needs up to mid-life. Transit may be able to negotiate better warranty terms if the batteries are purchased, but this would likely be difficult if the batteries are leased. Lack of established battery management protocols is likely to result in the capacity of batteries on Transit's initial battery-electric buses degrading at a faster rate than those in a more established fleet. Based on this it is highly likely that at least one battery pack replacement will be required prior to year 12, and two replacements may be necessary to reach year 18.

Under a purchase, finance or bus leasing agreement, Transit would be obligated to pay for battery replacements, recycling fees, and any additional engineering hours associated with retro-fitting buses with the latest technology. If technology is reliable and battery life is as predicted, then purchase and finance agreements would have potential to significantly lower operating costs. If not, premature battery failures could negatively impact annual operating budgets.

Under a battery lease agreement, financial risk relating to battery reliability transfers to the manufacturer. Battery maintenance, replacement, and recycling costs are covered by the bus manufacturer with Transit paying a fixed annual lease payment over the term of the contract for these services. Battery leasing was developed as a method to reduce initial capital costs, but it would also add predictability to Transit's annual operating budgets.

Based on Transit's expected capital and operating expenses, the financial impact of leasing or financing versus purchasing the buses outright is as follows:

Assumptions:

- For the purpose of comparing the capital, operational, and total cost of the various purchase, lease and finance options, the same based price of the battery-electric bus is assumed in all scenarios regardless of manufacturer.
- All operating costs not related to batteries are also assumed to be identical.

- A 5% interest rate is assumed for bus leasing with a required down payment equal to the cost of a diesel bus, and the bus to have no residual value at the end of the 12-year term.
- Under a bus leasing model, one additional pack will need to be purchased after the 12-year lease term has expires.
- Battery replacement costs are aligned with the 2028 and 2034 replacement values listed under maintenance.
- Battery financing and battery leasing payments have been provided by New Flyer and Proterra respectively.
- 4% annual inflation rate for operational costs has been applied to all scenarios.
- 7% PST has been applied to all scenarios.

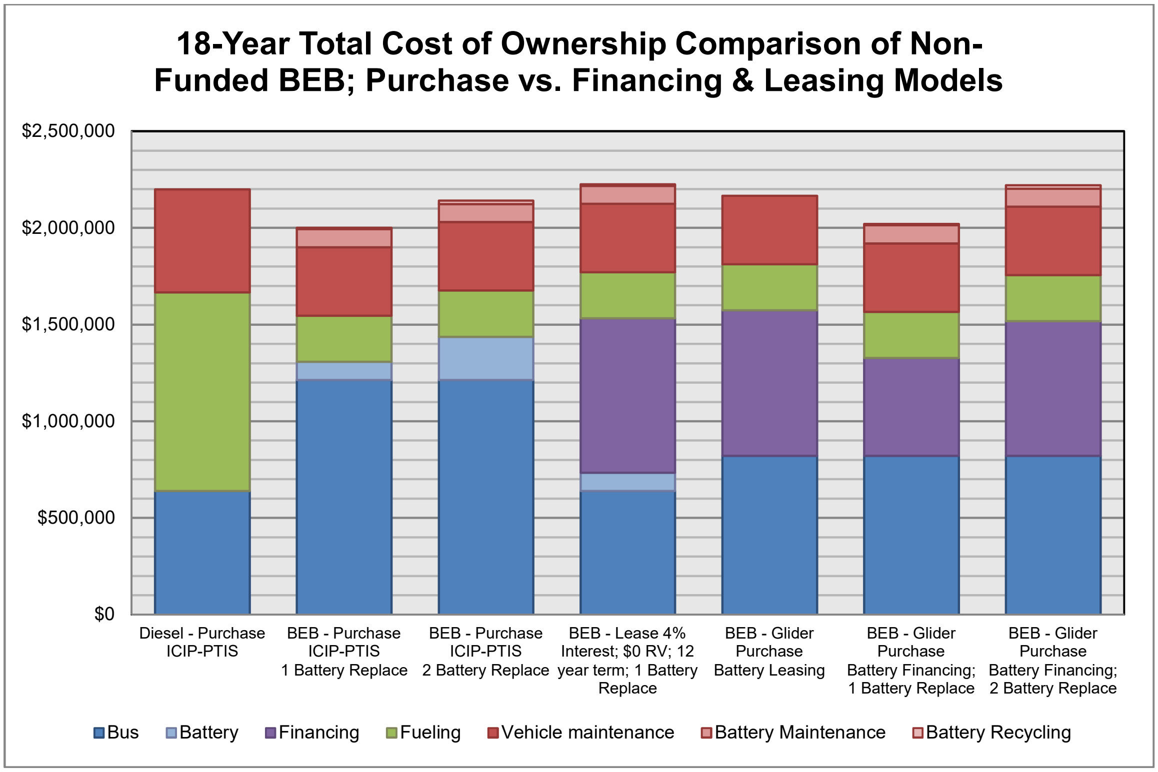


Figure 122: 18-year total cost of ownership comparison of non-funded battery-electric bus; purchase versus leasing and financing models [47] [234]

While financing and leasing options do lower the upfront capital investment required by Transit, not all options produce a lower total cost of ownership over an 18-year period. All battery leasing and financing options lower initial capital cost while still producing some operational savings over diesel. Bus leasing is the only option that results in higher operational costs than diesel.

Leasing rather than purchasing batteries adds some security as battery costs would become fixed over the life of the bus, but there is a cost trade-off for this security. With current leasing fees, annual operating costs would be around 14% lower than with the current diesel fleet, compared to an estimated 50% savings if the entire bus (including batteries) were purchased outright.

Low-cost capital financing is typically much easier for Transit to access as a result of federal and provincial programs, while operating budgets are continually being stretched [235]. While battery leasing or financing may lower capital expenses, there would be little flexibility in current operating budgets to cover unexpected expenses.

If the higher operating expenses are acceptable for a small test fleet, leasing or financing may enable Transit to include additional buses without increasing the project budget. However, when the availability of provincial and federal funding opportunities is considered, the case for leasing or financing becomes much weaker.

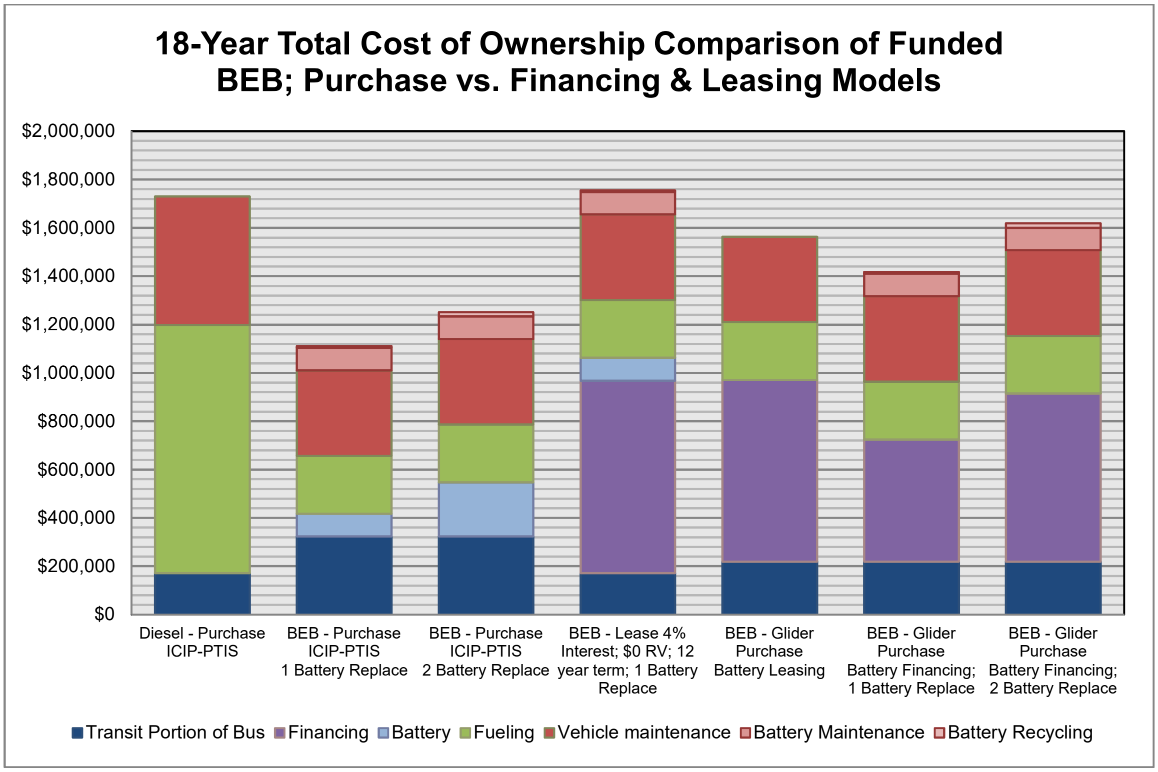


Figure 123: 18-year total cost of ownership comparison of non-funded battery-electric bus; purchase versus leasing and financing models

If Transit is able to secure provincial and federal funding for zero-emission buses, then buying the buses outright will produce the greatest lifecycle savings, even if batteries end up needing to be replaced more than once over an 18-year period. Purchasing the bus outright also provides Transit with more flexibility as to how operational savings are utilized, rather than being locked into repaying debt.

9.2 Government Programs for Zero-Emission Buses & Infrastructure

9.2.1 Investing in Canada Infrastructure Program (ICIP)

The governments of Canada and Manitoba are jointly committed to investing in infrastructure projects which benefit Manitoba. More than $3 Billion dollars is available through four funding streams. Zero-emission buses and refueling infrastructure would qualify through the Investing in Canada Infrastructure Program (ICIP) under either the Public Transit Infrastructure Stream (ICIP-PTIS) or the Green Infrastructure Stream (ICIP-GIS).

9.2.1.1 Public Transit Infrastructure Stream (PTIS)

ICIP-PTIS is a program available exclusively to transit agencies [236]. The program is targeted at improving reliability, efficiency, safety and accessibility of public transit systems. Winnipeg Transit is eligible to receive the majority of the funding allocated to this stream based on its ridership levels and the population of the City of Winnipeg municipalities [237] [238].

Only public transit infrastructure projects are eligible for this program, therefore an application for a zero-emission bus project under this program would only be competing against other Transit priorities for funding.

Program Overview:

- The Public Transit stream allocation for Manitoba is $546,139,840 [238].
- A zero-emission bus project qualifies for this program under the following eligibility:
  - Capital projects for the rehabilitation, optimization, and modernization of public transit infrastructure, or that improve the efficiency, accessibility and/or safety of public transit infrastructure (including rehabilitation or enhancement of existing guide ways, maintenance and storage facilities, or other existing public transit capital assets; refurbishment or replacement of existing rolling stock; and replacement or enhancement of transit stations);
- Federal funding is available up to a maximum of 50% for rehabilitation projects or 40% for new construction or expansion projects, with the total funding from provincial and federal funds not to exceed 75%.
- The Province of Manitoba is expected to cost-share a minimum of 33.3% of eligible expenses.

Of all current government programs, ICIP-PTIS potentially offers the largest overall reduction in capital costs.

9.2.1.2 Green Infrastructure Stream (GIS)

ICIP-GIS is available for any project that produces tangible benefits for communities through improved environmental, economic and social outcomes [239]. This stream requires a Climate Change Resilience Assessment to be submitted with an application, but projects are not necessarily ranked for eligibility based on the assessment.

Any green infrastructure project in the province is eligible for this program, therefore an application for a zero-emission bus project under this program would put it in competition against other provincial and City of Winnipeg priorities.

Program Overview:

- The Green Infrastructure stream allocation for Manitoba is $451,790,568 [238].
- A zero-emission bus project qualifies for this program under the following eligibility:
  - Climate Change Mitigation Sub-Stream (GIS-CCM);
    - Increased access to clean energy transportation (buses & refueling infrastructure).
    - Increased generation of Clean Energy (Solar installation & Hydrogen from electrolysis).
- Greenhouse Gas Mitigation Assessment required at time of submission.
- Project must be aligned with the Winnipeg Transit Master Plan
- The Province of Manitoba is expected to cost-share a minimum of 45% of eligible expenses.

9.2.2 Green Municipal Fund (GMF)

The Green Municipal Fund (GFM) is a $1 billon program, funded by the Government of Canada and delivered by the Federation of Canadian Municipalities (FCM). Through the GFM, FCM supports projects that reduce GHGs and mitigate the effects of climate change [240]. Funding and grants are available for plans, studies, pilot projects and full-scale capital projects. To be eligible for the program, a project must predict a minimum 20% reduction GHG emissions compared to an existing or modeled baseline measurement.

FCM utilizes the GMF to provide low interest loans to Canadian municipalities, with most eligible project also receiving a grant to cover a portion of the loan.

Program Overview:

- A zero-emission bus project qualifies for this program under the following eligibility:
    - Capital project: Reduce fossil fuel use in fleets
- Regular project - low-interest loan of up to $5 million and a grant worth up to 15% of the loan; covers up to 80% of your eligible costs.
- High-ranking project - low-interest loan of up to $10 million and a grant worth up to 15% of the loan; covers up to 80% of your eligible costs.

This program is not practical for large zero-emission bus procurements, but could be used to finance charging or hydrogen fueling infrastructure or to support future feasibility studies relating to future zero-emission fleet expansion.

9.2.3 Canada Infrastructure Bank (CIB) Canada Growth Plan

The Canada Infrastructure Bank has a mandate to invest, and to seek to attract investment from private sector investors and institutional investors, in revenue-generating infrastructure projects that are in the public interest [241]. To this end the CIB provides financing and investment for projects that align with Government of Canada infrastructure priorities.

The Government of Canada recently announced a new infrastructure initiative through the CIB called the Canada Growth Plan. Through this program, $1.5 billion was allocated to accelerate the adoption of zero-emission buses to modernize fleets, reduce greenhouse gases, and lower operating costs.

Based on preliminary information released by the CIB, this program would provide a loan to cover the incremental cost of zero-emission buses and infrastructure [242]. Debt services on the loan would be based on a portion of predicted fuel and maintenance saving as compared to diesel buses, with transit agencies also able to retain a small portion of the savings. Mid-life overhaul and battery replacement costs would not be included, but would be considered in the debt servicing calculation.

This program would be very similar to battery leasing options offered by bus manufacturers, with Transit paying the CIB rather than the bus manufacturer directly. Unlike leasing, this program would fund the incremental cost of both the buses and refueling infrastructure. Typically, the CIB's interest rates vary from 1-3% which are lower than the rates manufacturers are currently offering through private financing companies [243]. Earnings from interest would likely be used as seed money for the continuation of the program.

Much like leasing, this program is designed to lower the upfront purchase price of zero-emission buses and offer lifecycle costing similar to diesel buses when no other capital funding is available. Capital reductions are not as large as other programs, and the money is not offered interest-free; however, since the program does not rely on any financial commitment from provinicial governments, funding may be easier for transit agencies to access.

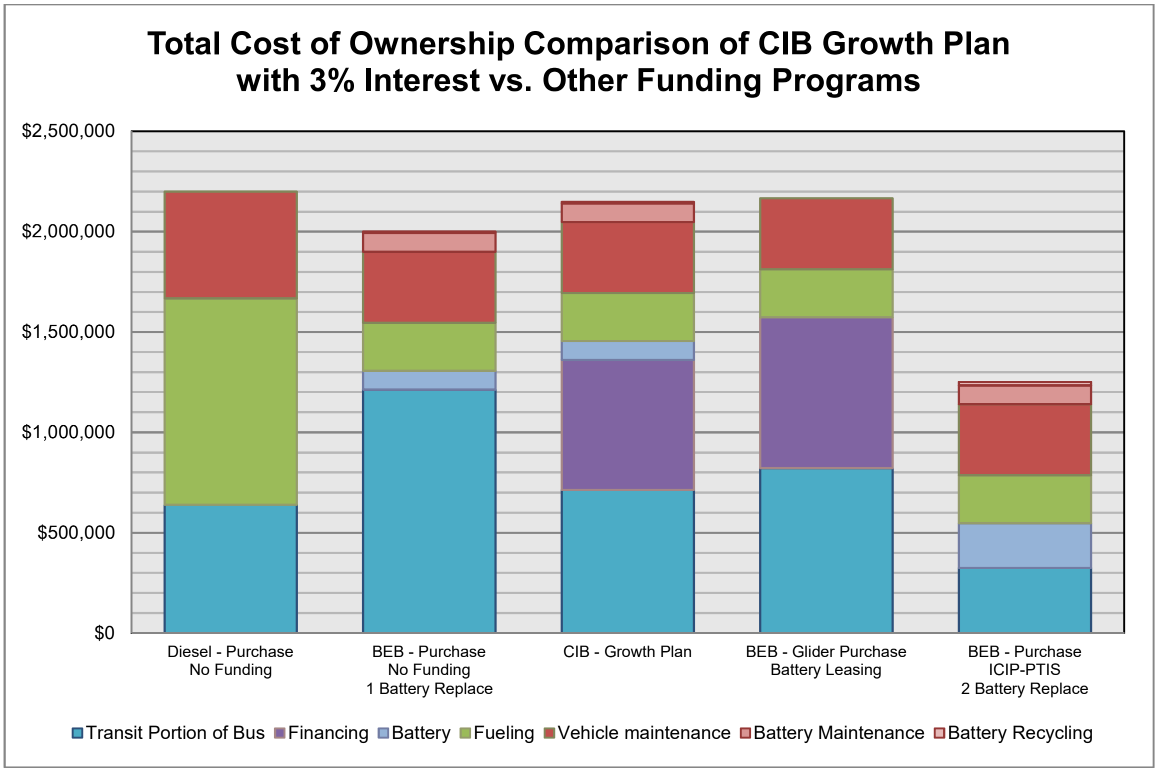


Figure 124:Total cost of ownership comparison of CIB Growth Plan with 3% interest vs. other funding programs

It is not clear at this time whether this program could be combined with other programs such as ICIP-PTIS, or if this would be a completely separate funding model.

9.2.4 Natural Resources Canada (NRCAN) Green Infrastructure Programs

From time to time NRCAN introduces funding for green infrastructure projects to accelerate the deployment and market entry of next-generation clean energy infrastructure [244]. Applications for funding are typically time sensitive.

Programs utilized by other transit agencies include:

9.2.4.1 Electric Vehicle and Alternative Fuel Infrastructure Demonstration

This program was originally launched in 2016 with the purpose of creating a coast to coast refueling network for electric, CNG, and hydrogen vehicles. In 2019 the program was extended to 2024 with an additional $130 million of available funding. While the original intent of the program was to create public fueling stations, non-publicly accessible stations utilized for the purpose of public transit are also eligible under this program.

Any charging station over 50 kW is eligible, but hydrogen fueling stations are only eligible for the program if they are capable of dispensing hydrogen at 700 Bar. Dual fueling with 350 Bar and 700 Bar is available, but the addition of a 700 Bar compressor is not necessary for transit bus fueling and would add expense. Discussions with NRCAN have indicated that a new program designed specifically for heavy duty hydrogen vehicles which eliminates the 700 Bar requirement may be launched in 2021.

While proposals to this program are no longer being accepted it is likely that another round of funding will be available through this program or a similar program in the future.

Program Overview:

- Maximum $5,000,000 available through the program per project
- Up to 50% of the total project costs to a maximum of $50,000 per charger
- Up to 50% of the total project costs to a maximum of $1,000,000 per hydrogen fueling station

9.2.4.2 Unsolicited Proposal for Hydrogen Infrastructure

NRCAN had indicated that hydrogen infrastructure will be a priority with the launch of the Canadian National Hydrogen Strategy. Establishing funding for hydrogen infrastructure has been identified in the Hydrogen Strategy for Canada report as a key strategic opportunity to grow the hydrogen economy in Canada [245].

NRCAN has indicated that a transit project putting battery-electric buses in head-to-head operation with fuel cell battery-electric buses would be of interest to them. It would be possible for Transit to submit an unsolicited proposal for a project including hydrogen infrastructure project prior to the announcement of funding.

Funding for an unsolicited project would likely be similar to other Green Infrastructure programs with projects eligible to receive up to 50% of total projects costs. There is no guarantee that Transit would receive funding from an unsolicited proposal; however, if the proposal were accepted there is potential that the maximum amount received could exceed the $5 million maximum normally awarded through a structured program.

Funding awarded through NRCAN would be in conjunction with, not additional to, funding from other Government of Canada programs.

9.3 Other Potential Funding

In addition to traditional funding methods, transit agencies are using creative new ways to fund zero-emission bus projects.

9.3.1 Green Bonds

Green bonds are similar to traditional bonds, but they are used specifically to raise funds for environmentally efficient initiatives. The majority of green bonds issued in Canada are “Use of proceeds” bonds, where the proceeds from a bond are to be used for green projects [246].

Many provinces and municipalities have started issuing green bonds to raise funds to support local green initiatives such as expansion of fleet electrification. Private transit agencies such as TransLink in Vancouver, BC have also issued green bonds to fund clean transportation initiatives, including electric vehicle and infrastructure purchases as well as cycling and walkway infrastructure [247].

Green bonds were identified in *Manitoba’s Climate Change and Green Economy Action Plan*, 2015; however, to date no green bonds have been issued by the province of Manitoba.

If the Province of Manitoba or the City of Winnipeg were to issue green bonds, transit electrification could be a potential project financed with the proceed. Alternatively, Transit could apply to be added to the portfolio of projects funded via a private green bond offering.

9.3.2 Volkswagen Emissions Scandal Settlement

In 2016 the United States settled a case with Volkswagen (VW) for illegally importing cars that violated emissions standards. A portion of the settlement was designated to be allocated for purchasing clean energy vehicles for public fleets and EV infrastructure. Bus electrification projects were not mandated, but several states have been utilizing this money to offset transit bus and charging infrastructure purchases.

In January 2020 VW settled a similar case with the government of Canada for $196,500,000 [248]. The money will be paid to the federal government's Environmental Damages Fund; however, it is recommended that the damages be divided and distributed to each province based on the number of vehicles sold in each jurisdiction.

If Canada takes a similar approach to the US, Winnipeg may be able to utilize the funds from the Canadian settlement for bus electrification. Based on information from Statistics Canada, Manitoba accounts for between 2-2.5% of all passenger vehicle sales in Canada. Assuming a similar division occurs with VW sales, Manitoba's portion of the VW settlement would likely be somewhere between $4-5 million dollars.

10 CONCLUSIONS

The decision on which technology best suits Winnipeg is highly dependent on Transit's operations as well as the local source of electricity and hydrogen. Manitoba's energy mix is 99% renewable, which creates a unique opportunity for Transit to potentially operate both battery-electric and fuel-cell battery-electric buses from renewable sources at costs significantly lower than other cities in North America.

10.1 Test Fleet Selection

When evaluated based on a small-scale deployment, battery-electric buses have clear economic advantages over fuel-cell battery-electric buses. However, when evaluated based on full-fleet electrification, and taking into consideration the technology constraints of both the buses and refueling infrastructure, there is no one technology from a strictly cost perspective that had a clear advantage over the others. With economies of scale, the purchase price of a both battery-electric and a fuel cell battery-electric bus are expected to be similar, so performance, infrastructure, and operational advantages will be the main drivers to separate the two technologies. These key performance drivers can only be properly assessed by operating a test fleet.

Battery-electric buses have the advantage of lower maintenance and predictable fueling costs; however, complexities associated with scaling up charging infrastructure, including power management, energy storage, back-up generation, equipment maintenance, and charger management will drive significant operational changes which may necessitate significant additional investment.

Fuel cell battery-electric buses have superior range, predictable mid-life overhaul cost, low large-scale infrastructure cost, and would drive no significant operational changes; however, the cost of hydrogen could be a barrier to unlocking maximum savings. If low-cost hydrogen could be sourced, the potential lifetime savings from fuel cell battery-electric buses could be on par with, or better than, battery-electric buses. If pricing remains as it is today, operational savings are likely to be only moderately better than diesel buses.

There are many things to consider beyond just the buses themselves. Operational considerations, including garage layout, depot management software limitations, and available electrical service, may influence decisions on future bus purchases. As it is not immediately clear which technology is the best solution for large-scale electrification, and more than one technology may need to be deployed in the long-term, it is recommended that Transit consider including more than one technology in the next phase of electrification. This should include both a mix of propulsion systems as well as a mix of vehicle lengths.

From a cost perspective, a test fleet with only 40-foot buses might make sense, but Transit's fleet currently includes more than just 40-foot buses. While there are only minimal differences between 30-foot and 40-foot buses, there are significant operational, performance, and maintenance differences between 40-foot buses and 60-foot articulated buses. Articulated buses tend to operate on a different duty cycle with higher speeds, less frequent stopping, and higher passenger loads. They also have different capacities of energy storage. Developing processes solely around 40-foot buses may result in the need to re-evaluate and modify systems once zero-emission 60-foot buses are introduced. The future purchase and operation of 90-foot double articulated buses is being considered in the Winnipeg Transit Master Plan, and the inclusion of 60-foot articulated buses in the zero-emission bus test fleet would give at least some insight into the operational characteristics of larger vehicles.

Establishing a test fleet which includes a mix of propulsion systems as well as a mix of vehicle lengths will provide Transit with the ability to collect data to assist with planning and decisions before determining the next steps in electrification. This direction will require a high initial investment and does not produce the highest operational savings for the test fleet, but as the intent of the program is to study and collect data for long-term decision making rather than to maximize short-term savings, taking a mixed fleet approach best fits this requirement. Focusing on short-term savings with the test fleet would result in a missed opportunity to achieve significant savings when fleet-wide electrification is pursued.

Despite the results of this evaluation indicating that on-route rapid-charge battery-electric buses would be a cost-effective solution for a small-scale test fleet, it is recommended that Transit only consider including long-range buses (BEB & FC-BEB) for inclusion in a test fleet for the following reasons:

1. Significant data on the performance and operation of on-route rapid-charge battery-electric buses was collected during the four-year battery-electric bus demonstration.
2. Energy consumption of rapid-charge and long-range battery-electric buses are virtually identical.
3. Charger availability more significantly impacts fleet availability and could result in less driving data being collected during the testing phase.
4. Significant route realignment is being proposed as part of the Winnipeg Transit Master Plan, creating the risk of charger locations becoming obsolete as the route network changes.
5. Limited range of on-route rapid charge buses results in buses being restricted to specific routes, reducing the amount of data that could be collected during the testing phase.
6. Battery-electric specific schedules would need to be developed which consider range as well charge layover time and spacing of buses between charge sessions.
7. Any schedule disruptions are likely to be amplified if buses start queuing at a charger.

Fuel cell battery-electric buses are currently only available in one configuration, but there are two capacity variations to consider for long-range battery-electric buses. The smaller mid-sized capacity buses paired with 75 to 150 kW high-powered DC plug in charging appears to be the best balance of cost, performance and passenger capacity for Winnipeg Transit. This includes 440 kWh battery capacity for 40-foot buses and 466 kWh for 60-foot buses. These buses have sufficient range to compete nearly 80% of Transit's current weekday runs. Adding mid-day charging would be an option for the remaining 20% of runs, or alternate technologies with longer single-deployment range could be deployed instead, such as fuel cell battery-electric buses or on-route rapid-charge buses. It is highly likely that this first generation of buses would be retired before the size of the zero-emission fleet requires this to be done on a regular basis.

It is recommended that a 16-bus fleet with four 40-foot long-range BEBs, four 40-foot FC-BEBs, four 60-foot long-range BEBs and four 60-foot FC-BEBs be operated for the purposes of evaluating the two remaining technologies based on their technical and operational constraints.

The test fleet should operate for a minimum of 18-24 months to allow Transit sufficient time to collect and review data to understand the true costs of each technology. The results of this trial, combined with the results from the earlier battery-electric bus demonstration, would be used to consider the systemic changes required to transform Transit from a diesel bus operator to a zero-emission bus operator, and to provide insight on fleet mix for future bus procurements.

After testing is complete, Winnipeg Transit will be well positioned to begin purchasing zero-emission buses as part of its Bus Replacement Program.

10.2 Capital Cost Consideration for Mixed fleet

Designing a robust test around two different types of zero-emission buses would require Transit to install infrastructure, purchase tooling, and upgrade facilities to support operating, servicing and maintaining both types of buses. Although this is the preferred approach to collect the data necessary to develop future fleet transformation strategies, it is the most expensive option for a test fleet.

A class 3 estimate of the proposed mixed test fleet of 16 buses operated out of Brandon Garage was completed, and after construction, equipment, consulting fees and contingencies are considered, the total cost of the Transition Fleet Project is expected to be approximately $38.3 million. This estimate considers the optimal amount of each bus type and the refueling infrastructure necessary to support a mixed test fleet of 16 buses. However, it is well understood that the City is currently facing significant operating and capital funding challenges. If required, it would be possible to adjust the total cost of the project based on the availability of funding, but this may have operational impact or reduce the amount of data during the test period. It may also limit the scope of the project and not allow for proper full consideration of all relevant technologies and bus sizes, necessitating the need for future evaluations and delaying the transition to zero-emission.

There are various programs available to supplement the capital costs associated with zero-emission vehicles and infrastructure. The Investing in Canada Infrastructure Program (ICIP) - Public Transit Infrastructure Stream (PTIS) appears to be the program that offers the greatest benefit. The project would require approval from multiple levels of government. Under ICIP-PTIS the maximum federal contribution would be 40% of eligible costs and the provincial contribution would be 33.3% of eligible expenses. The City of Winnipeg's remaining contribution towards the launch of a zero-emission test fleet would be approximately $11.4 million.

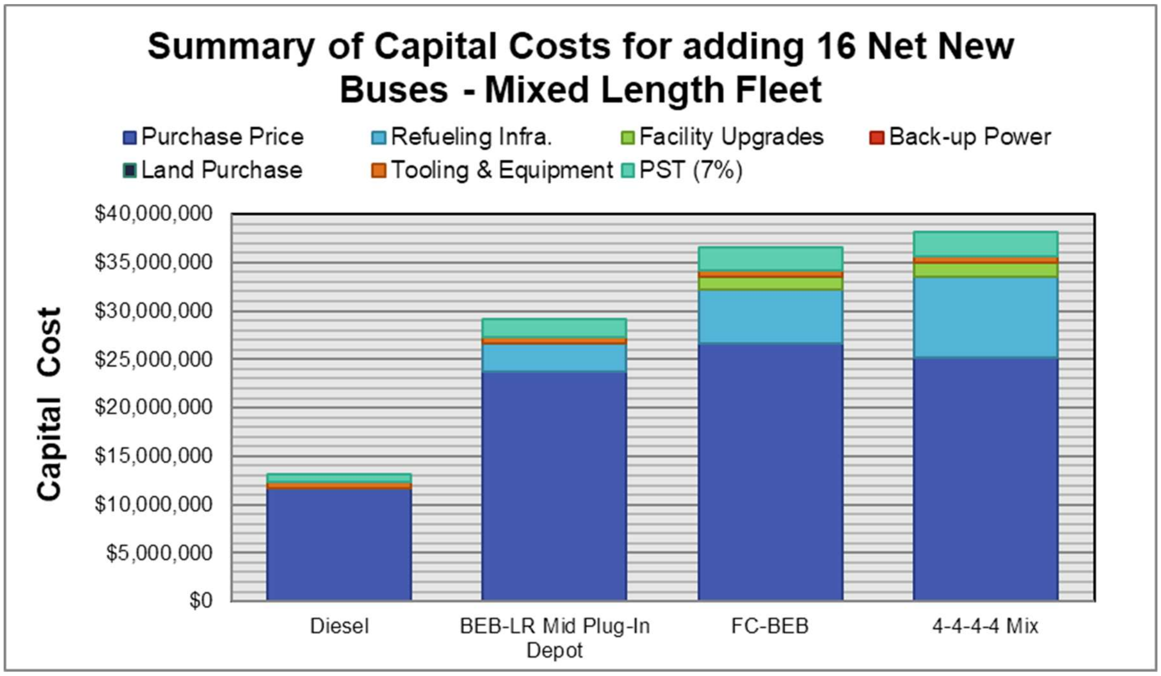


Figure 125: Summary of capital costs to purchase and operate 16 long-range Zero-Emission Buses

While both Brandon Garage and Fort Rouge Garage have the potential to support a small-scale deployment of zero-emission buses, Brandon Garage is the preferred location because it is the newest facility and has greater ability to expand electric grid capacity up to the levels necessary to support a zero-emission test fleet. There are however design constraints at this facility which result in higher-than-expected infrastructure costs, including the building footprint and layout, the first-in-first-out parking strategy, and electrical service limitations imposed by Manitoba Hydro.

Fuel cell battery-electric buses can be parked in a similar manner to diesel buses, but long-range battery-electric buses need to be parked at a charging-enabled location. While eight battery-electric buses could easily be charged on a single track, Transit requires the buses to be staged across two tracks based on concerns about bus positioning and the charger reliability. Staging buses across two tracks allows Transit greater flexibility to schedule any diesel buses parked behind battery-electric buses for late-day deployments. If a battery-electric bus were to stall in the track, this strategy would allow sufficient time for mechanics to move the bus without delaying any diesel bus deployments.

While Transit's schedule would accommodate a 4:1 bus to charger ratio, for a deployment of eight battery-electric buses this would result in just two chargers and a maximum of eight charging locations. If chargers were restricted to only the back of the track, then they would be limited to just late day deployments, which would restrict the amount of data that could be collected. If the charging locations were restricted to the front of the track there is increased risk of late diesel bus deployments. If the charging locations were equally distributed along the tracks, buses may end up parked in a location without access to a charger. At this time, the only option is to install charge points at each of the 34 parking spots along the tracks. With current sequential charging limitations of four plugs per charger, electrifying this number of spaces would require nine chargers for just eight buses. It may be possible to increase the number of plugs operating per charger, but it is unlikely that more than six could be daisy chained to a single charger, necessitating the need for at least six chargers. While it is unlikely that all chargers would be required to operate at the same time, a system of this size could utilize up to 1,350 kVA of available service.

From a capital cost perspective, hydrogen infrastructure developed around delivered fuel is the least expensive option. Unfortunately, there are currently no local sources to deliver green hydrogen. While Transit has been in discussions with several parties interested in supplying hydrogen, none would be available on a timeline that aligns with the planned arrival of the buses in the test fleet, and there is no guarantee that the supply would be available for the life of the bus. To ensure a stable supply of fuel for the test fleet, it is recommended that Transit install a hydrogen fueling station which includes an electrolyzer for on-site hydrogen production. Based on the combined amount of on-board hydrogen storage, the recommended production capacity for an eight-bus fleet of fuel cell buses would be 400 kg per day. This amount of fuel would accommodate all buses traveling from full to empty every day. However, since the buses are more likely to travel 150 km or less, a system of this size could actually support close to four times that many buses. While it is unlikely that transit will need to operate an electrolyzer at maximum capacity during the trial, a system of this size does require up to 1,450 kVA of available service.

While either system on its own could easily support over 30 buses, including both systems is necessary and there is no easy way to scale this down for 16 buses. Oversizing both charging and fueling infrastructure to support a test fleet results in both additional cost and combined electrical loads which exceed the available service at Brandon Garage. Reducing charging capacity or utilizing a portion of the unused service at Fort Rouge Garage are both options to resolve this issue. The over-sizing of both systems for the test fleet also allows for some growth of the ZEB fleet in the future before additional investment in charging/fueling infrastructure would be required.

10.3 Operating Cost Considerations for a Mixed Fleet

Winnipeg Transit currently intends to utilize the zero-emission test fleet to offset mileage that would have otherwise been completed by the same number of diesel buses. Any additional infrastructure maintenance costs associated with maintaining a combination of depot plug-in charging and fueling using on-site produced hydrogen will likely be offset by zero-emission bus maintenance and fueling savings. As such, there is no anticipated impact to the operating budget with the introduction of the test fleet. Operating costs are expected to fluctuate yearly based on actual electricity pricing; maintenance requirements of buses, chargers, and refueling infrastructure; and repair and overhaul needs. It is likely that any potential cumulative savings from fueling or maintenance will be negated by costs associated with mid-life overhaul such as battery replacement and fuel cell refurbishment. While the true operating costs of zero-emission buses will need to be evaluated as the buses are operated in regular service over several years, an 18-year lifecycle analysis of potential operating costs has been included for comparison. It should be noted that any small fluctuations in cost of diesel fuel or electricity could either improve or negate any potential savings.

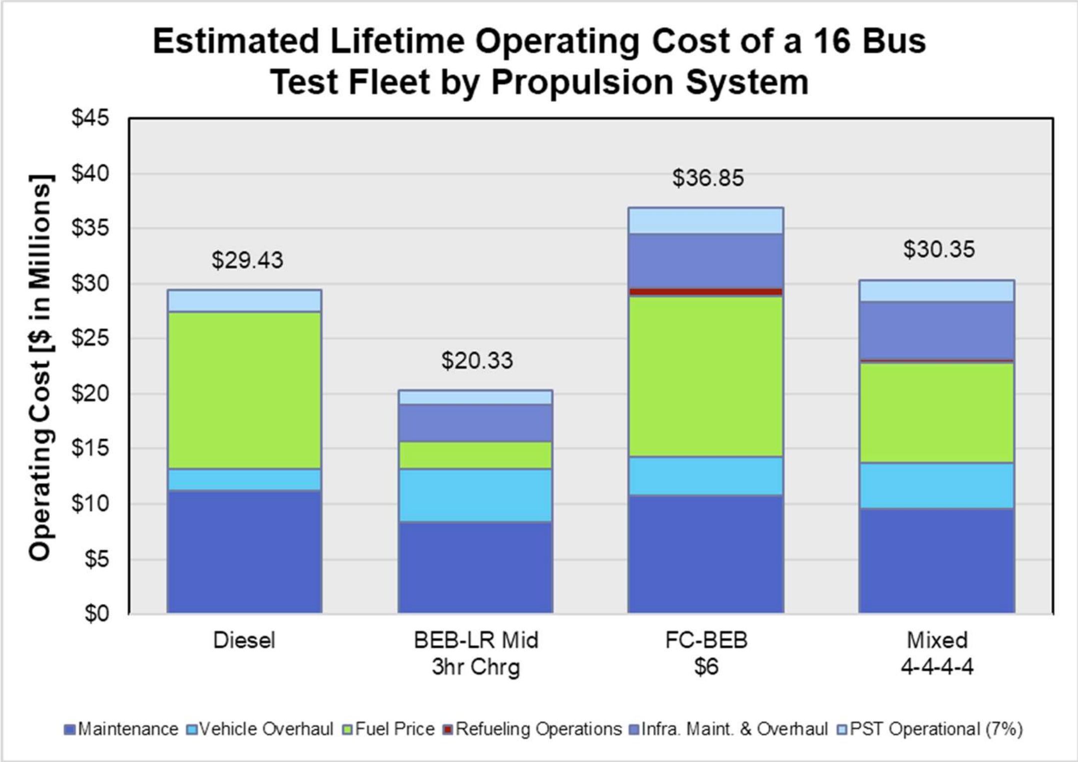


Figure 126: Summary of per kilometer operating costs for long-range zero-emission buses

The electricity pricing utilized in this analysis included Manitoba Hydro's current utility rate structure and considered the proposed mix of 16 buses and associated infrastructure. The cost of hydrogen was assumed to be $6 per kilogram dispensed. This is on the higher end of estimates for on-site production in Manitoba from hydro-electricity, and actual fuel pricing may be lower. Similarly, monthly utility charges for electricity were estimated based on worst case peak demand loads. As Transit becomes more familiar with the performance of the buses and refueling infrastructure, it may be possible to lower utility bills with a refined energy management strategy. Actual electricity costs may also vary if utility rates increase beyond the typical rate of inflation, if Manitoba Hydro alters its rate structure, or if the proposed fleet mix changes.

While mid-life overhaul costs associated with structural repair, battery replacement, and fuel cell refurbishment of the test fleet are shown under operating costs in this analysis, Transit could choose to include these costs in either the capital or the operating budget. In the case of diesel buses, some portion of the fleet is overhauled each year, and as such mid-life overhaul costs are included in Transit's operating budget. In the case of a test fleet, these costs will actually be incurred between years nine and 12, which would enable them to be forecast in a future capital budget. While it is unlikely that all buses would need to be overhauled in the same year, the total combined costs associated with mid-life overhaul of the zero-emission test fleet is anticipated to be $2-3 million dollars higher than a similarly sized diesel fleet.   In order to properly compare the operating costs of diesel and zero-emission buses in this analysis, the mid-life overhaul costs of the zero-emission fleet were applied in a similar manner as the diesel fleet by averaging costs over their useful lives and estimated per 1000 km of travel, making them operating costs rather than capital costs.

10.4 Cost to Purchase, Operate, and Maintain a Mixed Fleet of Sixteen Long Range Zero-Emission Buses and Associated Infrastructure

Based on an 18-year, 930,700 km life, Transit's current duty cycle and operations starting in 2022, and adjusted for annual inflation up to 2030, the lifetime capital and operating costs of a mixed test fleet of sixteen long range of zero-emission buses are estimated to be as follows:

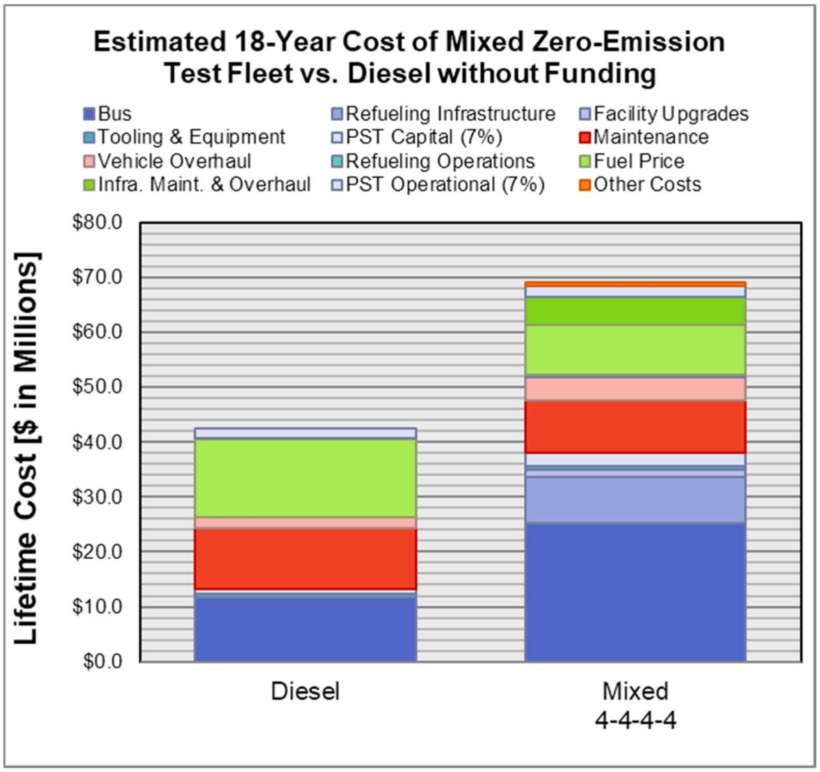


Figure 127: 18-year lifecycle costs of a mixed zero-emission test fleet compared to diesel replacement

Similar to analyses completed for a single propulsion type, the initial purchase price for a mixed fleet of zero-emission buses, plus additional supporting infrastructure, remains a significant barrier to the technology reaching parity with diesel buses over an 18-year useful life. Without receiving any funding to offset the incremental capital expenses, the lifecycle costs to purchase and operate a mixed zero-emission test fleet will not break even with diesel buses over their 18-year useful life.

Based on an 18-year, 930,700 km life and Transit's current duty cycle and operations starting in 2022, and adjusted for annual inflation up to 2030, the lifetime capital and operating costs with a PTIS eligible project are estimated to be as follows:

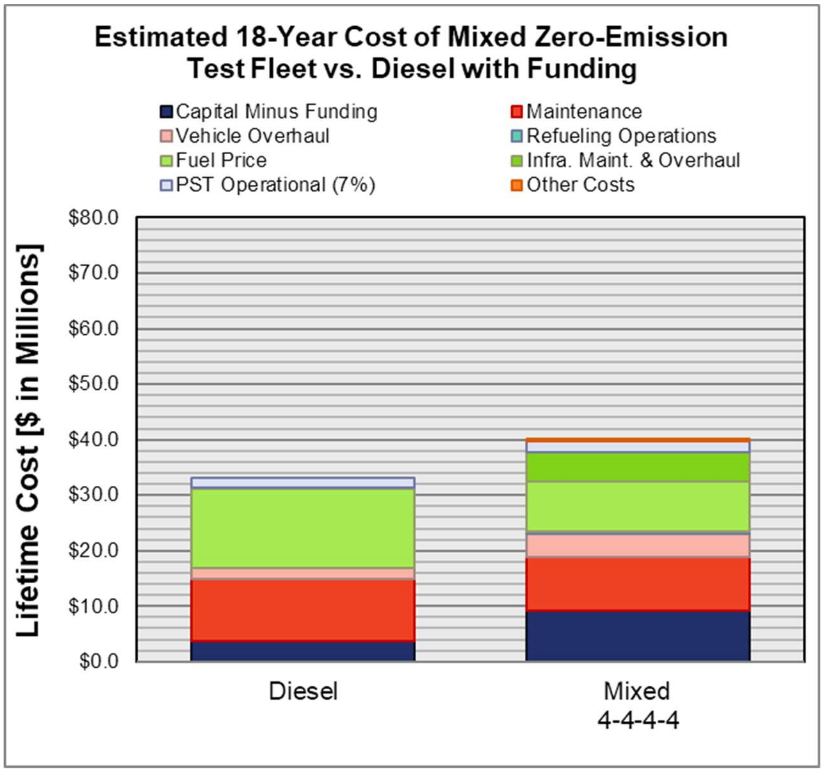


Figure 128: 18-year lifecycle costs of an ICIP-PTIS funding of a mixed zero-emission test fleet compared to diesel replacement

	Lifetime Savings	Avg. Lifetime Savings/Bus	Avg. Annual Operational Savings/Bus
BEB-LR Mid 3hr Charging	-$ 7,136,989	-$ 446,062	-$ 3,192

While preliminary results show that the test fleet would not produce savings over an 18-year period, it should be noted that if the fleet grows beyond 16 buses, the proposed infrastructure allows for some growth of the ZEB fleet. This would enable Transit to initially replace up to 60 diesel buses with zero-emission buses before any additional investment in charging or fueling infrastructure would be required. With the fleet size and infrastructure capacity properly aligned, it is likely that a mixed fleet of zero-emission buses would produce annual operating savings.

10.5 Future Considerations for Fleet Transformation Beyond the Test Fleet

After testing is complete, Winnipeg Transit will be well positioned to begin purchasing zero-emission buses as part of its Transit Bus Replacement Program. Transit would gradually retire diesel buses from service, initially procuring 18 zero-emission buses and associated refueling infrastructure each year, and eventually transitioning to full replacement with 30-35 zero-emission buses annually once transit operations are fully aligned to support the new technology. Based on the current status of fleet electrification at Winnipeg Transit, a 40% zero-emission fleet can be achieved by 2032, just two years behind the 2030 target, but the transition to a 100% zero-emission fleet would be completed several years ahead of the 2050 target. Purchasing any diesel buses after 2030, or accelerating the transition to zero-emission buses, or could result in the early retirement of diesel buses that have not yet reached the end of their estimated 18-20 year normal service life.

Transitioning Winnipeg Transit from a diesel bus operator to a zero-emission bus operator will not be as easy as replacing a diesel bus with a zero-emission bus. It will require a systemic change to operations throughout the entire organization, and will require significant amounts of planning over the course of several years to implement. It is recommended that Transit consider launching a Transition to Zero-Emission Bus Program for the purpose of planning and managing the various projects and sub-projects that will be created by the transition to zero-emission, with the Transition Fleet Project being the first project delivered under this program. The goal of the program should be to set the direction for establishing a zero-emission fleet and following through on initiatives subject to securing funding sources and Council approval.

Beyond the Transition Fleet project, Transit should be considering the next phase of electrification in this new program, i.e. how to increase the zero-emission fleet to 120-200 buses as recommended by the Joint Task Force on Transit Electrification. The fueling infrastructure selected for the test fleet includes 34 plug-in charging stations and an electrolyzer capable of producing 400 kilograms of hydrogen per day. While including 60-foot buses in the test fleet was essential, the next phase of the transition to zero-emission is likely to be focused on fleet replacement of 40-foot diesel with either 60-foot diesel buses or 40-foot zero-emission buses until such time as Transit has confidence in the performance of 60-foot ZEBs on high frequency routes. The charging infrastructure installed for the test fleet would be capable of accommodating the original eight buses plus an additional twenty-two 40-foot BEBs, for a total of thirty BEBs. Similarly, based on average travel, hydrogen production equipment could support the original eight buses, plus an additional twenty-two 40-foot FC-BEBs, for a total for thirty. To expand beyond thirty buses with either technology will require some additional investment. With current plans in place to begin replacement of diesel buses with zero-emission buses in 2024, additional infrastructure will need to be installed starting in 2025 and there may not be sufficient electrical service capacity at Brandon Garage or Fort Rouge Garage to support any further expansion after 2027 without significant investment.

Selecting Brandon Garage as the primary location for the test fleet will restrict future expansion of the zero-emission fleet at Fort Rouge Garage due to electrical service limitations imposed by Manitoba Hydro's existing local area infrastructure. The electrical service capacity at Fort Rouge Garage is not sufficient to support any significant number of depot-charged buses at that location without hampering plans for future maintenance garage expansion; however, there is some capacity to support limited expansion of a mixed fuel option at Brandon Garage.

Manitoba Hydro has indicated that expanding service capacity to support of larger electrification at either of these locations would require significant updates to their distribution system, and that a project of that magnitude would be expected to take 4-5 years to complete and have a large associated cost. Because of this, it is assumed that the combined electrical grid capacity across the two locations is restricted to 3,350 kVA.

The proposed hydrogen fill station with on-site hydrogen production requires approximately 1,450 kVA, and while this would leave at least 1,950 kVA available for charging or future expansion of hydrogen production, it is more conservatively estimated that a total of 1,500 kVA be allocated for this purpose order to leave some capacity for future equipment expansion of the maintenance section at Fort Rouge Garage. There are various different ways that this power could be distributed in support of transit electrification, but none accommodate expanding a zero-emission fleet beyond the current capacity of Brandon Garage.

Based on the electrical power constraints, the lowest cost solution for scaling up the zero-emission fleet would be to target a fleet mix of approximately 70% BEBs and 30% FC-BEBs. The existing hydrogen infrastructure could be utilized to expand the fleet to 30 FC-BEBs, and the remaining 1,500 kVA used entirely for charging. While 150 kW charging is preferred, the minimum charge power that Transit's schedule can support at large-scale is actually closer to 75 kW. With a 4:1 bus-to-charger ratio, there would be sufficient power to support a fleet of up to 80 battery-electric buses with minimal impact to operations. This would result in a total of 110 zero-emission buses.

If a 70/30 fleet mix of BEBs and FC-BEBs proves to be acceptable for the first 100-120 buses, this may be a good solution for expanding the zero-emission fleet beyond the Transition Fleet Project. This mix would allow Transit to test a single deployment strategy utilizing battery-electric buses on shorter runs, and fuel cell buses on longer runs. The applicability of on-route charging could also be evaluated if and when the process of planning and developing new routes creates a scenario that suits this technology.

The transition to zero-emission is purposely planned to be gradual to allow Transit sufficient time to plan and adjust its zero-emission roll-out strategy based on data collected from the test fleet. If a 70/30 BEB/FC-BEB fleet mix is acceptable in the short term, but not the long term, it would be relatively straight forward to plan for adjustments to this fleet mix after Brandon Garage is fully converted to zero-emission. It is possible, however, that the results of the zero-emission bus trial may produce a strong preference for one technology over the other. If this happens there are options available for accommodating a different fleet mixture of zero-emission buses.

If the cost of hydrogen proves to be too large of a financial barrier during the trial, and Transit decides not to purchase any additional FC-BEBs beyond the first 8, Transit would need to find additional power for at least 100 more BEBs. Since full hydrogen production is not required, it would be possible to restrict hydrogen production and utilize some portion of the service allocated for the electrolyzer to expand charging capacity. If the service available for charging was increased to 2,000 kVA, 75 kW charging could support a fleet of up to 104 BEBs in addition to the original 8 FC-BEBs fueling with hydrogen, for a total of 112 buses

Conversely, if the operational challenges associated with managing charging prove to be too onerous and disruptive to daily operations, and Transit decides not to purchase any additional BEBs beyond the first 8, Transit would need to find a way to expand hydrogen capacity for 100 more FC-BEBs. Increasing on-site hydrogen production would be difficult. If possible, the easiest solution would be to supplement on-site production with delivered fuel. Daily fuel requirements of 1,000 kg or more is usually the tipping point where delivered fuel makes financial sense, and a fleet of 108 FC-BEBs would utilize at least 1,200 kg of hydrogen per day. With an available supply of hydrogen fuel, theoretically Transit would be to transition its entire fleet to FC-BEBs without a concern for electric service limitations, but beyond 100 or so buses outdoor fueling becomes very inefficient, and retrofitting either Brandon or Fort Rouge Garage for indoor fueling may be expensive.

In the unlikely scenario that delivered fuel is not available by the time Transit needs to expand capacity, it may be possible to restrict charging output to just 500 kVA, allowing for the installation of an additional 1 MW electrolyzer stack to double the hydrogen production. Utilizing this capacity to support more than 80 FC-BEBs may require restricting weekly fleet mileage.

Purchasing on-route charged buses and charging infrastructure is another option to consider for further expansion of the zero-emission fleet operated out of existing facilities. At large-scale this technology is the most expensive battery-electric bus to operate, and Transit may be required to purchase up to 10% more buses to replace the outgoing diesel buses, but fleet growth is not restricted by garage electrical grid capacity. This technology has been identified as only being suitable in very specific cases, where a feeder route far from a depot has a very long span of daily service hours. They would otherwise be difficult to integrate with the network realignments proposed in the Winnipeg Transit Master Plan, which would make this a less than ideal solution for adding more than a few buses, especially in the near future before the Winnipeg Transit Master Plan route network is fully implemented.

Regardless of which mix is ultimately selected, transitioning from diesel to zero-emission buses will occur as diesel buses reach the end of their useful lives. Charging or refueling infrastructure purchases will also need to be aligned with bus procurements. The current diesel bus fleet will need to be replaced with a combination of both diesel and zero-emission buses to allow operations to transition more smoothly. Replacing the existing Transit Bus Replacement Program with the proposed Transition to Zero-Emission Bus Program will help to ensure a smooth transition to a zero-emission fleet. Including the initial 16 zero-emission buses, Transit can reach its goal of purchasing 100 to 110 zero-emission buses by the end of 2027 with a budget of $280.4 million, based on a completed Class 4 estimate. There may be some flexibility within this budget to adjust the quantity of buses, the propulsion mix, the length of buses, or the refuelling infrastructure based on the outcome of the trial or the evolution of ZEB technology.

The existing Transit Bus Replacement Program has a projected 7-year cost of $161 million (2021 Adopted Budget plus 6 year forecast). This program is funded through a combination of Federal, Provincial, and City financing, with the City's contribution being approximately 55% or $88.4 million. If Winnipeg's application to the Investing in Canada Program (ICIP) is successful, the City's expected contribution towards the new $280.4 million Transition of Zero-Emission Bus Program would be approximately 28% or $78.4 million, and the Federal and Provincial Governments would finance the remaining 72% or $202.0 million. This would result in an incremental savings of $10.0 million, while at the same time freeing Federal Gas Tax contributions for other transit projects. The long term impact, if any, on the operating budget as a result of the transition to zero-emission buses is still being analyzed.

A purpose-built zero-emission bus garage is recommended to be built in support of future zero-emission bus fleet purchases by the time the first 100-110 buses are delivered. If a new zero-emission garage is not completed by 2027, electrical service constraints at Brandon Garage or Fort Rouge Garage would restrict any future expansion of the zero-emission bus fleet to on-route rapid-charge battery-electric or potentially fuel cell battery-electric buses if a source of delivered fuel could be secured. Alternative solutions such as adding a roof-top solar installation with an energy storage system at either Brandon Garage or Fort Rouge Garage would help reduce utility costs, but will have minimal impact with regards to expanding charging or fueling capacity. Restricting future zero-emission fleet expansion to specific technologies may have operational and cost implications. Transit's North Garage replacement has been identified as a priority infrastructure project by Winnipeg Transit. There are potentially significant savings from designing a transit garage with future consideration for zero-emission bus charging and hydrogen fueling infrastructure, rather than retro-fitting a garage designed for diesel buses, both from a capital and operations perspective as well as from a planning and project management perspective. Based on a previously completed Class 4 estimate, this project is estimated to cost $210.9 million, excluding any future costs associated with purchasing and installing charging or fueling equipment.

If beyond the first 100-110 buses, Transit replaces retired diesel buses with zero-emission buses at a 70/30 BEB/FC-BEB ratio, the projected annual fleet mix could look as follows:

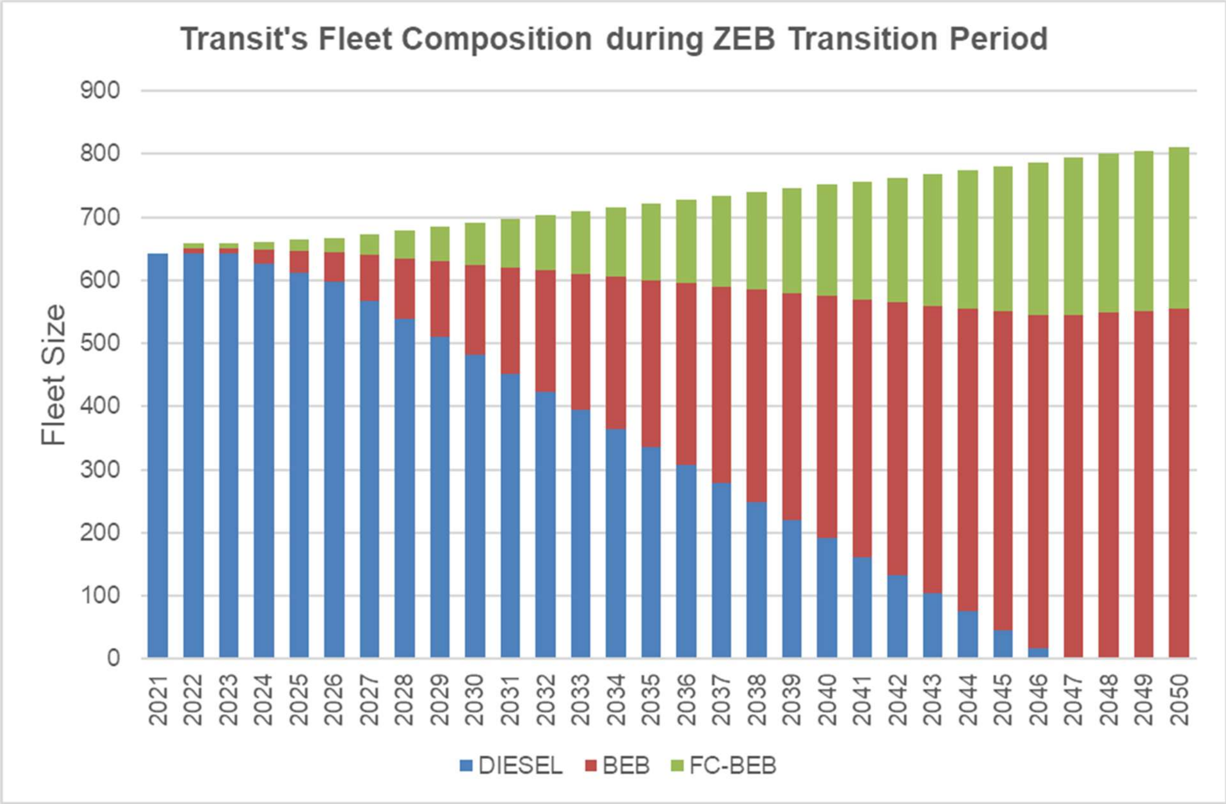


Figure 129: Projected transition from diesel to zero-emission up to 2050

Based on projected rate of transition, if fleet replacement with zero-emission buses begins in 2024 as planned, by 2030 Transit's fleet would be 30% zero-emission (210 of 700 buses), which is under the current target of 40% (280 of 700 buses). However, the entire fleet would be zero-emission by 2047, more than 3 years ahead of schedule.

The Winnipeg Transit Master Plan is proposing significant route network changes that could affect fleet size and fleet mix going forward. Efficiency improvements may not require Transit to expand its fleet at the same rate as it does today. Replacing 40-foot buses with 60-foot buses is one such way that service could be improved without directly increasing fleet size. As such, it may be possible for Transit to reach the target of 100% zero-emission sooner than shown without early retirement of diesel buses. Much of this will be determined by the actual efficiency gains and ridership increases realized under the Winnipeg Transit Master Plan.

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