Low Carbon Fleet Transition Plan

FINAL REPORT

February 24, 2020

Prepared for:

TRANSLINK

Coast Mountain Bus Company

Prepared by:

MJB&A

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This report was prepared for TransLink and the Coast Mountain Bus Company by M.J. Bradley & Associates, LLC. The report references and relies on electric bus charging conceptual designs and cost estimates created for TransLink by AES Engineering. MJB&A would like to thank Royce Bernard of AES for his thoughtful assistance in developing the Fleet Electrification Strategy, as well as Dom Repta and Sarah Buckle of TransLink for their guidance and assistance throughout the project.

This report was peer reviewed by Ben Sharpe, Ray Minjares, and Tim Dallman from the International Council on Clean Transportation; Michael Weston, an independent passenger transport consultant and former Director of Buses at Transport for London; and Alex Boston, Executive Director Renewable Cities, and Fellow at MJ Wosk Centre for Dialogue, Simon Fraser University. The authors would like to thank the reviewers for their thoughtful comments, many of which are reflected in this final report. The authors would also like to thank Anthony Courreges of C40 Cities for his efforts to coordinate the peer review process.

About TransLink & Coast Mountain Bus Company

South Coast British Columbia Transportation Authority (also known as "TransLink") was created by the Greater Vancouver Transportation Authority Act (British Columbia) in 1998. TransLink's mandate is to plan, finance and operate a regional transportation system that moves people and goods efficiently and supports the regional growth strategy, air quality objectives and economic development of the Greater Vancouver Regional District (Metro Vancouver). TransLink's subsidiary, the Coast Mountain Bus Company (CMBC), operates virtually all fixed-route transit bus service in the Vancouver metropolitan area, including in the municipalities of Burnaby, Coquitlam, Delta, Maple Ridge, New Westminster, North Vancouver, Pitt Meadow, Port Coquitlam, Richmond, Surrey, Vancouver, and White Rock.

About M.J. Bradley & Associates

M.J. Bradley & Associates, LLC (MJB&A), founded in 1994, is a strategic consulting firm focused on energy and environmental issues. The firm includes a multi-disciplinary team of experts with backgrounds in economics, law, engineering, and policy. The company works with private companies, public agencies, and non-profit organizations to understand and evaluate environmental regulations and policy, facilitate multi-stakeholder initiatives, shape business strategies, and deploy clean energy technologies.

EXECUTIVE SUMMARY

In 2016 TransLink engaged M.J. Bradley & Associates (MJB&A) to help the agency develop a Low Carbon Fleet Strategy (LCFS) that would produce significant reductions in greenhouse gas (GHG) emissions from the Coast Mountain Bus Company (CMBC) fleet, consistent with local and Provincial goals to achieve an 80 percent reduction in economy-wide GHG emissions by 2050.

The intent of the LCFS project was to develop a technology roadmap – for new bus and fuel purchases between 2020 and 2050 – to achieve the greatest practical GHG reductions, within the constraints of commercial and technical feasibility, projected future service and funding levels, and CMBC service constraints.

This report summarizes the Low Carbon Fleet Transition plan developed during the LCFS process, which relies on electrification of CMBC's 40-ft and 60-ft transit buses using battery-electric buses. Sections 1 provides background information on the LCFS planning process and the existing CMBC fleet and facilities. Section 2 summarizes the recommended high-level electrification strategy, as well as three detailed options for investments between 2020 and 2029 to put the fleet on that path. Section 3 summarizes the operational changes that will be required across the organization to accommodate electric buses. Supporting technical information is included in the Appendixes, including information on the status of the North American electric bus industry (Appendix A), discussion of electric bus charging options (Appendix B), a summary of the CMBC operational analysis that supports the recommended options (Appendix C), and a summary of the life cycle cost analysis (Appendix D).

The Low Carbon Fleet Transition Plan recommends replacement of existing 40-ft and 60-ft transit buses in the CMBC fleet with new battery electric buses at the end of their useful life, beginning with buses purchased in 2021, and delivered in 2023. Three different investment options are provided for the short term, between 2020 and 2029, but all scenarios anticipate only battery bus purchases after 2030, to achieve complete electrification of these fleets by 2050. The plan recommends that CMBC continue to operate 40-ft diesel highway coaches and gasoline shuttle buses, at least in the short term, with conversion of these bus types to battery-electric (highway, shuttle) or potentially fuel-cell electric vehicles (highway) beginning when the technology is more commercially advanced. The transition plan also recommends that CMBC employ both depot- and in-route charging strategies, with depot charging for slower speed routes through

Vancouver, and in-route charging on the higher speed routes through the other municipalities in the region.

Finally, the fleet transition plan recommends that during the transition to electric buses TransLink use low-carbon renewable natural gas (RNG) in existing compressed natural gas buses in the fleet, and also consider using low carbon renewable diesel fuel in existing diesel and hybrid-electric buses when it is commercially available in the Vancouver region.

The recommended plan will reduce annual fleet GHG emissions from the CMBC bus fleet (including 40-ft and 60-ft transit buses, 40-ft highway coaches, and shuttle buses) by 90+ percent from 2007 levels in 2050.

For the initial electrification investments between 2020 and 2029, three different options are provided. These options are characterized as Cautious fleet electrification, Progressive fleet electrification, and Aggressive fleet electrification, as they vary significantly in terms of the pace at which TransLink moves toward fleet electrification in the short term, with resulting differences in risk, cost, and short-term GHG reduction. However, all three options can put the CMBC fleet onto the recommended path to full electrification by 2050. The three potential investment options are summarized in Table 1.

Table 1 Summary of Fleet Electrification Investment Options 2020 - 2029

METRIC		CAUTIOUS	PROGRESSIVE	AGGRESSIVE
Electric Buses Purchased		95	314	635
In-route Chargers Installed		1	4	17
Depot Chargers Installed at		MTC	MTC	MTC and BTC
Routes Electrified	Depot Charging	30% of MTC routes	100% of MTC routes	100% of MTC routes 80% of BTC routes
	In-route Charging	Route 100	Routes 100, 159, 169, 188	Route 100 95% of PTC routes
CAPITAL INVESTMENT 2020-2029 (nom $ mill)	Buses	$37	$110	$199
	Infrastructure	$58	$89	$248
	TOTAL	*$95*	*$199*	*$447*
Operating Savings 2020 – 2030 (nom $ millions)		$27	$67	$124

METRIC	CAUTIOUS	PROGRESSIVE	AGGRESSIVE
GHG Reduction 2020 – 2030 (MT)	56,000	137,000	269,000
Annual GHG Reduction 2020 (MT)	9,800	33,600	59,500
Annual GHG Reduction 2030 vs 2007	14%	28%	44%

All three short-term investment options include the opening of the new Marpole Transit Centre in late 2023 or early 2024 as a 100 percent electric-capable depot, which will eventually utilize depot-based overnight charging for all assigned buses. The Aggressive electrification option also includes retrofit and expansion of the Burnaby Transit Centre in the next ten years to accommodate depot-based overnight charging; under the less aggressive options (Cautious, Progressive) this conversion happens after 2030. For these two transit centres the investments required to accommodate depot-based charging will be significant and will include the cost of the chargers and supporting electrical infrastructure, as well as the cost of depot expansion to accommodate a larger bus fleet and the charger installations.

The Low Carbon Feet Transition Plan ultimately envisions in-route charging for all buses operating from Hamilton, Port Coquitlam, Richmond, and Surrey transit centres. For these transit centres required investments at the depot to accommodate electric buses will be modest, but significant investments will be required to install high-power bus chargers at bus exchanges throughout the CMBC service area. Under all three short-term investment options these in-route charger investments begin by 2030, starting with the chargers required for routes 100, 159, 169, and 188.

The Cautious option for recommended electrification investments from 2020 – 2029 requires $95 million to begin the transition to electric buses. This level of funding would allow TransLink to open MTC as a 100 percent electric-ready depot, and to purchase a total of 95 electric buses and necessary chargers, including 80 buses to be operated from MTC using depot charging, and 15 to be operated on Route 100 using in-route charging. Together with the current pilot fleet of four electric buses and two in-route chargers already installed on this route, this level of investment would allow for complete electrification of Route 100 and electrification of approximately 30 percent of the routes operating from MTC by 2030, putting the fleet on a path to full electrification by 2050.

The Progressive option for electrification investments from 2020 – 2029 requires $199 million, for the purchase of 314 electric buses and necessary chargers. This level of investment would allow TransLink, by 2030, to fully electrify all routes operating from MTC, as well as Routes 100, 159, 169, and 188. This option would put the fleet on a path to full electrification by 2045.

The Aggressive option for electrification investments from 2020 – 2029 requires $447 million, for the purchase of 635 electric buses and necessary charging infrastructure. This level of investment would allow TransLink to fully electrify over 50 percent of all CMBC bus routes by 2030[1], and would put the fleet on a path to full electrification by 2040. This option represents the fastest possible fleet electrification transition without retiring buses early.

Annual operating cost savings between 2020 and 2030, which would result from fleet electrification, are projected to be between $27 million and $124 million, depending on the investment option chosen. Under all options, after 2024 CMBC is projected to see modest annual savings in bus maintenance costs and significant annual savings in fuel costs. These savings will be balanced by modest annual increases in bus operator labor costs as well as modest new costs for charging infrastructure maintenance.

Depending on the investment option chosen, annual fleet GHG emissions in 2030 are projected to be 14 - 44 percent lower than fleet emissions were in 2007[2].

Regardless of the investment option chosen, over the next ten years CMBC will need to make significant changes to all aspects of their current operations, to accommodate fleet electrification, including:

- Securing axle weight exemptions from the Province to operate electric buses, which are heavier than current buses in the fleet.
- Making changes to bus schedules and block assignments to accommodate the range limitations of electric buses
- Evolving bus maintenance and overhaul programs to handle electric drive systems
- Developing new tools and procedures to monitor and manage electric bus charging and to manage cold weather operations
- Developing completely new capabilities to maintain and repair electric bus charging infrastructure, and
- Procuring mobile power generation capabilities to ensure that electric buses can operate even if the electric grid is interrupted.

[1] This includes trolley routes
[2] 2007 is the base year for most local and provincial GHG reduction goals.

The Low Carbon Fleet Transition Plan presented here is based on current commercial electric bus and charger options in North America, and best available estimates of future technology development. The plan acknowledges and accounts for expected improvements in battery technology, and electric bus capabilities, over the next 30 years; nonetheless, the North American electric bus market is rapidly evolving, and there are significant uncertainties related to future costs and capabilities of electric buses. Of particular importance are uncertainties related to future battery costs and energy capacity, which have profound effects on battery bus life-cycle costs. The analysis that informed the Low Carbon Fleet Transition Plan presented here used a conservative view of future battery improvements and other cost reductions for both battery buses and charging infrastructure. If batteries improve more rapidly than projected, total electrification costs will be lower than estimated, and decisions around charging strategy may change for portions of the CMBC route network. Conversely, if batteries improve more slowly than projected total fleet electrification costs will be higher than projected. Future battery improvements and cost reductions will be based on both technology and market developments, including the pace at which other North American transit agencies adopt electric buses.

The plan presented here is also based on current CMBC route configurations and does not include potential future service increases or route changes that have not yet been approved or funded. Any such future changes may necessitate adjustments to the Low Carbon Fleet Transition Plan.

1 Background

This section provides background information about the low carbon fleet transition and investment plan, including the reasons why it was developed, the process used, and descriptions of the current Coast Mountain Bus Company fleet and facilities.

1.1 Purpose of This Project

In 2016 TransLink initiated the Low Carbon Fleet project to develop a technology roadmap for bus and fuel purchases between 2020 and 2050 which could put the Coast Mountain Bus Company (CMBC) fleet on a path to significant GHG reduction, consistent with organizational, local, provincial, and federal policies and goals. These policies and goals are summarized in Figure 1.

Figure 1 Federal, Provincial, and Local GHG Policies

Federal	The federal government has expressed a commitment to achieving net zero carbon emissions by 2050, and is developing a plan to meet this goal
Provincial	The CleanBC program targets a 40 percent reduction in economy-wide greenhouse gas emissions by 2030 (from 2007 levels), a 60 percent reduction by 2040, and an 80 percent reduction by 2050. CleanBC also calls for 100 percent of new car and light-truck sales in the province to be electric vehicles by 2040
Local	Metro Vancouver has carbon neutral goals by 2050 and 45% GHG reduction by 2030
Organizational	In 2018 TransLink formally adopted organizational goals to achieve an 80 percent reduction in GHG emissions from operations by 2050, and to utilize 100 percent renewable energy in all operations by 2050

The project was designed to identify and compare technologies and fuels expected to be commercially available by 2020 that could significantly reduce fleet GHG emissions, and to compare them on a life-cycle cost and emissions basis. The desired outcome of the analysis was to identify an approach that would result in the lowest practical levels of annual GHG emission by 2050, within the constraints of commercial and technical feasibility, projected future service and funding levels, and CMBC service constraints.

1.2 Low Carbon Fleet Strategy Development

In 2016 TransLink engaged M.J. Bradley & Associates (MJB&A) to help the agency develop their Low Carbon Fleet Strategy (LCFS). MJB&A identified two broad strategies for significant GHG reduction from the CMBC bus fleet: 1) use of reduced-carbon renewable liquid and gaseous fuels in conventional buses with internal combustion engines, and 2) vehicle electrification.

Renewable fuel options include hydrogenation-derived renewable diesel (HDRD) as a substitute for petroleum diesel in diesel and hybrid-electric buses, and renewable natural gas (RNG) as a substitute for fossil gas in compressed natural gas (CNG) buses. Vehicle electrification could be accomplished by expanding the existing trolley network or replacing diesel and CNG buses with battery-electric or hydrogen fuel cell electric buses.

See Figure 2 for a summary of projected greenhouse gas (GHG) emissions from 40-ft transit buses in average CMBC service, in terms of carbon-dioxide equivalent mass emissions per kilometer driven (g CO_2-e/km). The values shown in Figure 2 include tailpipe and up-stream emissions, of carbon dioxide as well as methane and nitrous oxide expressed in carbon-dioxide equivalents using their 100-year global warming potential[3]. Upstream emissions are emissions associated with production and delivery of each fuel. Emissions from trolley and battery electric buses are based on projected electricity use (kWh/km) and current average electric generation emissions (g/kWh) in British Columbia, of which approximately 90 percent is from zero-carbon hydro sources. Emissions from fuel cell buses assume that the necessary hydrogen fuel will be produced from water via electrolysis using electricity from the grid.

As shown, low-carbon renewable fuels can reduce net GHG emissions significantly, but only electrification of a significant portion of the CMBC fleet could achieve the local and provincial goals of an 80 percent or greater reduction in emissions from current levels. All the electrification options could achieve an 80 percent reduction in fleet emissions, but the use of battery-electric buses would produce the lowest level of emissions.

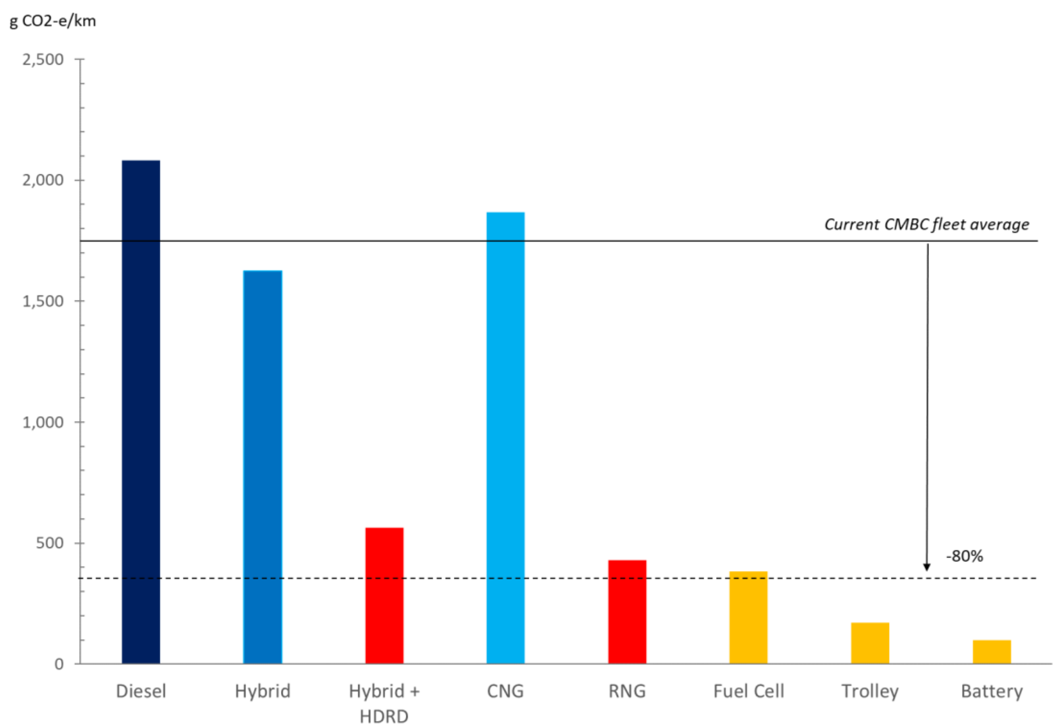
With respect to electrification options, life-cycle cost modeling indicates that the costliest option would be extension of the existing trolley network, due to the high cost of installing and maintaining new trolley overhead power systems. Battery electric buses are the least costly option today, with fuel cell buses less expensive than new trolley routes, but more expensive than battery buses on a life-cycle basis. The cost modeling indicates that for CMBC, life cycle

[3] Upstream emissions are from GHGenious 4.03 (regional default BC, 2020 target year). RNG is assumed to be sourced from landfills, and HDRD is assumed to be produced from a mix of canola oil, tallow, and yellow grease. In the Vancouver region approximately 90 percent of electricity is from zero-carbon hydro-electric generation. Tailpipe emissions of CO_2 are based on projected fuel use in average CMBC service, and average fuel carbon content. Tailpipe emissions of CH_4 and N_2O are based on EPA engine certification testing.

costs of battery buses will be lower than life cycle costs of fuel cell buses at least through model year 2030, and likely through model year 2040 or later.

This initial analysis resulted in a primary recommendation that TransLink pursue a long-term strategy to electrify the bus fleet, using battery-electric buses, as this was identified as both the most effective and most cost-effective approach to fleet GHG reduction. The secondary recommendation was to further investigate the use of low-carbon renewable fuels in existing buses as an interim strategy while the fleet turns over to electric buses. RNG is already available locally from Fortis BC. HDRD is available to fuel suppliers in BC for blending with petroleum diesel but is not yet available to retail customers for use in vehicles.

Figure 2 Projected Greenhouse Gas Emissions in CMBC Service, 40-ft Transit Bus



The analysis also identified 40-ft and 60-ft transit buses (80 percent of the fleet) as the primary focus for electrification efforts in the near term (through 2030), with electrification of highway coaches and 26-ft shuttle buses to begin later. This recommendation was primarily based on commercial availability; to-date manufacturers have focused electrification efforts on this "full-sized" segment of the transit bus market, and electric buses are already available as standard products from every transit bus manufacturer that sells into the North American market. To date, smaller electric shuttle buses are only available from a few small, secondary specialty manufacturers; they are not available from major original equipment manufacturers[4]. In addition, it was recommended not to electrify the 40-ft highway coaches in the CMBC fleet in the near term due to limitations on battery size and range, which are more constraining for highway coaches due to their higher daily mileage accumulation. The Phase 1 analysis recommended that TransLink focus LCFS Phase 2 efforts on electrification of 40-ft and 60-ft transit buses, but periodically re-evaluate whether it would be technically and commercially feasible to begin electrification of highway coaches and shuttle buses.

Electrification of the 40-ft and 60-ft transit buses can reduce total annual CMBC bus fleet GHG emissions (including from highway coaches and shuttle buses) by at least 80 percent. While electrification will require a significant up-front capital investment, the life cycle cost analysis indicated that annual fuel and maintenance cost savings could largely pay back this investment over the next 30 years, resulting in only a small increase in total costs compared to a business as usual scenario of continued replacement of retiring buses with new compressed natural gas and hybrid-electric buses.

CMBC also operates an electric trolley bus fleet, which is powered by an over-head catenary system installed on select routes throughout the city of Vancouver. These buses are already powered by electricity and therefore have virtually equivalent GHG emissions to battery buses. The current trolley fleet has been in service since 2006 and is scheduled for replacement in 2027 – 2028. Due to the projected high cost of trolley bus purchase, and the annual maintenance cost of the trolley overhead system, the possibility of replacing the existing trolleys with battery buses at the end of their service life was evaluated during the low carbon fleet planning process.

The life-cycle cost analysis indicated that replacement of existing trolleys with battery buses may result in life-cycle savings. However, there are significant uncertainties related to future trolley bus costs. In addition, replacement of trolleys with battery buses would require either significant modifications and likely expansion of the Vancouver Transit Center, or the development of in-route chargers in downtown Vancouver – neither or which could easily be accomplished before the current trolleys must be retired. Further, replacement of trolleys with battery buses would not contribute to further fleet GHG reduction. Given all these factors, it was recommended to maintain the current trolley system for the short and medium-term, and to replace the current trolley buses with new trolley buses in 2027-2028.

The recommendation to pursue electrification of the transit bus fleet, beginning with 40-ft and 60-ft buses, was subsequently endorsed by the TransLink Executive, the TransLink Board of Directors, and the TransLink Mayor's Council.

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[4] Smaller shuttle buses are made by different manufacturers than larger transit buses.

In 2018 TransLink re-engaged MJB&A to further develop the long-term fleet electrification strategy, and to develop a Fleet Electrification Transition Plan. The focus of this second phase was further development of battery bus charging strategies and implementation phasing, as well as determining the operational changes required to accommodate electric buses. On a parallel track TransLink engaged AES Engineering to develop conceptual designs for the necessary charging infrastructure to support electric buses. This report summarizes the LCFS Phase 2 analysis - including the operational and cost analysis done by MJB&A and the design work done by AES - and provides options for a detailed electrification implementation strategy over the next ten years.

As a separate effort, TransLink has also advanced the secondary recommendation from LCFS Phase 1 – the interim use of renewable fuels in existing buses. In February 2019 TransLink signed a 5-year contract with FortisBC, for supply of renewable natural gas (RNG) to existing CMBC buses. Available supply from Fortis is not yet sufficient to fuel all CNG buses in the fleet; RNG supply is projected to ramp up over the next few years, with all 299 CNG buses in the fleet operating on RNG as early as 2020.

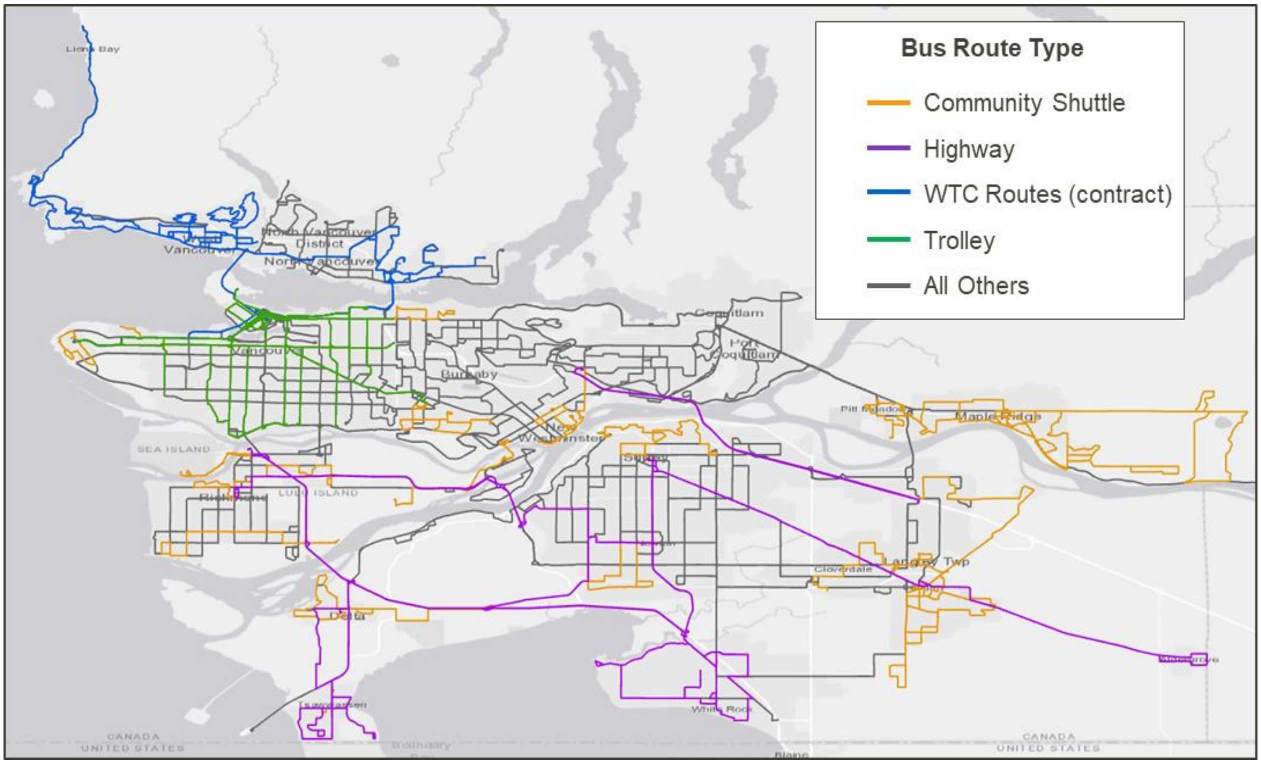
1.3 CMBC Fleet, Facilities, and Service Profile

This section briefly summarizes the current CMBC bus fleet, existing and planned transit centres from which the fleet operates, and the operating characteristics of the bus routes on which the buses operate.

1.3.1 CMBC Bus Routes and Service Profile

CMBC operates scheduled bus service on 128 different fixed routes throughout the Vancouver metropolitan region, including within the municipalities of Burnaby, Coquitlam, Delta, Maple Ridge, New Westminster, North Vancouver, Pitt Meadow, Port Coquitlam, Richmond, Surrey, Vancouver, and White Rock; service in West Vancouver is operated by a private company, under contract to TransLink.

Figure 3 TransLink Bus Routes



CMBC operates regular local and express bus service on major roadways throughout the region using 40-ft and 60-ft buses, and using 26-ft buses, operates local neighborhood "community shuttle" service on constrained roads which would be difficult for larger buses to negotiate. CMBC also operates twelve high-speed "highway" commuter routes which travel on highways between various downtown centers, with few intermediate stops. Within the municipality of Vancouver thirteen routes are equipped with overhead trolley power lines, for operation of rubber-tired electric trolley buses. See Figure 3 for a map of TransLink bus routes.

CMBC bus routes range in one-way length from three kilometers (km) to 45 km. Average scheduled speeds range from 13 kilometers per hour (kph) on downtown Vancouver routes to 67 kph on highway (commuter) routes; system wide average speed is 23 kph.

Service is provided 20 - 24-hours per day. Route headways (time between buses) during peak morning and afternoon commuting periods range from three to 60 minutes on different routes; headways are longer during mid-day and late evening/early morning hours. The total number of scheduled daily one-way trips ranges from about three (highway routes) to more than 170 per route. Approximately 1,250 buses are on the road during peak periods on weekdays.

1.3.2 CMBC Bus Fleet and Maintenance Facilities

CMBC currently has a fleet of 1,672 buses[5], including 26-ft shuttle buses, 40-ft and 60-ft transit buses, 40-ft highway coaches, and 40-ft and 60-ft trolley buses. The composition of the current CMBC fleet by bus type and propulsion system type is shown in Table 2.

CMBC's 40-ft and 60-ft transit buses are used on most local and express bus routes, which traverse the entire region on major roadways. Highway coaches are used only on specific high-speed "commuter" routes which operate on highways between various downtown centers, with few intermediate stops. Shuttle buses provide local neighborhood service on constrained roads which would be difficult for the larger buses to negotiate. The trolley buses operate only on specific routes in Vancouver which are equipped with overhead trolley power lines.

The bus fleet ranges in age from less than one year old to 19 years old (model year 2000). Thirty eight percent of the fleet is less than five years old; 22 percent is between five and ten years old, and 40 percent is greater than 10 years old. In order to maintain the fleet in good working order, CMBC has a general policy to retire 40-ft and 60-ft buses after they have been in service for 17 years[6]. As such, CMBC has a long-term need to purchase an average of 130 new buses per year, so that they can retire the oldest buses when they have reached the end of their useful life[7].

Table 2 CMBC Bus Fleet

Bus Type/Length	Propulsion System					TOTAL
	Diesel	Hybrid	CNG	Gasoline	Electric	
Transit / 40-ft	366	245	299	NA	4	**914**
Transit / 60-ft	62	156		NA		**218**
Highway Coach / 40-ft	78			NA		**78**
Trolley / 40-ft	NA	NA	NA	NA	188	**188**
Trolley / 60-ft	NA	NA	NA	NA	74	**74**
Shuttle / 26-ft				200		**200**
TOTAL	**506**	**401**	**299**	**200**	**266**	**1,672**

[5] This total includes 45 40-ft transit buses and 89 shuttle buses that are operated by third-party contractors; CMBC is responsible for purchase of new buses for these fleets.

[6] Shuttle buses are retired after five years.

[7] This is an annual average – new bus purchases do not necessarily happen every year.

In recent years CMBC has been replacing retiring 40-ft and 60-ft diesel transit buses with compressed natural gas buses and diesel hybrid-electric buses. Both of these bus types have lower fuel costs and lower GHG emissions than diesel buses. In 2018 CMBC also purchased four battery-electric buses, which are being used in a pilot program to further evaluate the technology and to inform future electric bus purchase specifications and operating plans.

CMBC buses are housed at seven transit centres around the region. Each transit centre includes one or more operations and maintenance building(s) with offices; locker rooms, a break area and other facilities for bus operators; storerooms and maintenance shops; and bus maintenance bays equipped with lifts or pits. Each transit centre also includes a bus fueling island and bus wash. At each transit centre buses are parked in outdoor storage areas, typically on parallel "tracks" which hold six to ten buses in a row parked nose to tail. See Figure 4, which shows half of the Burnaby Transit Centre (Burnaby South) as an example; in Figure 4 buses can be seen parked on the left, while the maintenance and operations building is on the right.

See Table 3 for a summary of the capacity, location, and assigned number of buses at each CMBC transit centre[8]. To accommodate expected future fleet growth TransLink and CMBC are in the process of designing a seventh facility – the new Marpole Transit Centre - which is projected to open in later 2023 or early 2024 with a capacity of 300 40-ft buses.

Figure 4 Burnaby South Transit Centre

[8] This table only includes transit centres directly operated by CMBC. An additional 45 40-ft transit buses and 89 shuttle buses are operated by third-party contractors; all of the 40-ft buses and 20 percent of the shuttle buses operate from the West Vancouver Transit Centre, which is owned by CMBC but operated by a contractor. The other shuttle buses operate from contractor-owned facilities.

Table 3 CMBC Bus Transit Centres

Transit Centre	Location	Maximum Capacity (buses[1])	Assigned Buses				
			60-ft Transit	40-ft Transit	40-ft Highway	26-ft Shuttle	Trolley
Burnaby (BTC)	Burnaby	312	92	150			
Hamilton (HTC)	Richmond	296	22	163			
Port Coquitlam (PTC)	Port Coquitlam	288	23	89	14	77	
Richmond (RTC)	Richmond	271	59	89	64		
Surrey (STC)	Surrey	285	22	193		34	
Vancouver (VTC)	Vancouver	539		185			262
Marpole (MTC)	Vancouver	300	Planned to open in 2023				

[1] *Listed capacity is 40-ft equivalent buses*

All of the transit centres operate a mix of different bus types, either 40-ft and 60-ft or 40-ft and 26-ft buses. All CNG buses are assigned to the Port Coquitlam, Hamilton, and Surrey transit centres, as they are the only facilities currently equipped to handle CNG buses[9]. Similarly, all of CMBC's electric trolleys operate from the Vancouver Transit Centre as it is the only location equipped with a trolley overhead power system.

Most other locations operate a mix of diesel and hybrid-electric buses. Most highway coaches operate from the Richmond Transit Centre, while a few operate from Port Coquitlam, based on the location of the commuter routes they serve. The 26-ft neighborhood shuttle buses operate from the Port Coquitlam and Surrey Transit Centres, based on the locations of the neighborhood routes they serve[10].

[9] Operation of CNG buses requires a natural gas fueling facility, and special depot safety systems.

[10] Another 89 shuttle buses are operated by third-party contractors from different locations.

2 Low Carbon Fleet Transition Plan

This section summarizes the recommended Low Carbon Fleet Transition Plan, including recommended bus technologies and charging strategies for a complete turn-over of 40-ft and 60-ft transit buses to battery electric buses by 2050. It also details three different options for the specific capital investments that would be required between 2020 and 2029 to put the fleet on the recommended transition path. These options vary in terms of their aggressiveness, cost, and short-term GHG reduction, but all can put the fleet onto the recommended path to full electrification by 2050.

2.1 Full Fleet Electrification 2020-2050

This section provides a high-level overview of the recommended approach to achieving an 80+ percent reduction in CMBC bus fleet emissions by 2050, including the major elements of the technology pathway and projected transition costs.

2.1.1 Technology Pathway

The recommended technology pathway for bus and fuel purchases between 2020 and 2050 includes the following major elements:

- Beginning with buses purchased in 2021[11] , start to replace retiring diesel and CNG 40-ft and 60-ft transit buses with battery-electric buses. Between 2021 and 2029, TransLink may elect to replace some retiring buses with new hybrid-electric buses, but after 2030 all retiring buses should be replaced with new battery buses to achieve complete electrification of the fleet by 2050
- To charge battery buses, employ both depot-based overnight charging and in-route charging, with depot charging for the lower-speed routes that generally operate in Vancouver, and in-route charging on higher speed routes through the other municipalities. Both the new Marpole Transit Center and the Burnaby Transit Centre are recommended to employ depot charging for 100 percent of assigned buses. Port Coquitlam Transit Centre and Surrey Transit Centre are recommended to employ in-route charging for 100 percent of assigned buses. Hamilton Transit Centre and Richmond Transit Centre are preliminarily recommended to employ in-route charging but may be appropriate for depot-based overnight charging if future battery technology improvements extend available daily range per charge sufficiently.

[11] These buses will not be delivered until 2023

- For depot-charged buses provide an average of 50 kW per bus[12] of charging capacity, using overhead-mounted conductive pantograph chargers.
- For in-route charged buses, use 450 kW[13] conductive pantograph chargers. On average one charger will be required for every eight in-route charged buses, but this will vary by route.
- Continue to assess commercial availability and cost of high-range battery buses and hydrogen fuel cell buses, as potential options for replacing retiring highway coaches. As the next highway coach purchase is not scheduled until 2027, final decisions about the future evolution of this fleet do not need to be finalized until 2025 or later. If long range battery bus and/or fuel cell technology has not sufficiently advanced by 2025, also consider conversion of this fleet to natural gas buses, to operate on RNG, if sufficient RNG fuel supply is available[14].
- Continue to replace retiring 26-ft gasoline shuttle buses with new gasoline buses, at least in the short term. Begin to replace retiring shuttle buses with battery electric shuttle buses when commercially feasible.
- Replace the existing trolley bus fleet with new trolley buses at the end of their useful life, in 2027-2028, and continue to operate the trolley bus system in the short and medium term. After 2040, re-evaluate the option of replacing trolley buses with battery buses in the 2047 - 2048 time frame.

In addition to the above technology pathway for new bus purchases, it is recommended that TransLink continue to increase its use of RNG in existing natural gas buses as additional supply becomes available, and continue to evaluate the commercial availability and cost of renewable diesel fuel, for use in existing diesel and hybrid-electric buses while they remain in the fleet.

[12] This is the average charging capacity required, based on current bus scheduling, which results in available depot charging time of 7 to 10 hours per bus. To increase flexibility, it is recommended that TransLink employ charging systems that link together three charging heads to a single 150 kW inverter block, so that individual buses can charge at rates as high as 150 kW if less than three buses are actively charging.

[13] This is the maximum charge rate currently supported by most North American bus manufacturers. In addition, due to limitations of the electrical distribution network, utility interconnection costs in many parts of the Vancouver Metro area would be significantly higher for in-route chargers with capacity greater than 500 kW.

[14] Conversion of highway coaches to operate on RNG would require CMBC to install natural gas fueling capability at a fourth transit centre, which would need to be considered in the decision-making process, and may make this option financially infeasible.

2.1.2 Fleet Transition Costs

MJB&A estimated total CMBC bus fleet costs between 2020 and 2050 under a "baseline" scenario and the Aggressive fleet electrification scenario, which results in complete electrification of the 40-ft and 60-ft transit bus fleets by 2040. The modeled electrification scenario represents the fastest possible transition of the CMBC fleet to electric buses. Total net transition costs would be marginally lower than shown below under the less aggressive short term transition scenarios discussed in Section 2.2 (Cautious fleet electrification, Progressive fleet electrification), since electric buses purchased later are assumed to have lower incremental purchase cost, due to battery cost reductions over time.

The baseline scenario assumes that CMBC will continue to replace 40-ft and 60-ft diesel transit buses with hybrid-electric buses when they have reached the end of their useful life (17 years) and will replace retiring CNG buses with new CNG buses. The fleet electrification scenario assumes that beginning with buses retired in 2023, all retiring 40-ft and 60-ft transit buses will be replaced with battery electric buses. Both scenarios assume that the existing trolleys will be replaced with new trolleys in 2027-2028. While the baseline scenario assumes that these trolleys will again be replaced by new trolleys in 2047-2048, the electrification scenario assumes that in 2047-2048 the trolleys will be replaced with battery buses.

The electrification scenario also assumes that all battery buses assigned to BTC, MTC, and VTC will use depot charging, but those assigned to HTC, PTC, RTC, and STC will use in-route charging.

See Figure 5 for a summary of total projected fleet costs for both the baseline and Aggressive electrification scenarios. In Figure 5, total estimated costs are shown in both nominal dollars (including projected inflation) and in net present value terms, assuming a 4 percent discount rate.

Figure 5 Projected CMBC Bus Fleet Costs 2020 – 2050, for Baseline & Electrification

nom$ millions		BASELINE	ELEC
CAPITAL	Bus Purchase	$3,896	$4,130
	Fueling Infrastructure	$0	$1,183
	Depot Expansion	$0	$50
MAINT	Overhauls	$323	$285
	Battery Pack Replace	$109	$358
	Annual Bus Maint	$3,565	$3,363
	Annual Infra Maint	$146	$212
FUEL		$2,850	$1,609
BUS DRIVER LABOR		$9,949	$10,121
TOTAL		$20,838	$21,311
Difference			$473 2.3%

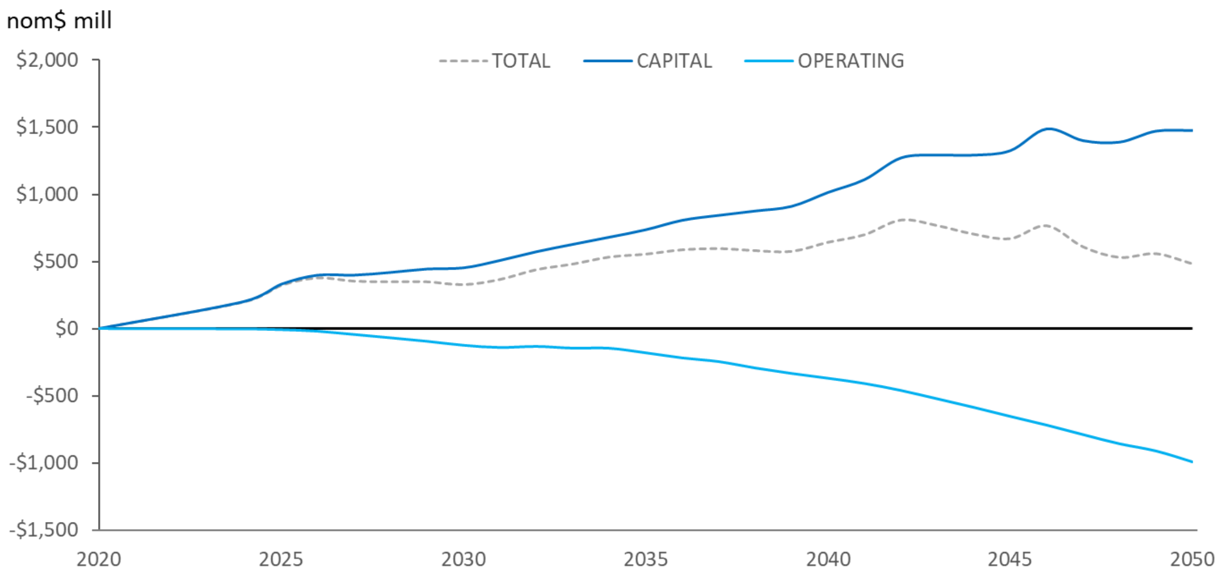
NPV $ millions (4% discount rate)		BASELINE	ELEC
CAPITAL	Bus Purchase	$2,005	$2,209
	Fueling Infrastructure	$0	$594
	Depot Expansion	$0	$35
MAINT	Overhauls	$172	$156
	Battery Pack Replace	$58	$172
	Annual Bus Maint	$1,940	$1,855
	Annual Infra Maint	$79	$110
FUEL		$1,496	$946
BUS DRIVER LABOR		$5,482	$5,560
TOTAL		$11,233	$11,638
Difference			$405 3.6%

Over the next 30 years, aggressive CMBC fleet electrification is projected to cost $473 million more than the baseline scenario (nominal $), or an average of $15.8 million more per year. Compared to the baseline this is an increase of 2.3 percent. In net present value terms, the incremental cost of fleet electrification is $405 million, or an increase of 3.6 percent. The difference between the nominal and NPV values has to do with the timing of incremental costs and savings; fleet electrification will require near- and medium-term increases in capital costs but will yield medium- and long-term operating cost savings, primarily in expenditures for fuel.

This reality is seen more clearly in Figure 6, which plots cumulative incremental costs for the fleet electrification scenario over time, relative to the baseline scenario. In Figure 6, the dark blue line is cumulative additional capital costs for purchase of electric buses and charging infrastructure, the light blue line is cumulative net operating cost savings (fuel and maintenance), and the dashed grey line is cumulative net costs for fleet electrification.

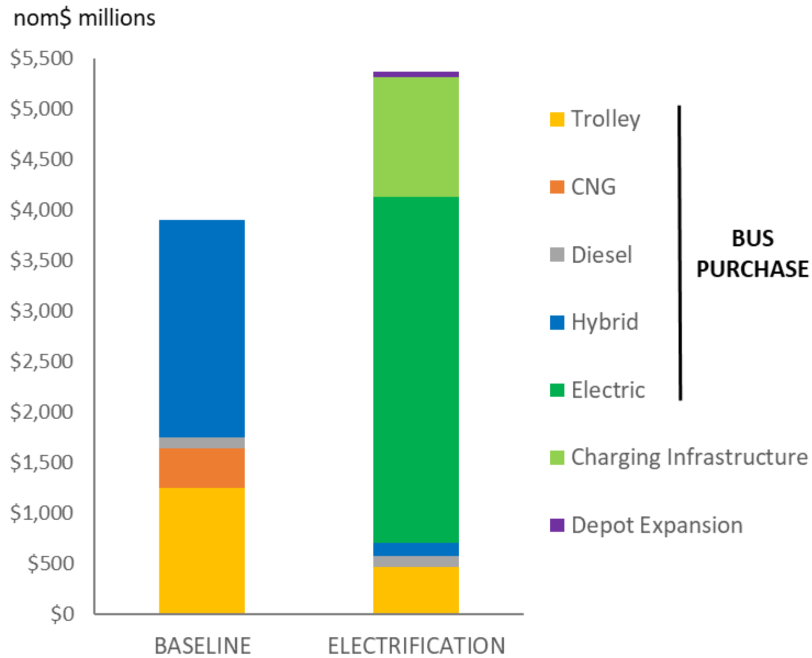
The electrification costs shown in Figure 5 and Figure 6 account for projected reductions in battery bus purchase costs of 14 percent for in-route charged buses and 16 percent for depot-charged buses between 2020 and 2050 (in constant dollars). This is based on a projected 40 percent reduction in electric drive train costs and a 50 percent reduction in battery costs ($/kWh) over this time period. For depot charged buses they also assume that battery energy capacity (kWh/bus) will increase by 33 percent between 2020 and 2050, due to advances in battery energy density[15]. These assumptions are conservative. If electric bus prices fall more quickly, the net cost of fleet electrification will be lower.

Figure 6 Incremental Fleet Electrification Costs 2020 – 2050, Relative to Baseline Fleet Costs



[15] The assumed increased battery capacity increases bus purchase costs relative to buses with a smaller battery but reduces the number of buses required, due to longer range. The financial analysis indicates that use of the larger batteries for depot-charged buses as they become available reduces over-all net costs.

Figure 7 Capital Costs for Fleet Electrification 2020 – 2050



Through 2050, the modeled fleet electrification scenario will require $1.47 billion (nom $) in additional capital funding, compared to baseline fleet replacement with hybrid electric, CNG, and trolley buses[16]. However, there will be a net operating cost savings of $994 million (nom $), for a net total cost of $473 million to electrify the fleet. Cumulative net total costs peak at $800 million in 2042, then fall in future years. After 2050 net savings from fleet electrification are projected to average over $15 million per year, as annual fuel and maintenance costs savings significantly outweigh the average incremental cost of fleet renewal with new electric buses.

Figure 7 breaks out required capital costs under the baseline and electrification scenarios, highlighting the relative amounts that must be spent on bus purchases and charging infrastructure under the electrification scenario, as well as the relative amounts spent on different bus types under both scenarios[17].

[16] This incremental capital cost does not include any debt financing costs.

[17] The charging infrastructure costs shown in Figure 7 are based on conceptual level designs developed for this project. Total estimated costs include equipment purchase, installation, 10 percent construction contingency, design, project management, and interest costs during construction. Costs are shown in nominal dollars, including projected inflation. For all buses projected charger costs assume overhead pantograph conductive charging, both at the depot and in-route. Estimated costs for pantograph connectors are based on current commercial prices; there are reportedly efforts underway to reduce the cost of overhead pantograph connectors for depot-based overnight charging, but these potential future cost reductions were not included in this analysis.

2.2 2020-2029 Investment Plan

This section provides three options for electrification investments between 2020 and 2029, to begin to implement the recommended Low Carbon Fleet Strategy. The first option could be described as "cautious fleet electrification"- it is the least aggressive and lowest cost option, in recognition that full funding is not yet secured, and that the technology is continuing to evolve rapidly, such that moving at a measured pace may result in lower net costs over the long term. The second option represents a faster pace of investment, representing a "progressive" approach to fleet electrification which achieves greater short-term GHG reductions while still managing technology risk. The third option represents an even faster pace of electrification in the short term , and in fact represents the fastest possible turn-over of the fleet to electric buses without retiring existing buses early. This option represents TransLink and CMBC taking a very aggressive approach to fleet electrification, achieving maximum short-term GHG reductions, but at higher cost over the next ten years, and also incurring a greater level of financial and technology risk in this evolving market.

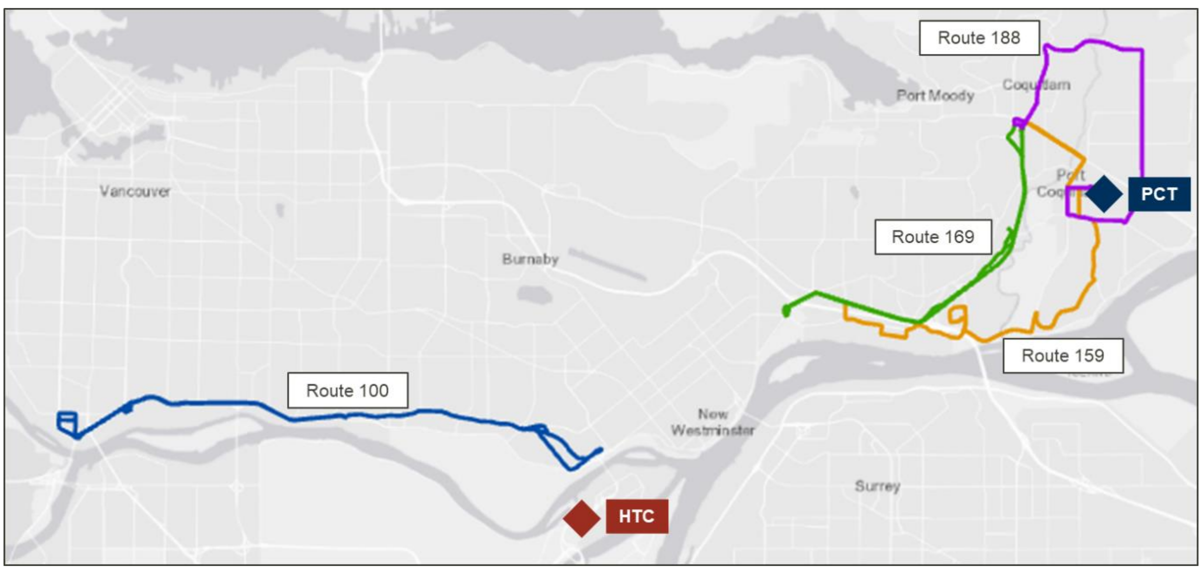
The investment options detailed here are based on current service levels and resulting bus procurement plans to maintain the fleet in a state of good repair. They do not include any service or bus fleet expansions beyond those planned through 2020. Significant service/fleet expansion between 2020 and 2029 may affect one or more of these scenarios, especially the Aggressive fleet electrification option, as it would necessitate development of additional new depot space beyond what is available from expansion of the current BTC property.

Each investment option identifies the scale and timing of specific investments through 2029 to put the fleet on a path to an 80+ percent reduction in annual GHG by 2050; under all three options additional investments will be required after 2029 to fully implement the recommended Low Carbon Fleet Strategy.

Under all three investment options it is recommended that depot charged buses be equipped with battery packs with a minimum name plate capacity of 450- 500 kWh (40-ft) or 600-660 kWh (60-ft)[18] and be equipped with supplemental fuel heaters for cold weather operation[19]. In-route charged buses are recommended to be equipped with battery packs with a minimum name plate capacity of 150 kWh (40-ft) or 200 kWh (60-ft) and to be equipped with automated battery thermal management systems to maintain battery temperature within specified range while parked at transit centres overnight in cold weather, using energy from on-board battery packs.

All three options prioritize the new Marpole Transit Centre to open in late 2023 or early 2024[20] as a 100 percent electric ready depot, and to be the first location to receive electric buses, which will be depot charged. All three options also include in-route charged buses and charging infrastructure, starting with Route 100, which operates from HTC. The faster-paced Progressive and Aggressive options include in-route charging investments on additional routes, starting with routes 159, 169, and 188, which all operate out of PTC. See Figure 8, for a map of the first routes recommended to be converted with in-route charging.

Figure 8 First Routes to be Converted to Battery Buses with In-route Charging



[18] These pack sizes are projected to be the largest available from most bus manufacturers in the next 5 – 10 years. The financial analysis indicates that larger packs reduce total life cycle costs for depot charging, despite higher bus purchase costs, by reducing the required replacement ratio. If available, TransLink should consider buying buses with larger packs for depot charged buses, but allowable pack size may be limited by Provincial axle weight restrictions.

[19] Current commercially available fuel heaters use diesel fuel, but in the future, it may be possible to use a renewable liquid fuel such as ethanol or methanol.

[20] Exact timing of MTC opening is uncertain. Current projections are fourth quarter 2023 or first quarter 2024.

The Aggressive fleet electrification option, which is the most aggressive electrification scenario possible, also requires that in the next ten years the Burnaby Transit Centre be expanded and converted to depot-charging operation. Under the Cautious and Progressive scenarios these investments are not required until after 2030.

In addition to installing charging infrastructure, BTC investments to accommodate fleet electrification include expansion of the bus parking area, to accommodate the additional buses required when implementing depot charging. These additional buses are required due to electric bus range limitations. In order to expand the bus parking at BTC, several existing buildings that house fleet support functions must be removed, and new space to house these functions must be purchased or leased at another location in the Metro Vancouver area.

By design there is significant overlap between the three different investment scenarios, and they are not mutually exclusive. If TransLink begins along one of these paths based on available funding, in later years the pace of electrification could be accelerated to get onto a higher path if additional funding is made available.

In the near term, the most important decision required to get onto any of these fleet electrification paths is to design, then construct, the new Marpole Transit Center to be 100 percent electric ready when it opens in late 2023 or early 2024. If this is done it will provide sufficient depot charging space to maintain either the Cautious or Progressive electrification pace through 2030, with supporting electric bus purchases between 2021 and 2024. To move from Progressive to Aggressive electrification will require a decision to either: 1) expand and retrofit BTC for 100 percent electric operation, or 2) aggressively install in-route chargers along routes operating from PTC, STC and potentially HTC and/or RTC. However, these decisions do not necessarily need to be made today; they could be delayed to 2023 or 2024, without missing an opportunity to pursue more aggressive fleet electrification.

2.2.1 2020-2029 Cautious and Constrained Investment Option

See Table 4 for electric bus purchases, and Table 5 for charging infrastructure investments, required between 2020 and 2029 under the Cautious fleet electrification option. The costs shown in these tables are incremental costs, over and above the projected costs of required bus purchases under the baseline or business as usual scenario[21]. Incremental costs for purchasing 95 electric buses total $36.8 million[22], and infrastructure investments total $57.7 million, for a total incremental capital cost (above baseline costs) of $94.5 million to begin implementing the Low Carbon Fleet Transition Plan. These estimated incremental costs for electrification include an assumed reduction in electric bus purchase costs of 6 percent between 2020 and 2030, based on a 20 percent reduction in electric drive train and battery costs ($/kWh), but also an 11 percent increase in battery capacity for depot-charged buses[23].

Under this investment option MTC would open in late 2023 or early 2024 as a 100 percent electric-ready depot, with 16 40-ft electric buses, with an additional 64 40-ft electric buses added over the next two years, for a total of 30 percent of assigned buses electric through 2030. The depot charger make-ready investment at MTC includes up-sizing the depot electrical supply and installing electrical distribution conduit to every bus parking space. The projects to install chargers at MTC include installation of power modules and pantographs and pulling wire through the installed conduits to power each pantograph.

In 2021 Route 100 would be converted to 100 percent electric operation, with a total of three in-route chargers and 19 electric buses[24].

Figure 9 shows the portion of CMBC's route network that would be electrified by the end of 2031 under the Cautious fleet electrification investment option.

See Table 6 for an estimate of annual incremental operating costs between 2020 and 2030 resulting from fleet electrification under the Cautious investment option. Over the next ten years this electrification scenario is projected to reduce bus maintenance costs by $3.4 million and reduce fuel costs by $25.9 million compared to continued renewal of the fleet with new hybrid electric and CNG buses as old buses are retired. Bus operator labor costs are projected to

[21] Under the baseline scenario, TransLink will purchase 433 40-ft and 80 60-ft hybrid-electric buses, and 50 40-ft CNG buses between 2020 and 2029, at an estimated cost of $597 million (nominal).

[22] These incremental costs are additional to the baseline cost of purchasing new hybrid electric buses to replace retiring buses.

[23] The assumed increased battery capacity increases bus purchase costs but reduces the number of buses required due to longer range. The financial analysis indicates that use of the larger batteries reduces over-all net costs.

[24] There are currently four electric buses operating on Route 100 with two in-route chargers, as part of a pilot program.

increase by $0.9 million and estimated new costs for charger maintenance total $1.2 million. Net operating cost savings are projected to be $27.1 million, or an average of $2.7 million per year.

Figure 9 Routes Electrified by 2031 – Cautious Fleet Electrification Option

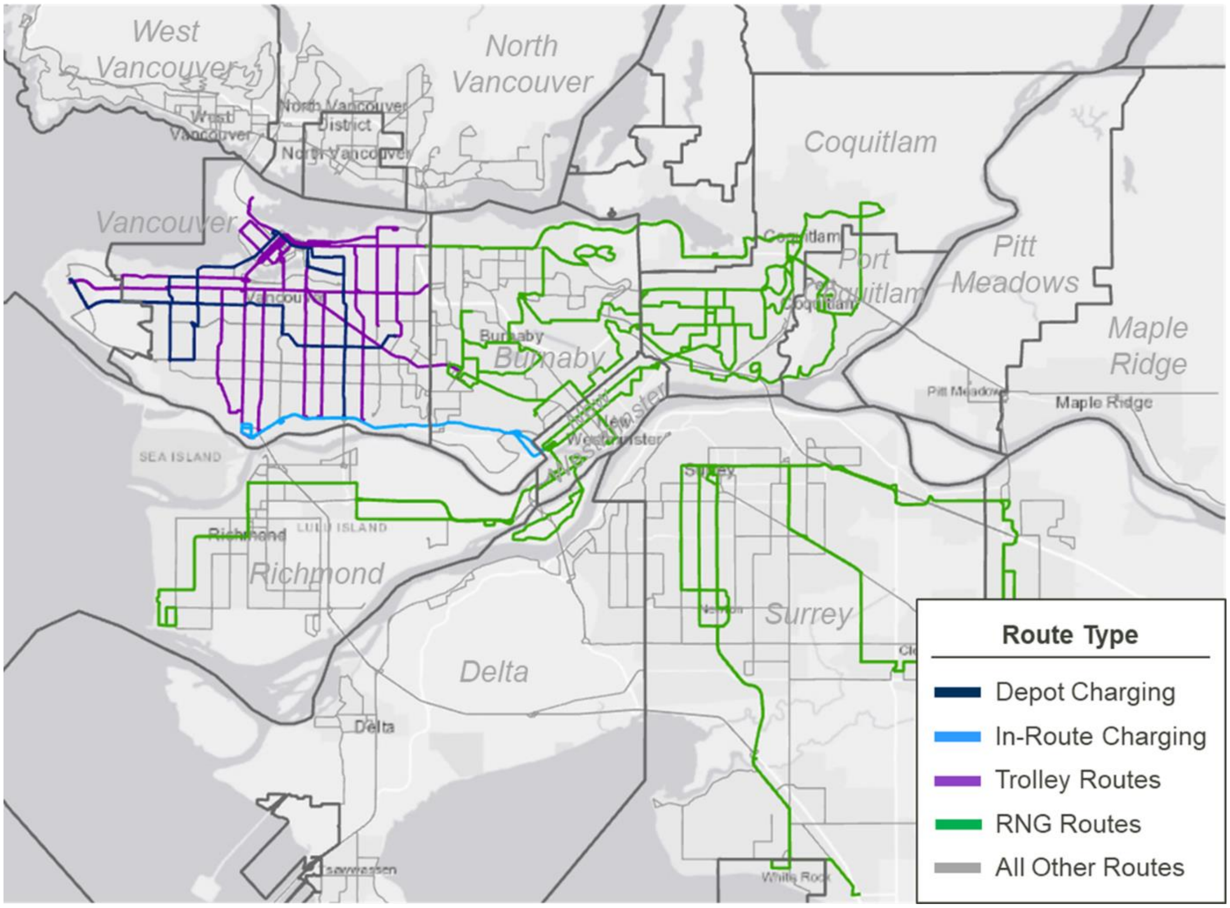


Table 4 Electric Bus Purchases – Cautious Investment Option

Length	Charging Type	Award Year 2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	TOTAL
40-ft	Depot		16	37	27							80
	In-route	15										15
	Total	15	*16*	*37*	*27*							*95*
INCR COST (nom $ mill)			**$6.7**	**$15.5**	**$14.6**							**$36.8**

Table 5 Depot and Charging Investments – Cautious Investment Option

Purpose	Location	Scope	Award	Completion	Cost (mill nom $)
Depot Charging	MTC	Make ready for full depot electrification; installation of 16 SAE J3105 chargers	2021	2023	$43.0
	MTC	Installation of 37 SAE J3105 chargers	2022	2024	$7.3
	MTC	Installation of 27 SAE J3105 chargers	2023	2025	$5.4
In-route Charging	Rte 100	Install 1 in-route charger	2020	2021	$2.0
TOTAL COST					**$57.7**

Table 6 Projected Incremental Operating Costs – Cautious Investment Option

Cost Type	million nominal $											
	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**TOTAL**
Bus Maintenance	$0.0	$0.0	$0.0	$0.0	$0.0	($0.02)	($0.6)	($0.7)	($0.7)	($0.7)	($0.7)	**($3.4)**
Charger Maintenance	$0.0	$0.0	$0.0	$0.0	$0.0	$0.1	$0.2	$0.2	$0.2	$0.2	$0.2	**$1.2**
Fuel	$0.0	$0.0	$0.0	$0.0	($0.7)	($2.2)	($4.2)	($4.4)	($4.6)	($4.8)	($4.9)	**($25.9)**
Bus operator Labor [1]	$0.0	$0.0	$0.0	$0.0	$0.0	$0.1	$0.2	$0.2	$0.2	$0.2	$0.2	**$0.9**
TOTAL	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**($0.6)**	**($2.2)**	**($4.5)**	**($4.7)**	**($4.8)**	**($5.0)**	**($5.2)**	**($27.1)**

[1] Bus operator labor costs increase due to increased dead-head time (depot charging) and additional on-route lay-over time (in-route charging).

2.2.2 2020 – 2029 Progressive Investment Option

See Table 7 for electric bus purchases, and Table 8 for charging infrastructure investments, required between 2020 and 2029 under the Progressive fleet electrification option. The costs shown in these tables are incremental costs, over and above the projected costs of required bus purchases under the baseline or business as usual scenario. Incremental costs for purchasing 314 electric buses total $110.1 million[25], and infrastructure investments total $89.1 million, for a total incremental cost of $199.2 million to begin implementing the Low Carbon Fleet Transition Plan. These estimated incremental costs for electrification include an assumed reduction in electric bus purchase costs of 6 percent between 2020 and 2030, based on a 20 percent reduction in electric drive train and battery costs ($/kWh), but also an 11 percent increase in battery capacity for depot-charged buses[26].

Under this investment option MTC would open in late 2023 or early 2024 as a 100 percent electric-ready depot, with 16 electric buses, with an additional 224 40-ft and 40 60-ft electric buses added over the next six years; after 2029 100 percent of assigned buses at MTC would be electric. In 2021 Route 100 would be converted to 100 percent electric operation, with a total of three in-route chargers and 19 electric buses[27]. In 2029 routes 159 and 169 would be converted to 100 percent electric operation, followed by route 188 in 2031. This will require 19 electric buses and three in-route chargers.

Figure 10 shows the portion of CMBC's route network that would be electrified by the end of 2031 under the Progressive fleet electrification investment option.

See Table 9 for an estimate of annual incremental operating costs between 2020 and 2030 resulting from fleet electrification under the Progressive investment option. Over the next ten years this electrification scenario is projected to reduce bus maintenance costs by $8.7 million and reduce fuel costs by $65 million compared to continued renewal of the fleet with new hybrid electric and CNG buses as old buses are retired. Bus operator labor costs are projected to increase by $3.6 million and estimated new costs for charger maintenance total $3 million. Net operating cost savings are projected to be $67.1 million, or an average of $6.7 million per year.

[25] These incremental costs are additional to the baseline cost of purchasing new hybrid electric buses to replace retiring buses.

[26] The assumed increased battery capacity increases bus purchase costs but reduces the number of buses required due to longer range. The financial analysis indicates that use of the larger batteries reduces over-all net costs.

[27] There are currently four electric buses operating on Route 100 with two in-route chargers, as part of a pilot program.

Figure 10 Routes Electrified by 2031 – Progressive Fleet Electrification Option

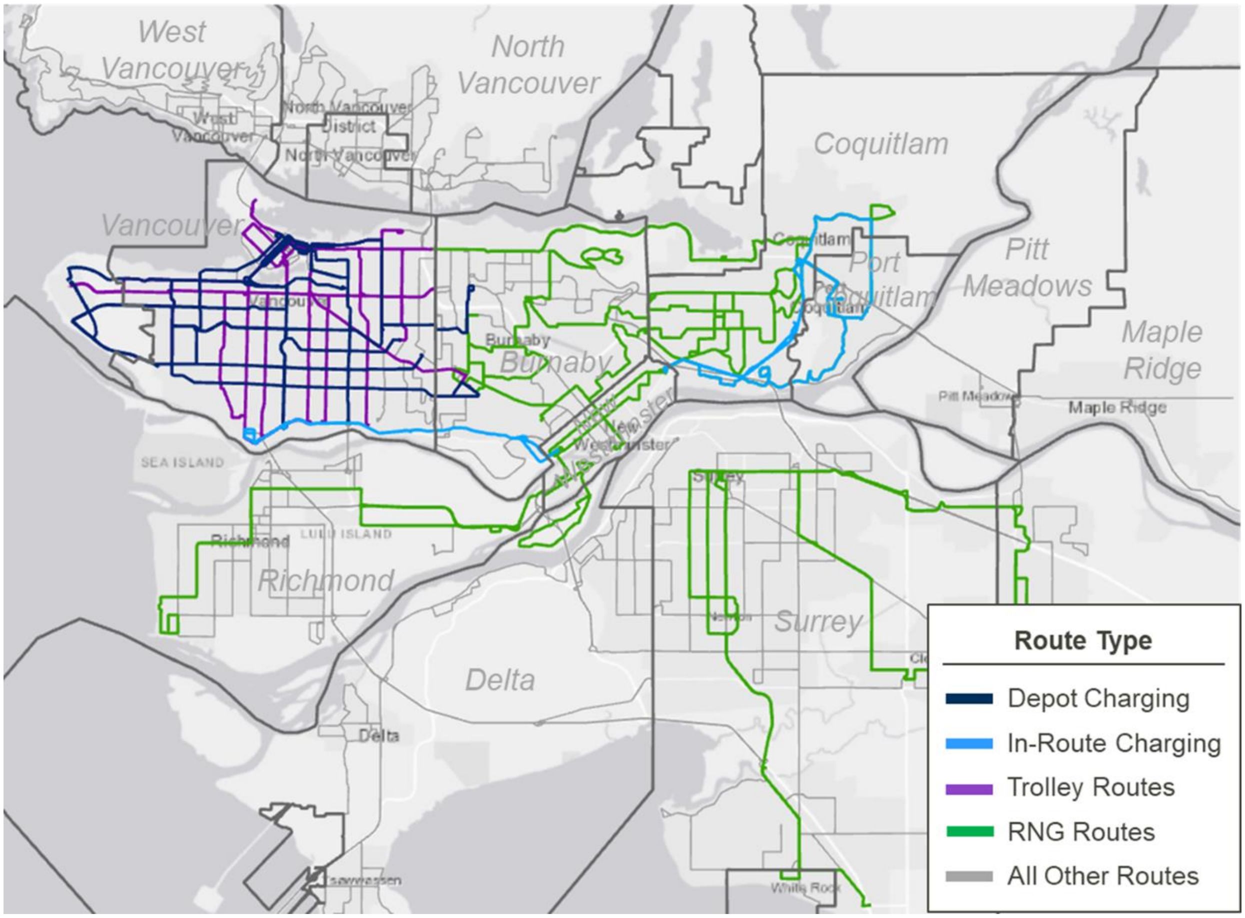


Table 7 Electric Bus Purchases – Progressive Investment Option

Length	Charging Type	Award Year										TOTAL
		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	
40-ft	Depot		16	37	40	147						240
	In-route	15							10		9	34
	Subtotal	15	*16*	*37*	*40*	*147*			*10*		*9*	*274*
60-ft	Depot			5		21			14			40
	In-route											
	Subtotal			*5*		*21*			*14*			*40*
TOTAL		**15**	**16**	**42**	**40**	**168**			**24**		**9**	**314**
INCR COST (nom $ mill)			**$6.4**	**$17.0**	**$14.7**	**$64.6**			**$7.4**		**$0.01**	**$110.1**

Table 8 Depot and Charging Investments – Progressive Investment Option

Purpose	Location	Scope	Award	Completion	Cost (mill nom $)
Depot Charging	MTC	Make ready for full depot electrification; installation of 16 SAE J3105 chargers	2021	2023	$43.0
	MTC	Installation of 42 SAE J3105 chargers	2022	2024	$5.9
	MTC	Installation of 40 SAE J3105 chargers	2023	2025	$5.7
	MTC	Installation of 182 SAE J3105 chargers	2024	2026	$25.7
	Route 100	Install 1 in-route charger	2020	2021	$2.0
In-route Charging	Routes 159, 169	Install 2 in-route chargers	2027	2029	$3.8
	HTC, PTC, STC	Install SAEJ1772 depot chargers and maintenance area upgrades	2027	2029	$1.3
	Route 188	Install 1 in-route chargers	2029	2031	$1.7
TOTAL COST					**$89.1**

Table 9 Projected Incremental Operating Costs – Progressive Investment Option

Cost Type	million nominal $										
	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**TOTAL**
Bus Maintenance	$0.0	$0.0	$0.0	$0.0	$0.0	($0.02)	($0.7)	($1.9)	($1.9)	($1.9)	($2.3)	**($8.7)**
Charger Maintenance	$0.0	$0.0	$0.0	$0.0	$0.03	$0.1	$0.2	$0.6	$0.6	$0.6	$0.8	**$3.0**
Fuel	$0.0	$0.0	$0.0	$0.0	($0.7)	($2.2)	($5.0)	($12.9)	($13.3)	($13.9)	($16.9)	**($65.0)**
Bus operator Labor [1]	$0.0	$0.0	$0.0	$0.0	$0.01	$0.1	$0.5	$0.7	$0.7	$0.8	$1.0	**$3.6**
TOTAL	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**($0.6)**	**($2.2)**	**($4.9)**	**($13.5)**	**($13.9)**	**($14.4)**	**($17.5)**	**($67.1)**

[1] Bus operator labor costs increase due to increased dead-head time (depot charging) and additional on-route lay-over time (in-route charging).

2.2.3 2020 – 2029 Aggressive Investment Option

See Table 10 for electric bus purchases, and Table 11 for charging infrastructure investments, required between 2020 and 2029 under the Aggressive fleet electrification option. The costs shown in these tables are incremental costs, over and above the projected costs of required bus purchases under the baseline or business as usual scenario. Incremental costs for purchasing 635 electric buses total $199.1 million[28], and infrastructure investments total $248.4 million, for a total incremental cost of $447.5 million to begin implementing the Low Carbon Fleet Transition Plan. These estimated incremental costs for electrification include an assumed reduction in electric bus purchase costs of 6 percent between 2020 and 2030, based on a 20 percent reduction in electric drive train and battery costs ($/kWh), but also an 11 percent increase in battery capacity for depot-charged buses[29].

Under this investment option MTC would open in late 2023 or early 2024 as a 100 percent electric-ready depot, with 66 electric buses, with an additional 174 40-ft and 40 60-ft electric buses added over the next three years; after 2026 100 percent of assigned buses at MTC would be electric.

Beginning in 2021 a total of 17 in-route chargers would be installed at up 10 different locations, to support conversion of Routes 100, 159, 169, 188 and most other routes operating from PTC[30] to battery-bus operation using 136 total in-route charged buses. To support these buses minor upgrades are also required at HTC and PTC – to install a small number of depot chargers to support maintenance operations[31].

Starting in 2024, make-ready infrastructure would be installed at Burnaby Transit Centre (BTC) for 100 percent depot charging at the existing facility, along with 127 depot chargers, so that 127 40-ft electric buses could start operating there in 2026. In 2027, a project would start to expand BTC, to provide bus parking for an additional 100 buses. These additional bus spaces are required because fleet expansion is required to accommodate depot charging at MTC and BTC, due to electric bus range restrictions. This expansion will require that existing buildings that house maintenance support operations be torn down, and that new space(s) in other location(s) be

[28] These incremental costs are additional to the baseline cost of purchasing new hybrid electric buses to replace retiring buses.

[29] The assumed increased battery capacity increases bus purchase costs but reduces the number of buses required due to longer range. The financial analysis indicates that use of the larger batteries reduces over-all net costs.

[30] The exact routes to be converted to in-route charging under the Aggressive scenario are yet to be determined, but routes out of PTC are prioritized for early conversion because they have the highest average daily energy intensity of all routes in the system, and are unlikely to be suitable for depot charging even if battery energy density increases faster than projected. The transit center with the second highest priority for in-route charging due to high daily energy intensity is STC.

[31] The exact number of chargers needed will vary based on the manufacturer of the buses.

purchased or leased to house these operations.

Figure 11 shows the portion of CMBC's route network that would be electrified by the end of 2031 under the Aggressive fleet electrification investment option.

See Table 12 for an estimate of annual incremental operating costs between 2020 and 2030 resulting from fleet electrification under the Aggressive investment option. Over the next ten years this electrification scenario is projected to reduce bus maintenance costs by $17.2 million and reduce fuel costs by $123.6 million compared to continued renewal of the fleet with new hybrid electric and CNG buses as old buses are retired. Bus operator labor costs are projected to increase by $10.0 million and estimated new costs for charger maintenance total $6.9 million. Net operating cost savings are projected to be $124 million, or an average of $12.4 million per year.

Figure 11 Routes Electrified by 2031 –Aggressive Fleet Electrification Option

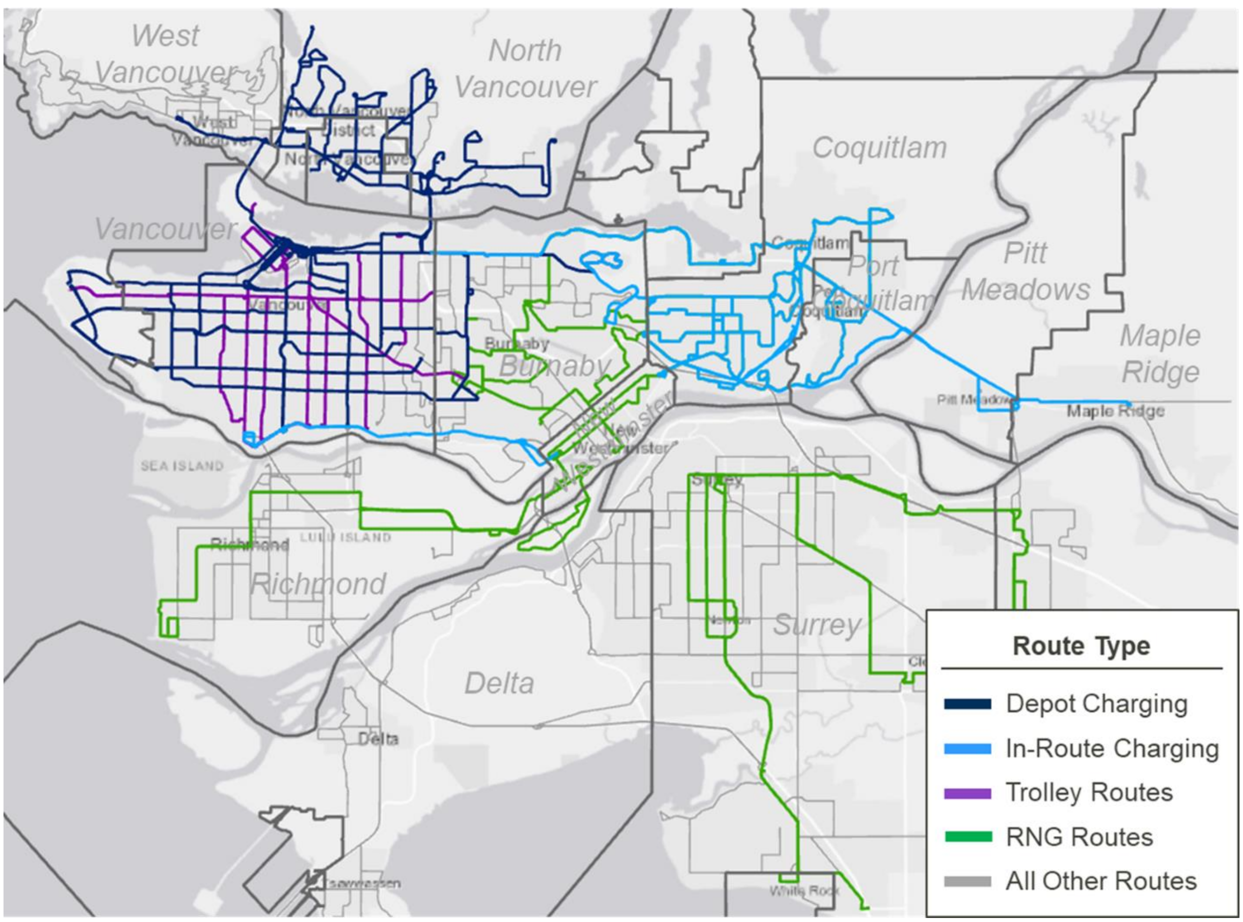


Table 10 Electric Bus Purchases –Aggressive Investment Option

Length	Charging Type	Award Year										TOTAL
		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	
40-ft	Depot		66	138	36	127			20		20	**407**
	In-route	15		7	43	71						**136**
	Subtotal	*15*	*66*	*145*	*79*	*198*			*20*		*20*	***543***
60-ft	Depot			18		45			29			**92**
	In-route											
	Subtotal			*18*		*45*			*29*			***92***
TOTAL		**15**	**66**	**163**	**79**	**258**			**49**		**20**	**635**
INCR COST (nom $ mill)			**$24.1**	**$59.6**	**$14.7**	**$71.7**			**$21.7**		**$7.3**	**$199.1**

Table 11 Depot and Charging Investments –Aggressive Investment Option

Purpose	Location	Scope	Award	Completion	Cost (mill nom $)
Depot Charging	MTC	Make ready for full depot electrification; installation of 66 SAE J3105 chargers	2021	2023	$50.1
	MTC	Installation of 156 SAE J3105 chargers	2022	2024	$22.0
	MTC	Installation of 58 SAE J3105 chargers	2023	2025	$8.2
In-route Charging	Route 100	Install 1 in-route charger	2020	2021	$2.0
	Routes 159, 169, 188	Install 3 in-route chargers	2022	2024	$3.3
	HTC, PTC	Install depot chargers and maintenance area upgrades	2023	2025	$5.2
	PTC service area	Install 13 in-route chargers	2023	2025	$24.6
Depot Charging	BTC	Make ready for full depot electrification; installation of 127 SAE J3105 chargers	2024	2026	$61.1
	BTC	Depot expansion	2027	2029	$50.2
	BTC	Installation of 140 SAE J3105 chargers	2027	2029	$21.7
TOTAL COST					**$248.4**

Table 12 Projected Incremental Operating Costs –Aggressive Investment Option

Cost Type	million nominal $											
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	TOTAL
Bus Maintenance	$0.0	$0.0	$0.0	$0.0	$0.1	$0.3	($1.8)	($3.8)	($3.8)	($3.8)	($4.3)	**($17.2)**
Charger Maintenance	$0.0	$0.0	$0.0	$0.0	$0.1	$0.4	$0.6	$1.4	$1.4	$1.4	$1.5	**$6.9**
Fuel	$0.0	$0.0	$0.0	$0.0	($2.6)	($6.6)	($11.2)	($23.8)	($24.5)	($25.7)	($29.1)	**($123.6)**
Bus operator Labor[1]	$0.0	$0.0	$0.0	$0.0	$0.2	$0.4	$0.6	$2.0	$2.1	$2.4	$2.3	**$10.0**
TOTAL	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**($2.3)**	**($5.5)**	**($11.8)**	**($24.2)**	**($24.9)**	**($25.7)**	**($29.6)**	**($124.0)**

[1] Bus operator labor costs increase due to increased dead-head time (depot charging) and additional on-route lay-over time (in-route charging).

2.2.4 Comparison of Investment Options

The three fleet electrification investment options are summarized in Table 13. The Aggressive Investment option (last column) represents the fastest pace of fleet electrification possible – under this scenario all new bus purchases after 2023 are battery electric buses. This option requires the largest capital investment over the next 10 years and the greatest amount of change to CMBC operations, but also produces the greatest reduction in fleet GHG and the greatest operating cost savings through 2030.

Under the other two investment options (Cautious; Progressive) TransLink will continue to purchase hybrid electric buses, along with battery buses, to replace retiring buses through 2027 and 2024, respectively. These options require a smaller capital investment over the next ten years, and fewer changes to CMBC operations, but also result in lower GHG reductions and lower operating cost savings through 2030.

The trend in net operating cost savings under each investment option is shown in Figure 12.

The projected trend in CMBC fleet GHG emissions is shown in Figure 13. Figure 13 includes projected emissions from all CMBC buses, including 40-ft and 60-ft transit buses, highway coaches, and shuttle buses. In Figure 13 all three investment options are assumed to follow the recommended Low Carbon Fleet strategy after 2029 – i.e. beginning in 2030 all new 40-ft and 60-ft transit buses will be battery buses, but TransLink will continue to purchase new diesel highway coaches. All three scenarios in Figure 13 also assume that gasoline shuttle buses will be converted to battery electric buses between 2035 and 2045[32] .

As shown, the recommended Low Carbon Fleet strategy results in greater than 90 percent reduction in CMBC bus fleet emissions in 2050 (compared to 2007), regardless of which fleet electrification investment option is chosen for 2020 – 2029. However, greater investment in fleet electrification in the short term will provide greater net GHG reductions over the next thirty years. The Aggressive scenario achieves a 40 percent reduction in fleet emissions in 2027, while the Cautious scenario delays achievement of a 40 percent reduction until 2038. Compared to the Cautious investment option, the Aggressive option is estimated to reduce total fleet GHG emission by an additional 850,000 metric tons between 2020 and 2050.

Table 13 Summary of 2020 – 2029 Fleet Electrification Investment Options

<table>
<tr><th colspan="2">METRIC</th><th>CAUTIOUS</th><th>PROGRESSIVE</th><th>AGGRESSIVE</th></tr>
<tr><td colspan="2">Electric Buses Purchased</td><td>95</td><td>314</td><td>635</td></tr>
<tr><td colspan="2">In-route Chargers Installed</td><td>1</td><td>4</td><td>17</td></tr>
<tr><td colspan="2">Depot Chargers Installed at</td><td>MTC</td><td>MTC</td><td>MTC and BTC</td></tr>
<tr><td rowspan="2">Routes Electrified</td><td>Depot Charging</td><td>30% of MTC routes</td><td>100% of MTC routes</td><td>100% of MTC routes
80% of BTC routes</td></tr>
<tr><td>In-route Charging</td><td>Route 100</td><td>Routes 100, 159, 169, 188</td><td>Route 100
95% of PTC routes</td></tr>
<tr><td rowspan="3">CAPITAL INVESTMENT 2020-2029 (nom $ mill)</td><td>Buses</td><td>$37</td><td>$110</td><td>$199</td></tr>
<tr><td>Infrastructure</td><td><u>$58</u></td><td><u>$89</u></td><td><u>$248</u></td></tr>
<tr><td>TOTAL</td><td>$95</td><td>$199</td><td>$447</td></tr>
<tr><td colspan="2">Operating Savings 2020 – 2030 (nom $ millions)</td><td>$27</td><td>$67</td><td>$124</td></tr>
<tr><td colspan="2">GHG Reduction 2020 – 2030 (MT)</td><td>56,000</td><td>137,000</td><td>269,000</td></tr>
<tr><td colspan="2">GHG Reduction in 2030 (MT)</td><td>9,800</td><td>33,600</td><td>59,500</td></tr>
<tr><td colspan="2">Annual GHG Reduction 2030 vs 20007</td><td>14%</td><td>28%</td><td>44%</td></tr>
</table>

32 This is a conservative assumption – this transition could happen sooner based on commercial availability of battery shuttle buses.

Figure 12 Fleet Electrification Net Operating Cost Savings 2020 – 2030

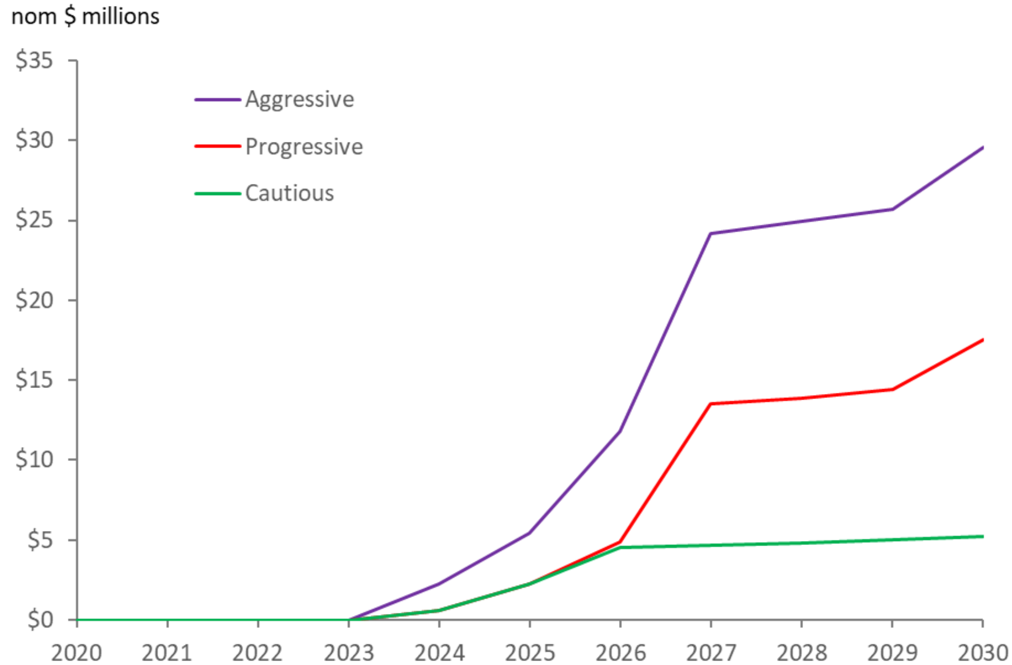
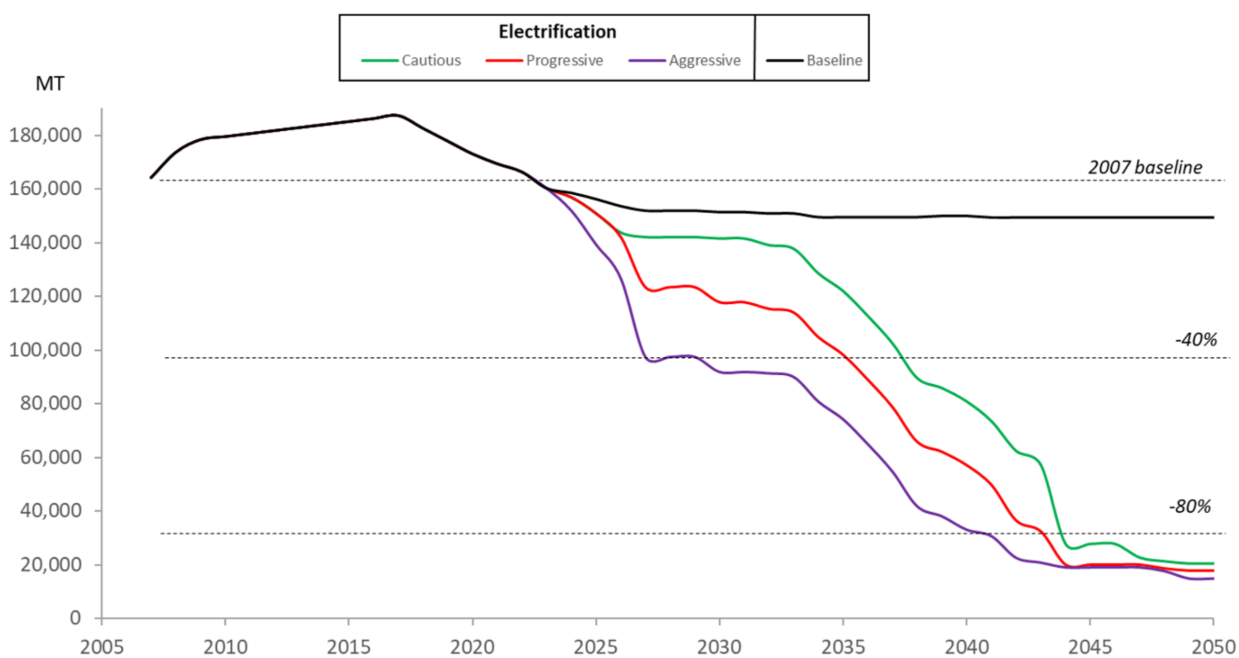


Figure 13 Projected CMBC Fleet GHG Emissions 2020 - 2050



3 Fleet Electrification – Operational Considerations

This section summarizes the major changes to CMBC bus fleet operations that will be required to accommodate battery electric buses under any fleet electrification scenario. Changes will be required to bus schedules, bus maintenance programs, and cold weather operations. CMBC will also need to develop completely new capabilities to regularly monitor bus charging activities, and to maintain and repair charging infrastructure.

3.1 Bus Scheduling

Depot charged buses have limited in-service range before needing to be re-charged. Current scheduling policies result in some daily bus assignments (blocks) that are too long for depot-charged buses to handle on a single charge, given available on-bus battery energy capacity.

Assuming nominal battery pack capacity of 500 kWh for 40-ft buses and 660 kWh for 60-ft buses[33], all daily bus blocks operating from MTC and BTC with depot-charged buses will need to be limited to no more than 11 hours or 220 kilometers between the bus leaving and returning to the transit centre[34]. This limitation is projected to increase peak bus requirements at these transit centres by 15 percent on average, and to increase dead-head mileage; these increases are accounted for in the bus purchase and charging infrastructure investments, and projections of incremental operating costs, summarized in Tables 4 – 12.

Assuming a charge rate of 450 kW, in-route charged buses will need to charge for an average of approximately 6 minutes per in-service hour during their scheduled lay-overs at one or both route termini, after completing each one-way trip or round trip on the route[35]. Scheduled lay-over time system-wide is approximately 9 minutes per in-service hour, but during peak periods much of this time is often used for recovery, due to congestion which causes buses to run late. To ensure that in-route charged buses have sufficient charge time, while maintaining on-time performance, an average of approximately 3 minutes will need to be added to scheduled lay-over time for every hour of scheduled running time, for most if not all routes. This additional lay-over time does not need to be added during peak periods, so will only minimally affect peak bus requirements. This additional lay-over time, which will result in additional bus operator paid

[33] Projected industry norm maximum battery size in 2025.

[34] One bus manufacturer already offers larger batteries on 40-ft buses. If buses with larger battery packs are used these limits could be extended proportionally.

[35] Most routes only require charging at one route terminus (once per round-trip), but a few routes will require charging at each terminus (once per one-way trip). The 450-kW charge rate is the maximum supported by current North American Bus suppliers. In addition, the local utility BC Hydro has advised that based on limitations in the distribution network in parts of the Vancouver Metro region, the use of in-route chargers with greater than 500 kW charge rate would significantly increase their cost to provide service interconnections.

hours, is accounted for in the projections of incremental operating costs summarized in Tables 6, 9, and 12.

3.2 Bus Maintenance

The bus maintenance program will need to evolve over the next ten years, to accommodate the introduction of electric buses. Ultimately it may require re-training of existing employees to develop new skills and recruitment of new employees with different skill sets than those of traditional automotive mechanics.

Most systems on electric buses will be the same or similar as systems on current internal combustion engine buses; only 25 – 40 percent of current maintenance activities will change. In addition, CMBC already maintains hybrid-electric buses which incorporate very similar drive train components as battery electric buses, including electric drive motors, inverters/power electronics, and battery packs. Drive train diagnostics and maintenance activities for battery buses will be similar to those for CMBC's current hybrid buses. Nonetheless, the following maintenance issues will require attention:

- All maintenance employees will require high voltage training, and a greater percentage of maintenance activities will require high voltage awareness and safety procedures (for example lock-out/tag-out).
- Current preventive maintenance (PM) cycles are often aligned to engine oil change intervals. Since electric buses will not require frequent oil changes there may be opportunities to re-think current maintenance intervals and packaging of PM activities.
- Drive train diagnostic procedures will change, with an even greater reliance on electronic diagnostics tools.
- Mid-life overhaul programs will need to migrate from engine and transmission overhaul/rebuild to rebuilding and/or replacement of electric drive motors, inverters, and battery packs. These new activities could be performed in-house at the transit centres or at the Central Maintenance Facility, or CMBC could contract with a third party for this work. If performed in-house it will require investments in equipment and tooling, as well as employee training.
- Lithium-ion batteries lose capacity (kWh) as they are charged and discharged, but the exact deterioration rate in transit service is unknown. This analysis assumes up to 2.4 percent capacity loss per year, which will require 100 percent battery replacement at bus mid-life (year 8). This will be a major expense which must be budgeted for annually, beginning in 2030. Expenses will include material purchases and mechanic labor.

- Electric drive components are expected to have a lower in-service failure rate than diesel engines and transmissions, but individual failures are likely to be more consequential, requiring replacement of entire components or major sub-systems at a cost of $5,000 or more per unit. These units may also have a long lead time, particularly in the short and medium term when annual production of electric buses is low. CMBC must set up appropriate procurement or service contracts to ensure that buses can be repaired expeditiously. This may include holding drive system component replacement inventory locally and/or requiring suppliers to maintain certain inventory levels dedicated to CMBC. It will also be advisable to develop a core/exchange program in which failed parts are removed and replaced with factory rebuilt components, with the failed part returned to the factory for rebuild and financial credit.

3.3 Cold Weather Operations

While battery chemistries vary, in general the chemical batteries used in battery-electric buses work best when the internal temperature in the battery pack is between approximately 0 °C and 20 °C. Both higher and lower battery temperatures will reduce the allowable charge and/or discharge rate without compromising battery life. In practical terms, failure to maintain appropriate pack temperatures in extreme ambient conditions (hot or cold) can reduce bus power, regen capability, or both.

While the Vancouver climate is generally temperate year-round, there are a few days a year when overnight temperature can fall below 0 °C. Since all CMBC buses are stored outdoors in unheated space, equipment and procedures will need to be put in place to ensure successful electric bus operations on cold days.

For electric buses at MTC and BTC that use overnight depot charging, on cold nights every bus parked at the depot must have a charging pantograph lowered to connect the bus to a charger, even if the battery is fully charged. The depot chargers and buses should be set up to allow the chargers to power the battery heaters on-board the bus – even after battery charging is complete - to maintain a target internal battery pack temperature.

For in-route charged buses at the other transit centres, the buses should include the capability of the on-board battery pack to power the battery heater to maintain appropriate pack temperature on cold nights. This capability may be able to be fully automated based on ambient and battery pack temperature monitoring or may require maintenance personnel to leave the bus in "run" mode, and/or toggle a switch to enable this functionality.

Maintenance procedures must be put in place to:

- Monitor projected overnight temperature during winter months and implement cold weather procedures if the temperature will fall below 3 °C
- When cold weather procedures are in effect, ensure that all buses are connected to a charger (depot charging) or that all buses have battery heating mode enabled (in-route charging) when parked at the depot for the night.
- When cold weather procedures are in effect, monitor all buses periodically through the night to ensure that battery heaters are active and maintaining proper battery temperature.

3.4 Charge Monitoring

Given the range limitations of battery buses, the negative consequences of mis-fueling (i.e. not charging when scheduled) are more severe for battery buses than they are for current internal combustion engine buses, which typically have 600 kilometers or greater range from a full tank of fuel. As such, CMBC will need to develop specific tools and procedures to minimize the potential for electric buses to miss scheduled charging events due to miscommunications, operator error, or equipment failures. Necessary activities will include fostering awareness of the need to maintain proper charging among bus operators, mechanics, and supervisors; regularly monitoring all charging to ensure that it is proceeding properly; and reacting quickly to malfunctions to re-start charging when it is interrupted.

At a minimum, CMBC should:

- Equip MTC and BTC with a centralized monitoring station that displays charge status for every depot charger at the location. Assign a maintenance supervisor to periodically check charging status throughput the night and/or provide the maintenance supervisor with automated real-time alerts if charging is interrupted for any bus.
- Develop the maintenance capability to respond to MTC and BTC charger failures within 30 minutes of detection and maintain a supply of repair parts – readily accessible – to repair common failures within an hour. This maintenance capability should be available 24 hours per day but will be in highest demand between 10 PM and 6 AM.
- Create a charging network control center with the capability to monitor the status of every in-route charger in real time, and to dispatch maintenance personnel to diagnose and repair identified failures.
- Develop the maintenance capability to respond to in-route charger failures within 60 minutes of detection and maintain a supply of repair parts – readily accessible – to repair

common failures within two hours. This maintenance capability should be available 24 hours per day but will be in highest demand between 6 AM and 8 PM.

- Develop procedures and systems to monitor charging status (in-route charging) and state of charge (in-route and depot charging) for buses in service throughout the day, with that information relayed to the bus command center on an exception basis for buses missing scheduled charges or with low state of charge. Set specific standards and thresholds for when the command center should intervene to either hold a bus for a longer charge session or take a bus out of service (and return it to the transit centre) due to low charge state.

3.5 Charging Infrastructure Maintenance

CMBC will need to develop an entirely new maintenance capability, which does not exist today, involving servicing, diagnostics, and repair/replacement of charging infrastructure, for both depot chargers and in-route chargers.

Annual scheduled charger maintenance will include visual inspection, tightening and retorquing of connectors, cleaning or replacement of filters, and cleaning inside and out, including cleaning of pantograph charge blades; a software diagnostic may also be recommended by some manufacturers. Software and/or hardware updates may also be scheduled during some maintenance visits. For high-use chargers, semi-annual maintenance may be recommended or required.

In terms of failures, connectors and cords may require replacement due to wear and abuse from users. Ventilation filters can also become clogged and fans can overheat and/or fail over time. Software can also crash and require rebooting.

In British Columbia, anyone working on electrical components when there is a potential to contact live conductors must be licensed as an electrical contractor by the province. Employees conducting some routine maintenance tasks may not require licensing, but those performing failure maintenance likely will.

CMBC could recruit and train licensed employees to perform charger maintenance or could contract for maintenance services from the charger manufacturer(s) or from third-party electrical contractors.

3.6 Contingency for Loss of Grid Power

For a full fleet roll-out of electric buses, TransLink should make contingency plans for maintaining some level of bus charging even if grid power is disrupted to one or more charging locations.

Information provided by BC Hydro indicates that their system has historically been very reliable. Between 2015 and 2018, 70 percent of all circuits had annual outage time of less than 5 hours, and 90 percent had annual outage time of less than 10 hours. In addition, for 86 percent of circuits average outage time per incident was less than an hour. Most outages were caused by either weather or vehicle damage.

Given the high reliability of the system, the recommended alternative it to use mobile diesel generator(s) that can be moved between locations as needed, rather than providing fixed back-up generation at every charging location.

For depot charging one or more 750 kW mobile generators would be required, with each providing the ability to supply power to up to 15 buses charging concurrently overnight at a depot. For in-route charging one or more 450 kW mobile generators would be required[36], with each providing the ability to supply power to one in-route charger.

The number of mobile generators required would depend on the number of electric buses deployed, and the likelihood of losing power at each charging location separately, and at multiple locations simultaneously. TransLink should work with BC Hydro to further evaluate historical trends and to project future needs.

It is possible that TransLink can contract for rental/lease of emergency power generation as required, rather than having to purchase and own mobile generating capacity.

3.7 Axle Weight Exemption

As discussed in Appendix A, current electric buses are heavier than diesel and hybrid-electric buses, primarily due to the weight of their battery packs. The rear axle weight of a 40-ft depot-charged electric bus (with a large battery) will be 1,200 – 1,800 kg more than the rear axle weight of a 40-ft diesel bus with the same number of passengers. In-route charged electric buses, with a smaller battery, will typically have 300-750 kg higher rear axle weight.

The additional weight of electric buses could cause them to exceed Provincial axle weight limits when heavily loaded during peak periods, though such conditions will be infrequent. TransLink

[36] It may also be possible to develop a mobile battery pack system that could power an in-route charger for 12-hours or more.

will need to coordinate with Provincial road authorities to determine whether electric buses will require an axle weight limit exemption to be deployed in CMBC service.

Ultimately, the available axle weight exemption(s) may limit the maximum battery capacity that can be installed on CMBC buses, and their effective daily range when depot charging is used.

3.8 Management of Bus Charging Load

As discussed in Appendix C (section C-2.2), BC Hydro's proposed EV rates have no demand charges assessed for demand that occurs between 6 AM and 10 PM. For in-route charging, peak demand will occur during day-time peak service hours, and CMBC will have little or no opportunity to manage this demand for either individual chargers, or the network as a whole, without affecting service. However, CMBC does have the ability to manage depot charging demand, to minimize or eliminate demand between 6 AM and 10 PM, to minimize demand charges and reduce total electricity costs.

When implementing depot charging at MTC and BTC, CMBC should install a demand management system, to control the timing and charge rate of individual buses, to manage total depot charging demand. The system should be able to:

- Delay the start of any charging until after 10 PM, regardless of when buses are parked at the depot when returning from evening service
- Increase the charge rate of late-returning buses, to complete a full charge before 6 AM.

3.8 Management of Service Disruptions and Service Expansion

The limited range of battery buses will introduce limitations on how CMBC will be able to deal with service disruptions and will complicate planning for some kinds of service expansion.

BUS BRIDGES: For some special events, and when SkyTrain service is disrupted, CMBC is required to temporarily, but significantly increase service on some routes – referred to as operating a "bus bridge". Routes that use in-route charging will have limited capacity to absorb such a temporary increase in service (especially during peak hours) due to limits on installed charger capacity. Depot charged buses have longer independent range but will still be limited to only 10 – 12 hours per day in service.

In the short and medium-term (through at least 2035) there will be enough diesel and hybrid-electric buses remaining in the fleet to cover this need. However, in the long-term TransLink and CMBC will need to develop contingency plans to effectively operate bus bridges with battery buses (with a focus on how the bridge buses will be charged) or retain a small diesel/hybrid fleet for this purpose.

BUS BUNCHING: As in most large cities, CMBC bus service experiences "bus bunching" when certain routes are congested, or if there is some kind of disruption on the route. Bus bunching refers to the tendency of buses to run close together, arriving at bus stops at the same time or less than a minute apart, rather than maintaining scheduled headways along the route. For routes that use in-route charging bus-bunching at in-route charging locations will reduce the ability of buses to maintain sufficient charge throughout the day. When planning the in-route charge network, CMBC should evaluate historical data to identify specific routes/locations/times when bus bunching is an issue and develop plans to ensure that all buses can get sufficient charge across the day. There may be opportunities to implement active headway management on some routes. In the extreme it might be necessary to install additional chargers at some locations, and/or insert additional recovery time into some schedules if bus bunching is determined to be a chronic issue that cannot be addressed any other way.

SERVICE EXPANSION: For any given route the number of buses required each day is primarily determined by peak hour headways, but the average daily mileage accumulation per bus is more a function of headways during off-peak hours; i.e. for a given number of peak buses average daily mileage will be higher if off-peak headway is shorter (more trips per hour) and will be lower if off-peak headway is longer (fewer trips per hour). Based on current service levels, and daily mileage accumulation, the electric bus implementation plan assumes that 15 percent more buses will be required to implement depot charging at MTC and BTC, due to electric bus range limitations. However, if additional mid-day service is added to the routes operating from these depots this will increase daily average bus mileage, resulting in the need to adjust daily bus blocks and potentially increasing peak bus requirements further.

For routes that use in-route charging increasing average daily mileage accumulation per bus will not create a problem as long as the route has sufficient charging capacity. For the conceptual in-route charge network developed under this project, the required number of chargers on each route is based on peak hour headways. As such, adding mid-day service will not increase the number of required chargers if mid-day headway is equivalent to or longer than peak headway.

APPENDIXES

Status of North American Electric Bus Industry

This section summarizes the status of the electric bus industry in North America, including the number of battery electric buses currently in service and on order, the manufacturers that produce electric buses, and the capabilities of commercially available battery bus models.

A-1 Electric Buses In-service and on Order

Full-sized[37] battery electric transit buses have been in limited operation in the North America for a decade, but their use has increased dramatically in the last three years. According to the American Public Transportation Association, there are currently at least 49 U.S. agencies operating a total of more than 550 battery electric buses, with 70 percent of them entering service since 2016[38]. A number of Canadian agencies also have electric buses in service or on order, including Toronto, Ontario; Edmonton, Alberta; St. Albert, Alberta; Brampton, Ontario; Winnipeg, Manitoba; Windsor, Ontario; and Montreal/Laval, Quebec[39]. There are also at least 1,200 battery buses on order for delivery to more than 100 different North American transit agencies over the next three years[40]. When these buses have been delivered, approximately 6 percent of North American transit agencies will be operating electric buses, and they will comprise about 2 percent of the transit bus fleet. One leading North American transit bus manufacturer estimates that 27 percent of their sales over the next 5 years could be battery-electric buses.[41]

Most agencies are still operating less than ten battery buses each, but some agencies have already placed orders for 100 or more electric buses. Some notable recent battery bus orders include Los Angeles Department of Transportation (118); Los Angeles Metro (210); Edmonton Transit, Canada (100); Antelope Valley, California (89); King County Metro, Seattle (73); Foothill Transit, California (50); Toronto Transit Commission, Canada (60); Minneapolis Metro (27); SEPTA in Philadelphia (25); Chicago Transit Authority (30), and Montreal/Laval, Canada (40).

[37] Full-sized buses are those that are greater than 30-ft long; a limited number of 22-foot battery electric buses have been operating at a handful of U.S. agencies since the early 2000s.

[38] American Public Transportation Association, *Public Transportation Vehicle Database*, https://www.apta.com/research-technical-resources/transit-statistics/vehicle-database/, accessed June 26, 2019. The first battery-electric bus listed in the database was manufactured in 2009

[39] Clean Energy Canada, *Will Canada miss the bus?,* March 2019

[40] Based on news articles and press releases from various sources, and bus manufacturer websites

[41] Personal communication with J. Gibson, New Flyer of America

An important driver of U.S. electric bus adoption is the *Innovative Clean Transit Regulation*, which was adopted by the California Air Resources Board (ARB) in December 2018[42]. This regulation requires all transit agencies in California to phase in purchasing of "zero-emission" buses[43] between 2020 and 2029, after which 100 percent of all new bus purchases must be zero emission. ARB estimates that this will result in a 100 percent zero emission fleet in the state by 2040. Approximately 20 percent of all U.S. transit buses are in California.

A-2 Electric Bus Manufacturers

See Table A-1 for a summary of the manufacturers that currently offer battery electric transit buses in the North American Market. Virtually every full-line bus manufacturer that produces diesel, CNG, and hybrid-electric buses for the North American market also offers at least one battery-electric option, including New Flyer, Gillig, Nova, and Alexander Dennis. Battery buses from these manufacturers use the same bus platform as the other bus types, with only minor modifications to accommodate the electric propulsion system. Proterra, BYD, and Green Power Motor Company manufacture only battery buses, and do not offer buses with conventional propulsion systems. Complete coach works remanufactures old diesel buses with a new electric propulsion system.

To-date, BYD, Green Power, Alexander Dennis, and Complete Coach Works have focused on buses that use plug-in charging, typically overnight at the depot. Nova Bus offers only overhead conductive charging, which is typically used for in-route charging, but could also be used in a depot setting. Proterra, New Flyer, and Gillig offer both plug-in and overhead conductive charging on their buses. See Section 3 for a discussion of the different charging options.

The data in Table 2 is current as of July 2019. There have been significant changes in the electric bus market over the past three years and it is likely to remain a fluid market; in the future additional new entrants are possible, along with additional charging options from existing manufacturers.

[42] *https://ww2.arb.ca.gov/news/california-transitioning-all-electric-public-bus-fleet-2040*
[43] Zero emission buses include battery-electric buses and hydrogen fuel cell buses

Table A-1 North American Electric Bus Manufacturers

Manufacturer	Location	Vehicle Types / Sizes	Charging Infrastructure
Alexander Dennis	UK	45-ft double decker	Depot
BYD	Lancaster, CA	30-ft, 35-ft, 40-ft, 60-ft	Depot
Complete Coach Works	Riverside, CA	40-ft remanufactured	Depot
Gillig	Livermore, CA	40-ft	Depot, In-route
Green Power Motor Company	Porterville, CA	30-ft, 35-ft, 40-ft, 45-ft, 45-ft double decker	Depot
Nova Bus	Saint-Eustache, QC, Canada; Plattsburg, NY	40-ft	In-route
New Flyer	St. Cloud & Crookston, MN; Anniston, AL; Winnipeg, MB, Canada	35-ft, 40-ft, 60-ft	Depot, In-route
Proterra	Los Angeles, CA; Greenville, SC	35-ft, 40-ft	Depot, In-route

Note that transit bus manufacturers typically do not produce buses shorter than 30-ft. The smaller shuttle buses used by CMBC for neighborhood service are produced by different manufacturers. While there are several small, specialty manufacturers that currently produce small electric "cut-away" buses[44], none of the major shuttle bus manufacturers currently produce electric buses. While many North American transit agencies operate small shuttle buses, none of the battery electric buses listed in the American Public Transportation Association *Public Transportation Vehicle Database* are shorter than 30-ft.

A-3 Available Electric Bus Models

Table A-2 compares relevant characteristics of the 40-ft electric bus models offered by the different manufacturers. The major differences between various models, and their relevance to bus operations, are discussed below.

[44] A cut-away is a bus built by installing a passenger body on a standard cab/chassis. These specialty manufacturers purchase a cab/chassis without an engine from a major manufacture and install an electric drive system. Production volumes are very low.

STRUCTURAL DESIGN

All manufacturers except Proterra manufacture electric buses using a welded tubular steel frame, with steel, aluminum, or composite body panels riveted, bolted or bonded to the frame – the same construction used for traditional transit buses with internal combustion engines. The load bearing structure, walls, roof, and floor of Proterra electric buses are all constructed or fiberglass composite, with a design and construction method like that used for many small and medium-sized marine vessels. The composite structure is lighter than a steel structure, and is not subject to corrosion, but may experience other deterioration over time due to structural stress– for example cracking or delamination. The composite structure also behaves differently than steel structures in a crash and will require different repair methods.

Since the Proterra composite structure is lighter than a steel structure, the Proterra bus has 900 – 1,360 kg lower curb weight than other electric buses with the same sized batteries.

Table A-2 Commercially Available 40-ft Battery Buses

Parameter	BYD	Gillig	New Flyer	Nova	Proterra
Length (m)	12.2	12.7	12.5	12.4	13.0
Wheelbase (m)	6.1	7.1	7.2	6.2	7.5
Height (m)	3.4	3.4	3.3	3.3	3.4
Front Overhang (m) [1]	2.6	2.6	2.2	3.0	2.6
GVWR (kg)	19,741	20,455	20,140	19,545	19,841
Curb Weight (kg) [2]	14,963	13,477/15,341	13,697/14,964	14,545	12,113/15,067
Passenger Capacity [3]	77	75	75	71	70
Battery Type	Iron-phosphate	Lithium-ion	Lithium-ion	Lithium-ion	Lithium-ion
Battery Size Options	324 kWh	148 kWh 296 kWh 444 kWh	160 kWh 267 kWh 388 kWh 466 kWh	150 kWh	220 kWh 440 kWh 660 kWh
Battery Locations [4]	A	A, B, C	A, B	A, B	D
Plug-in Charging	SAE J1772 CCS-Type 1	SAE J1772 CCS-Type 1	SAE J1772 CCS-Type 1	Not available	SAE J1772 CCS-Type 1
Conductive Charging	Not available	SAE J3105-1	SAE J3105-1	SAE J3105-1	SAE J3105-1

Structure	Tubular steel	Tubular steel	Tubular steel	Tubular steel	Composite
Drive Motor	Dual 150 kW AC synchronous	No Data	200 kW Permanent magnet	230 kW Permanent magnet	Dual 190 kW or single 250 kW Perm magnet
Gear Box	None- direct drive	No Data	None – direct drive	None – direct drive	2-speed auto shift
Top Speed	100 KPH	No Data	No Data	No Data	105 KPH
Energy Use [5]	1.23 kWh/km (2014 - CBD)	No Data	1.09 kWh/km (2014 - CDB)	1.20 kWh/km (2018 – OCC)	1.25 kWh/km (2017 – OCC)

[1] Center of front axle to front bumper [2] With smallest/largest available battery

[3] Maximum, with largest battery. Based on GVWR and 68 kg/passenger

[4] A = on roof; B = in rear compartment behind passenger cabin; C = under floor, just ahead of rear axle; D= under floor between front and rear axles

[5] From Altoona testing. For testing prior to 2017 listed results are from track testing on Central Business District (CBD) cycle. For testing in 2017 and 2018 listed results are from dynamometer testing on Orange County (OCC) cycle. Stated values do not include energy for air conditioning or cabin heating.

PHYSICAL DIMENSIONS

All electric buses have similar dimensions (height, length, wheelbase) as CNG and hybrid-electric buses on the market[45]. For buses that will use overhead high-power conductive charging, all electric bus manufacturers install the on-bus charge port on the roof, essentially centered over the front axle. Therefore, the front overhang length (center of front axle to front bumper) may be important when siting in-route chargers. As shown, the front overhang of 40-ft electric buses ranges from 2.2 meters to 3.0 meters.

BATTERIES

All manufacturers except BYD use lithium-ion batteries, while BYD uses iron-phosphate batteries. Individual battery modules are packaged into two – six separate battery packs which are then wired in parallel. Different manufacturers install the battery packs in different locations. Proterra installs all battery packs under the bus floor, between the front and rear axles, while BYD installs all battery packs on the roof. Depending on total battery capacity the other manufacturers may install battery packs on the roof, in a compartment behind the

[45] CNG, hybrid-electric, and battery buses are all slightly taller than many diesel buses due to roof-mounted equipment.

passenger cabin (where the engine and transmission would be on a diesel bus) and/or under the floor just in front of the rear axle.

One key parameter is the installed battery energy capacity (kilowatt hours of energy, kWh), which – together with vehicle energy efficiency - determines how far the bus can go on a single charge (range). Most manufacturers offer a range of battery sizes, from approximately 150 kWh to approximately 450 kWh. BYD currently only offers one battery size (324 kWh), but is reportedly working to offer a larger, extended range battery. Proterra offers the largest battery currently available in the market, at 660 kWh. The larger the battery the longer the range (miles) per charge. Also, the larger the battery the heavier the bus, and the practical limitation on maximum battery size is primarily weight, not volume. Proterra can offer a larger battery than other manufacturers due to the lower weight of their composite structure.

The smaller battery offerings (<250 kWh) are primarily intended for buses that will use in-route opportunity charging. The larger battery offerings are primarily intended for buses that will charge overnight at the depot (see section 3 for a discussion of charging options).

Since batteries are the single largest cost element for electric buses, larger batteries also typically increase the purchase cost of the bus.

The data in table 3 represents commercial offerings for the 2019 model year. In the future battery energy density (watt-hours per kilogram, wh/kg) is projected to continue to increase, allowing for installation of battery packs with greater energy capacity. It is likely that battery offerings will continue to evolve for all manufacturers.

WEIGHT & PASSENGER CAPACITY

All electric buses have similar interior lay-out and capacity as diesel buses from the same manufacturer, with a maximum of 36 – 40 seats in a 40-ft bus, depending on seating configuration.

Electric buses have a gross vehicle weight rating (GVWR) of 19,550 – 20,450 kilograms (kg), and curb weight of 12,100 – 15,350 kg, depending on manufacturer and installed battery capacity. The curb weight of 40-ft diesel buses is typically in the range of 11,800 – 12,700 kg, so electric buses with the largest available battery, appropriate for overnight depot charging, will typically weigh 1,800 – 2,700 kg more than a similar diesel bus, with 1,200 – 1,800 kg more on the rear axle. In-route charged electric buses, with a smaller battery, will typically weigh 450 – 1,150 kg more than a diesel bus, with 300-750 kg more on the rear axle. The only electric bus on the market with a similar curb weight to a diesel bus is the Proterra bus with the smallest available battery; Proterra buses with larger batteries, and all battery buses from the other manufacturers will be heavier than current diesel buses.

The maximum passenger capacity of 40-ft electric buses with the largest available batteries range from 70 – 77 passengers, based on GVWR and assuming 68 kg per passenger.

DRIVE SYSTEM

The electric propulsion system on battery buses includes an energy storage system (battery packs), an alternating current (AC) electric drive motor, an inverter/power electronics to convert direct current (DC) from the battery to AC to power the motor, and a control system. Nominal propulsion system voltage is typically 500 – 650 volts. Electric buses typically also include a DC-DC converter to power 12- and 24-volt auxiliary systems (lights, fare box, etc.) and may include a second inverter to power HVAC systems at a higher voltage.

Some manufacturers use a single large drive motor and others use two smaller motors. Peak motor power on 40-ft battery buses ranges from 200 to 380 kW. All manufacturers except Proterra utilize a direct drive system with no transmission or gear box between the drive motor and rear axle. Proterra uses a 2-speed auto-shifting gear box between the drive motor(s) and rear axle.

CHARGING

All manufacturers except Nova offer plug-in direct current (DC) charging, using a charge port compatible with an SAE J1772 CCS-Type 1 connector[46]. As such, a single DC charger equipped with this type of connector can be used to charge buses from all manufacturers. All manufacturers provide a charge port on the curb-side rear of the bus and all manufacturers offer the option of a second charge port, on the street-side rear or street-side front of the bus.

BYD also offers AC charging using a connector that is not offered by any other North American manufacturer[47]. With AC charging the inverters installed on the bus convert incoming 480-volt AC current to DC to charge the batteries, and a separate DC charger is not required. However, the connectors used by BYD on the cord and bus cannot be used to charge buses from other manufacturers.

[46] CCS stands for Combined Charging System. These connectors are often referred to as just "CCS connectors"
[47] BYD uses a GB/T 20234 connector, constructed to a standard adopted in China.

Nova, and all other manufacturers except BYD also offer over-head conductive charging, at charge rates up to 450 kW. For overhead conductive charging all manufacturers intend to comply with the SAE J3105 -1 charging standard, which has been in progress for the last few years, and was published on January 20, 2020[48]. All manufacturers install the J3105-1 vehicle connection interface on the roof of the bus, centered over the front axle.

While there are several manufacturers that offer wireless inductive charging systems for transit buses (see section 3), none of the bus models listed in Table 3 currently offer wireless charging as a standard option. There are only a handful of wireless bus charging systems currently installed in either North America or Europe.

CABIN HEATING

A bus with an internal combustion (IC) engine uses waste heat captured via the engine cooling system to heat the passenger cabin in cold weather. Electric buses also have waste heat produced by the inverters and drive motor, which are typically cooled with a water-ethylene glycol (WEG) system. However, electric buses produce significantly less waste heat than IC engine buses, and the WEG loop operates at lower temperature. No electric bus manufacturer currently harvests this waste heat for cabin heating.

Instead, electric buses are equipped with electric resistance heating coils fed by energy from the propulsion battery. Details of how the heat is distributed from the coils to the passenger compartment vary by manufacturer, to include heating WEG to feed floor-mounted heat exchangers, distributing heated air from the rear through a ceiling level plenum, and directly re-circuiting cabin air over the coil mounted on the roof in the middle of the bus.

As discussed in section 4, the amount of battery energy used for cabin heating can be significant during cold weather and will affect bus range. All manufacturers offer the option of a diesel-fired heater to supplement the electric heating system. Some manufacturers integrate the electric and diesel systems while others keep them separate.

While the use of fuel heat will increase GHG emissions relative to the use of electric heat, the increase will be small. In CMBC service, total annual GHG emissions from an electric bus with a supplemental diesel-fired heater are estimated to be 90 percent lower than annual GHG

[48] SAE is also developing J3105-2 and J3105-3 standards for a blade-type connector and a vehicle-mounted pantograph (pantograph-up) connector, respectively. Many European bus manufacturers are adopting the J3105-3 standard for bus charging.

emissions from a hybrid bus and 92 percent lower than emissions from a diesel bus. Even with supplemental diesel heating, electric buses will easily meet targets for 2050 GHG reduction.

EXTREME WEATHER OPERATION

While battery chemistries vary, in general the chemical batteries used in battery-electric buses work best when the internal temperature in the battery pack is between approximately 0 °C and 20 °C. Both higher and lower battery temperatures will reduce the allowable charge and/or discharge rate without compromising battery life. In practical terms this means that operation of electric buses in extreme temperatures (hot or cold) can reduce bus power, regen capability, or both.

Bus manufacturers provide active cooling and heating to battery packs to maintain appropriate battery pack temperature and allow for continued operation in extreme weather. Given the temperate summer environment in Vancouver hot weather operation is not expected to be problematic for CMBC battery electric buses. Winter temperatures are also mild in Vancouver, but there are a handful of days per year when over-night temperatures fall below freezing, which could negatively affect electric buses – particularly those stored outdoors in unheated space, as all CMBC buses are currently[49]. To be used successfully in Vancouver, electric buses will likely require active battery-pack heating when stored outside at the transit centres overnight on cold nights (5 – 15 nights per year); without active heating pack temperatures may fall below the allowable minimum, thus limiting available bus power when buses enter service.

For buses that use overnight depot charging, every bus parked at the depot will likely be plugged into a charger (see section 3); these chargers can be set up to power on-board battery heaters during cold weather – even after battery charging is complete - to maintain a target internal battery pack temperature. For depot-charged buses not connected to a charger all night, or for in-route charged buses, the on-board battery pack can be used to power the battery heater, to maintain appropriate pack temperature on cold nights. Projected power required for battery pack heating is on the order of 2 – 5 kW when ambient temperature is 0 °C to -10 °C; for a 200-kWh battery pack this would use up 10 – 25 percent of battery power for 10-hours overnight storage (typical), if power is drawn from the on-board battery pack.

[49] Battery packs have high thermal mass (they cool off slowly) and also generate heat as they are dis-charged over the day. As such, daily operation on cold days is not expected to be a significant problem, as long as the battery packs are sufficiently warm to start the day.

BUS PURCHASE PRICE

Definitive data on current pricing for electric buses is difficult to develop due to significant differences in purchase specifications and contract details for different transit agencies, and the fact that the technology, and bus manufacturer offerings, are still evolving. Review of public bid documents indicates that between 2017 and 2019 different U.S. agencies have paid between $650,000 and $1.2 million (U.S. $) per bus for 40-ft battery-electric buses; the weighted average price of 40-ft electric buses listed in the APTA transit vehicle database is $889,000 per bus and the weighted average price of 60-ft electric buses is $1.3 million per bus [50]. However, on the high end some contracts have included charging infrastructure in the per-bus price and may also have included significant spare parts. On the low end the purchase price was reduced by the agency's decision to lease the bus batteries rather than buying them outright. In 2018 TransLink paid approximately $1.0 million each (CDN$) for the fleet of four 40-ft electric buses in their pilot program.

Bus manufacturers are also tight-lipped about current battery costs, which are a significant contributor to over-all electric bus purchase costs. In 2017 published reports put the cost of batteries for electric buses as high as $750/kWh (U.S. $). Current public pricing data from Proterra's battery leasing program implies that costs have fallen into the range of $445/kWh (U.S. $), at least for Proterra.

In recent years the price of buses to TransLink, in Canadian dollars, has been approximately 25 percent higher than the U.S. average price in U.S. dollars, based on currency exchange rates. Based on the totality of available information, MJB&A estimates that 40-ft electric buses purchased in volume (30+ buses) over the next few years by TransLink will cost approximately $1.1 million per bus for depot-charged buses with a large battery (450 kWh) and $950,000 - $970,000 per bus for in-route charged buses with a smaller battery (150-200 kWh). Estimated prices for 60-ft electric buses are $1.6 million per bus for a bus with the largest available battery, and $1.4 million per bus for buses with smaller batteries, for use with in-route charging. These prices are in Canadian dollars.

[50] American Public Transportation Association, *2019 Public Transportation Vehicle Database*, https://www.apta.com/research-technical-resources/transit-statistics/vehicle-database/, downloaded on 9/26/19. There are 191 electric transit buses listed with length between 37 and 43-ft, and 26 articulated buses (length >55 ft) listed, with "year built" between 2017 and 2021 (some are on order but not yet delivered). These buses were manufactured by Proterra, BYD, and New Flyer.

This compares to the approximately $630,000 (CDN $) estimated purchase price for TransLink 40-ft diesel buses, and approximately $890,000 purchase price for TransLink 40-ft diesel hybrid-electric buses. Estimated prices for 60-ft diesel and hybrid electric buses are approximately $1.0 million, and $1.3 million per bus, respectively.

Electric Bus Charging Options

This section discusses and compares the two major options for charging battery buses: 1) depot charging, and 2) in-route charging.

B-1 Depot Charging

Depot charging is generally analogous to home charging for personal electric vehicles; usually a charger is provided at every bus parking spot in the depot, and buses are plugged in and charged during the time that they are parked, which is typically between about 9 PM and 5 AM. Minimum charging rates of 50 – 75 kW are required, to complete the necessary charging in the available 6- to 8-hour overnight window. Higher charge rates could also be used, to finish necessary daily charging faster. Some agencies are experimenting with higher depot charge rates to reduce the required number of depot chargers, but these charging scenarios typically also entail additional bus shifting costs, since buses must be moved away from the charging position when done, to allow the next bus to be charged.

Figure B-1 Commercially Available CCS Connector Compatible Chargers

The most common way to implement depot charging is to use direct current chargers equipped with an SAE J1772 CCS-Type 1 connector. Incoming alternating current from the grid is converted to direct current by inverters in the charger, to directly charge the bus batteries. In North America input power for these direct current chargers is 480 volt, 3-phase. To charge, the standard connector is plugged into a compatible port on the bus, and direct current power is transferred from the charger to the bus via an electrical cord.

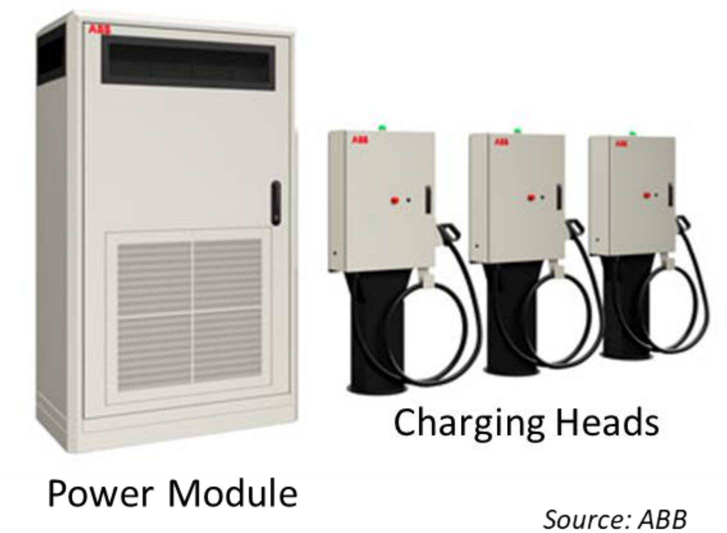
There are a number of appropriately sized chargers on the market (50 kW – 62 kW), which are also used for "fast-charging" electric cars. These chargers combine required inverters, control equipment, and switches into one "box" equipped with one or two charge cords. See figure B-1 for several examples of commercially available chargers. See Figure B-2 for the configuration of the CCS connector and on-bus charge port.

Several companies also sell charging systems which separate the power inverters and controller/cord connections into separate units. Under this scenario a 100 – 150 kW power module will feed up to three charging heads, and the power module/power cabinet (inverter) can be physically separated from the charge heads. Larger capacity charging cabinets with capability to supply a larger number of charge heads (often referred to as charging posts) are under development, most notably by ChargePoint; which plans to release a 500kW charging cabinet with ability to supply 8 charge posts, in 2020. Tesla currently has a 1 MW charging system (V3 Supercharger) with ability to supply up to 8 charge posts, but the connectors are proprietary Tesla type.

Figure B-2 CCS Connector

The charge heads for systems that separate the charger cabinet are typically smaller and lighter than all-in-one units and require less space between bus lanes if the charge heads are ground-mounted, or less structure to support the charge heads if mounted overhead. In addition, these systems are able to be configured to allow any individual bus to charge at the maximum rating of the charge cabinet if only one of every three charge heads are actively charging. See Figure B-3.

Figure B-3 Corded Charger with Separate Power Module and Charging Heads



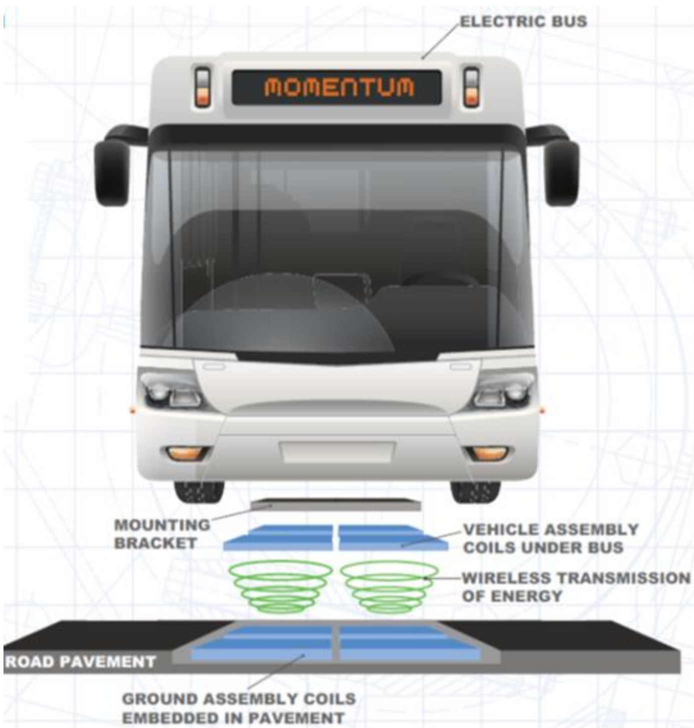
Source: ABB

When implementing depot charging with CCS chargers, each bus will need to be plugged in to start the charge and unplugged before the bus leaves the depot. In addition, the space required to install the chargers will reduce depot parking capacity by 5 to 25 percent, depending on whether they are mounted on the ground or overhead. While overhead mounting will reduce the space requirements it will add cost, due to the need to add overhead structure to carry the weight of the chargers.

To reduce operational requirements of plugging and unplugging buses, and to minimize charger space claim, some transit agencies are experimenting with using SAE J3105-1 overhead conductive chargers for depot charging; these are the same chargers used for in-route charging, as described in Section B-2 below. There are various ways to implement depot-based overhead conductive charging; for example a pantograph could be installed at each bus parking space to implement "slow" charging (50 – 75 kW; 6 – 8 hour charge time per bus), or a smaller number of higher-power overhead chargers could be installed – for example 450 KW overhead chargers could charge each bus in less than an hour.

While operationally simpler, overhead depot charging is typically more expensive than using corded chargers, due to the cost of the overhead pantographs used to connect the charger to the bus (slow charging), or operational costs for shifting buses through the chargers (fast charging). In North America overhead charging is usually implemented "pantograph- down" – i.e. the movable pantograph that makes the electrical connection between the charger and bus is installed on the charger and it moves down to connect to charge rails on the bus. A number of European transit agencies are using “pantograph – up” systems for depot charging. In this scenario a movable pantograph is installed on every bus; to charge, the pantograph moves up to contact a fixed charging rail at the overhead charging point.

Figure B-4 Wireless Inductive Charging



Source: Momentum Dynamics

Several companies also sell wireless inductive chargers that could be used for depot charging. With a wireless charger a power pad is embedded in or on the floor of the depot and a power receiver is mounted on the bus. With the receiver positioned over the ground-mounted pad, power is transferred across the air gap via magnetic fields generated by magnetic coils in the source and receiver. See Figure B-4.

Similar to other chargers, wireless systems require power modules (inverters, switches, controls) to feed direct current power to the ground-mounted power pads. These power modules are of similar size as for other direct current chargers and can be located up to 100 feet away from the ground-mounted pads.

The on-bus charge receiver is only a few inches thick but requires approximately four-square feet of surface area for every 75 kW of power transferred and weighs 100 – 200 pounds. The on-bus power receiver must be actively cooled during charging, which requires a higher level of integration to bus systems than the other charging methods; none of the bus models listed in Table 3 offer wireless charging as a standard option.

Wireless charging is reported by one manufacturer to be as efficient as wired and conductive charging, with a similar cost for purchase and installation of the necessary equipment. However, this is an infant technology with only a handful of installations in North America or Europe, less than 3 years of in-use experience, and a small and potentially fragile manufacturing base.

The biggest issue associated with depot charging is a limitation on daily bus operating range (miles, hours), due to limitations on the size of batteries that can be installed on the bus. As discussed in Section 4.2, depot-charged buses would have shorter daily range than required on many CMBC routes. This would require existing long daily bus assignments to be shortened, which would increase the number of peak buses required to provide current service levels.

Another potential disadvantage of depot charging is that total peak charging load could be 8 - 10 MW for a 200-bus depot. Depending on the capacity of the existing distribution infrastructure, interconnection costs for such a large load could be very high. For example, estimated interconnection costs to handle the projected depot charging load at TransLink transit centres ranges from a low of $350,000 to a high of $11 million (see Section C-2.2)

B-2 In-route Charging

With in-route charging energy is added periodically while the buses are in service each day, rather than buses being charged at the depot overnight. In-route charging requires much higher charge rates than depot charging– typically 300 to 450 kW – but fewer chargers; as discussed in Appendix C, in-route charging would require one charger for approximately every seven peak buses on CMBC routes.

In-route chargers are typically installed at one or both termini on a route, and buses are charged for 5 -15 minutes each time they come to the end of the route where the charger(s) is located.

Depending on route length, and whether charging is done at one or both termini, buses may charge once every 1 – 2 hours in service. With 450 kW in-route chargers total in-route charge time will typically be 45 – 90 minutes per day per bus.

In-route charging is typically done using overhead conductive chargers. See Figure B-5 for an example of a typical in-route charger installation. A movable pantograph, powered by electricity or compressed air, is installed on a pole which extends over the roadway. When a bus pulls under the charger the pantograph moves down, and contacts power rails installed on top of the bus; power is then transferred between the rails on the pantograph and the rails on the bus.

Figure B-5 Typical In-route Charger Installation

There are two main companies that sell overhead conductive chargers in the North American market, ABB and Siemens. Both companies offer chargers with nominal charge rate of 150 kW, 300 kW, 450 kW, or 600 kW. The power modules used by these companies are very similar to the power modules used to provide power to corded or wireless chargers (see figure 5); their main purpose is to convert supply power (alternating current at a range of potential voltages) to 600 – 1,000 volt direct current to charge the bus batteries. For in-route charging these power modules are typically located in an enclosure in the vicinity of the charging location (less than 100 feet) and power is transferred between the power module and the charging pole/pantograph via under-ground conduit. See Figure B-6 for two typical in-route charging power module installations; both examples are for 450 kW in-route chargers.

Figure B-6 450 kW In-route Charger Power Modules

There are several transit agencies that are experimenting with inductive wireless in-route charging. The same type of equipment as is used for inductive wireless depot charging is used for inductive wireless in-route charging, but the charging pad is installed in the roadway at the in-route charge point. Manufacturers indicate that wireless power transfer is unaffected by rain or snow on the charge pad. The largest system currently in-use has a maximum charge rate of 300 kW, which requires an on-bus power receiver with 1.5 square meter of surface area. Given current systems it may be impractical to use inductive charging at higher charge rates, due to practical limitations on the size of the on-bus receiver without affecting bus break-over angle or placement of other bus equipment[51].

[51] At least one research & development team is working on 500 kW wireless units in which the on-vehicle receiver has a surface area smaller than current 300 kW units

One of the most significant advantages of in-route charging compared to depot charging is that with a properly designed charging network there is virtually no limitation on daily bus range; buses would leave the depot in the morning with a near full battery and return with a near full battery after periodic charge events throughout the day which replenished all of the energy used on route. In addition, the battery on the bus can be smaller than the battery on a depot-charged bus, which reduces bus weight and cost.

A potential dis-advantage of in-route charging is that, depending on the battery chemistry used, some bus manufacturers may require periodic "slow" charging over a period of several hours or more to "balance" the charge in the on-board batteries. This requires some number of lower power chargers at the bus depot, increasing total infrastructure costs and complicating over-all charging operations. The four pilot buses currently being operated by CMBC using in-route charging were produced by two different manufacturers; one manufacturer requires a battery balancing charge at the depot and the other does not.

While in-route charging eliminates the range restrictions of depot-charged buses, time may need to be added to bus schedules to accommodate the periodic charging. In addition, to ensure that every bus receives a proper charge without affecting on-time performance proper spacing between buses on the route must be maintained. Many transit agencies experience "bus bunching" when routes are congested, or if there is some kind or disruption on the route. If this is a significant problem, additional time may need to be added to schedules on some routes, and additional lay-over spaces may be required at charging locations, to ensure that every bus has time to charge even when service is disrupted.

In addition, an optimized in-route charge network will have limited ability to absorb short-term but significant increases in service on a given route – for example to operate a "bus bridge" if the Sky Train is out of service - because there will be insufficient charger capacity to charge the additional buses on the route. Planned permanent increases in service can be accommodated by adding additional chargers at existing charging locations, or by adding new charging locations to the network.

In addition, TransLink will need to procure easements or other agreements to install the necessary chargers on public or private land across the service area. Prior experience of other transit agencies has shown that the process of siting and permitting in-route chargers can be time-consuming and the time from site acquisition to commissioning may take two years or more for some sites.

B-3 Comparison of Charging Methods

This section compares and contrasts the advantages and disadvantages of depot charging and in-route charging, and also compares the different ways to implement depot charging.

See Table B-1 for a comparison of the advantages and dis-advantages of depot charging versus in-route charging. In general depot charging will have lower costs for charging infrastructure but higher costs for bus purchase than in-route charging. Depot charging will require additional space at bus depots, but in-route charging will require the agency to purchase or lease space at in-route lay-over locations.

Table B-1 Comparison of Depot and In-route Charging

	Depot Charging	In-Route Charging
PROS (+)	• Direct control of infrastructure (on transit-owned property) • Lower infrastructure costs • Potentially lower electricity cost due to reduced demand charges (load in non-peak hours)	• No limitation on daily bus range; can keep existing daily bus schedules with no increase in peak buses • No loss of depot parking capacity • Lower bus purchase cost due to smaller battery • Potentially greater resiliency/reliability - loss of power at a single charging location will have limited effect on bus operations
CONS (-)	• Limited bus range – will need to shorten long assignments, resulting in increased peak buses • Higher bus purchase cost due to larger battery • Charger space claim reduces bus parking • Loss of power at depot will significantly effect bus operations	• Less control over infrastructure (may need to locate chargers on land not owned/controlled by transit agency) • Time and effort for site acquisition and permitting of charger sites • Higher infrastructure costs • Potentially higher electricity cost due to higher demand charges (load during peak hours) • Potentially higher cost/difficulty of charger maintenance • Must add time to existing schedules to accommodate charging • Bus bunching will reduce charging effectiveness • Limited ability to absorb temporary increases in service for special events due to limited charging capacity

Both options will require changes to existing bus schedules. With depot charging long daily bus assignments will need to be shortened due to range limitations, which will increase peak bus requirements. With in-route charging there will be no limitation on the length of daily bus assignments, but time will likely need to be added to all schedules to accommodate in-route charging time; this may also increase peak bus requirements, but not as much as depot charging.

Development of an in-route charging network will likely take longer than installation of chargers at a depot due to time for planning, site acquisition, permitting, and obtaining electrical service at multiple sites. However, because it is more distributed, an in-route charge network is inherently more resilient than depot charging; the loss of grid power at the depot would affect bus service over a large area if buses could not be charged, but the loss of grid power at one in-route charging location would affect a much more limited service area.

It is also possible to employ a hybrid charging strategy which uses over-night depot charging to replenish the bulk of the energy used by buses for daily service, with limited in-route charging to extend daily range to cover long daily assignments. This type of hybrid strategy could potentially minimize required changes to existing bus schedules but would likely be more expensive than either a pure depot- or pure in-route charging strategy due to the need for both expensive buses with large batteries, and a greater amount of charging infrastructure.

See tables B-2 and B-3 for a comparison of the different depot-charging options: corded charging, inductive wireless charging, and overhead conductive charging. Table B-2 addresses the differences between charging technology for "slow" overnight depot charging and Table B-3 addresses requirements for fast depot charging and the pros and cons of this approach compared to slow charging.

Compared to other charging options corded chargers have the lowest capital cost and the largest number of commercially available options. The main draw-back of these devices is the need to plug in the charge cords to initiate charging, and to unplug the cords when charging is complete. It is reasonable to expect that some connectors and cords will be damaged and require replacement. These chargers also have higher space claim than the other options when implementing slow charging (one charger per peak bus), especially if the charging heads are ground mounted.

Both inductive wireless chargers and overhead conductive chargers can eliminate the operational issues and costs associated with charge cord handling and can reduce charger space claim for slow charging, but each introduces trade-offs for these benefits. Wireless chargers require active cooling of the on-bus charge receiver during charging and therefore require a greater level of integration with other bus systems. At this point in time this technology is also likely riskier than the others due the fact that it is still an infant technology with few North American installations, a limited amount of in-use experience and a limited manufacturing base. For slow depot charging the capital cost of overhead inductive chargers is significantly more than the cost of corded chargers, due to the need for a pantograph at virtually every bus parking space (or on every bus under the European pantograph-up charging scenario).

Table B-2 Comparison of Options for Slow Depot Charging

Charge Rate	Minimum 50 – 75 kW		
Charge Time	6 – 8 hours per bus		
Chargers required	One per peak bus		
	SAE J1772 CCS Type 1 Corded Chargers	**SAE J3105-1 Overhead Conductive Chargers**	**Inductive Wireless Chargers**
PROS (+)	• Lowest capital cost • Largest number of commercial options	• Do not need to plug and unplug buses • No cords to damage • Lower space claim – less loss of parking space	• Do not need to plug and unplug buses • No cords to damage • Lower space claim – less loss of parking space • Potentially similar capital cost to corded chargers
CONS (-)	• Requires plugging and unplugging buses • Charger space claim reduces bus parking space • Potential to damage cords and connectors	• Higher capital cost than corded chargers due to cost of pantograph at each charging location	• Charge receiver on bus requires active cooling during charging • Not a standard option on commercially available buses • Infant technology; small and potentially fragile commercial base

The concept of “fast” depot charging (at charge rates up to 450 kW) is primarily intended to reduce the number and cost of depot chargers compared to slow charging; to that end it is most effective in reducing costs for overhead conductive chargers because significantly fewer expensive pantographs are required. However, even at 450 kW charge rate most buses will require 30 – 60 minutes to receive a full charge, and one charger will be required for every 6 – 8 peak buses to be able to charge all buses in the available 6 – 8 hour over-night window when buses are parked at the depot. Given this charge time, the use of fast depot charging will require buses to be shifted through the chargers, which adds operating costs compared to slow charging. Also, the required space claim for the chargers will increase to either allow for uncharged buses to stack up behind the chargers as they come off the road, or to allow drive through access to each charger to allow buses to be moved from the parking area to the charger and back to parking.

Table B-3 Comparison of Options for Fast Depot Charging

Charge Rate	150 kW	300 kW	450 kW
Charge Time	Up to 140 min/bus	Up to 72 min/bus	Up to 60 min/bus
Chargers required	One for every 3 – 4 peak buses	One for every 5 – 7 peak buses	One for every 6 – 8 peak buses
Charger Options	CCS corded SAE 3105-1 Overhead conductive Inductive Wireless	SAE 3105-1 Overhead conductive Inductive Wireless	SAE 3105-1 Overhead conductive
Compared to slow depot charging			
PROS (+)	• Fewer chargers required, and likely lower capital costs, especially for SAE 3105 Overhead conductive charging, due to the need for fewer pantographs		
CONS (-)	• Corded chargers likely limited to ~ 150 kW charge rate without cooled cords • Inductive wireless chargers likely limited to ~300 kW due to required space claim on bus for charge receiver • Will add operating costs for shifting buses through the chargers when charging is complete • Charger space claim likely higher than for slow charging, to allow for drive-through access to chargers		

CMBC Operational Analysis

This section summarizes the analysis of CMBC bus operations, and implications for transition to electric buses. The subjects covered include projected energy use on CMBC routes, range per charge and required bus replacement ratio if using depot charging, the required charging network if using in-route charging, projected electricity cost, and capital costs for charging infrastructure, for both depot charging and in-route charging. Estimated capital costs for charging infrastructure are based on conceptual charging designs developed by AES Engineering, and are specific to CMBC facilities.

C-1 Projected Electric Bus Energy Use

The energy required to operate an electric bus includes propulsion energy (i.e. driving) and energy to cool or heat the passenger cabin. Propulsion energy varies with average in-service speed on the route – the lower the average speed the more energy required (kilowatt-hours per kilometer, kWh/km), primarily because lower speed correlates to more stops per kilometer, which requires more energy to repeatedly accelerate from a stop.

The energy required for heating and cooling varies with temperature – the lower or higher the ambient temperature the more energy is required. In the case of an electric bus, the energy required for heating during cold weather is significantly greater than the energy required for cooling during hot weather. Available in-use data indicates that the average daily cooling load (air conditioning) is approximately 2.5 kilowatts (kW) when ambient temperature is 27 °C, while the average daily heating load could be as high as 14 kW (electric resistance heating) when the ambient temperature is -18 °C.

See figure C-1 for the historical average monthly high and low temperature in Vancouver. Historically the annual average high temperature is 17 ° C (in July and August), but could reach 22 °C or higher. The annual average low temperature is 3 °C (in January), but could fall below 0 °C.

See Figure C-2 for a summary of the estimated energy use by 40-ft electric buses in service on CMBC routes. The average in-service speed of the different CMBC routes ranges from 13 kph to 36 kph[52]. As such, the estimated energy required for propulsion will range from 1.26 – 1.70 kWh/km, depending on the route. On the coldest winter day (0 °C), the additional energy required for cabin heating will add 0.22 – 0.62 kWh/km, for a total load of 1.48 – 2.31 kWh/km.

[52] This range does not include highway routes, which have higher average speed

Across the entire year, average 40-ft bus energy use is projected to total 1.37 – 2.00 kWh/km for the different routes, including both propulsion and heating/cooling. Average energy use for all 40-ft buses in the fleet is projected to be 1.60 kWh/km across the year, and 1.79 kWh/km on the coldest winter days. 60-ft electric buses are projected to use proportionally more energy, based on their greater weight; a fleet average of 2.15 kWh/km across the year, and a fleet average of 2.42 kWh/km on the coldest winter days.

Figure C-1 Average High and Low Temperature, Vancouver, BC

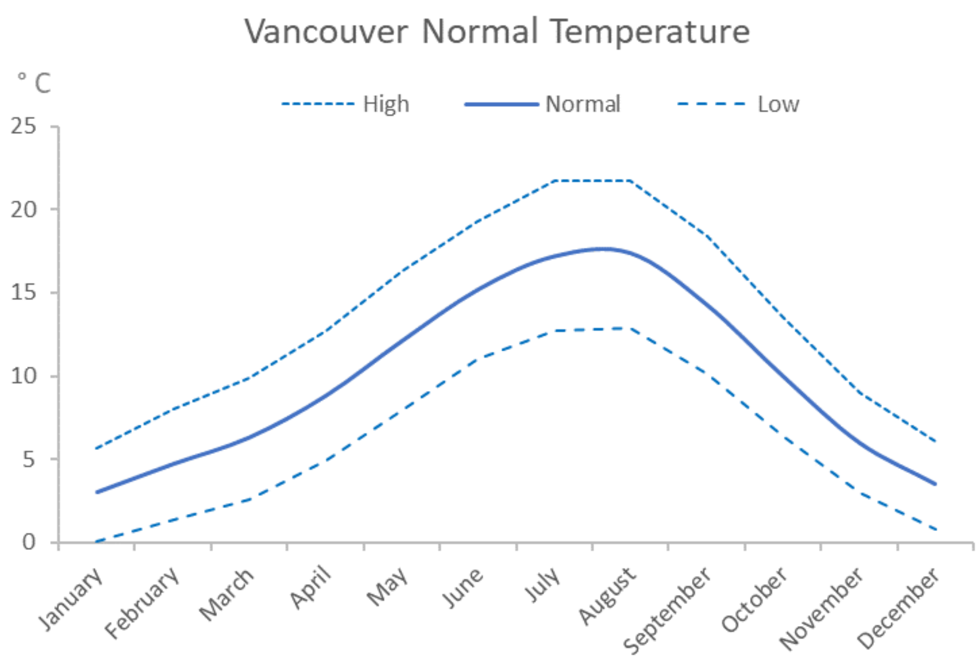
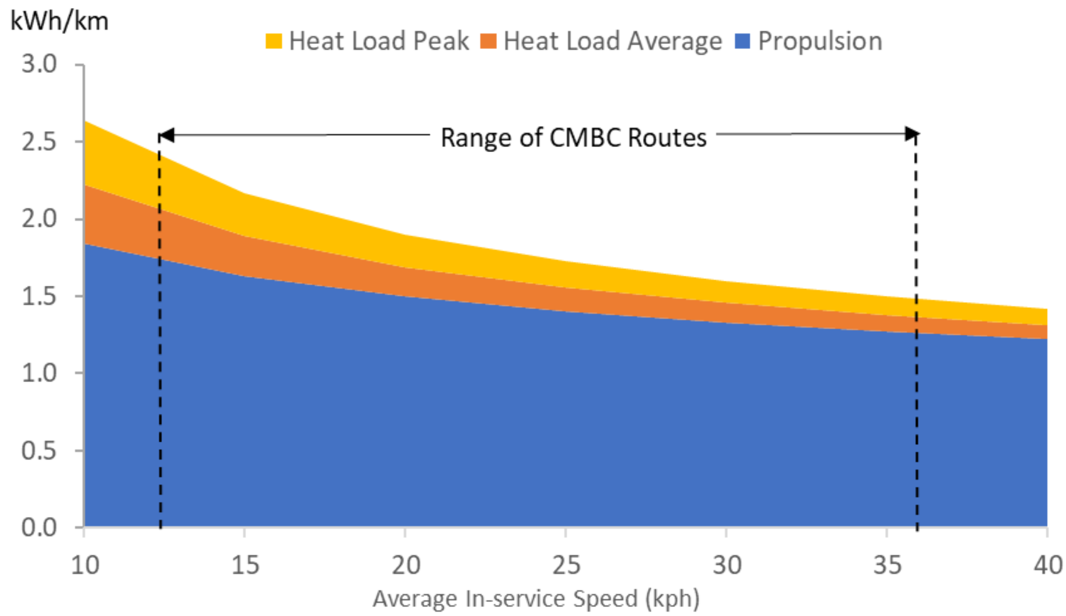


Figure C-2 Projected 40-ft Electric Bus Energy Use in CMBC Service



C-2 Depot Charging Analysis

This section summarizes the analysis of cost and operational considerations for CMBC fleet electrification using over-night depot charging of electric buses. The analysis encompasses estimated range per charge on different CMBC routes and the resulting number of electric buses that would be required to replace existing diesel buses (replacement ratio); estimated daily depot charging load and electricity cost; and infrastructure costs for installing the necessary chargers at CMBC depots.

C-2.1 Range per Charge & Replacement Ratio

As discussed in section Appendix A, for most manufacturers the nameplate energy capacity of the largest battery currently available on 40-ft buses is 450 kWh; the exception is Proterra which offers battery packs as large as 660 kWh. This is the theoretical capacity when the battery pack is new[53], but not all that energy is available for use. Batteries degrade (i.e. lose capacity) as they are charged and dis-charged over time, and this degradation typically accelerates if the battery is regularly fully discharged. Most battery manufacturers recommend that batteries not be discharged below 15-20 percent of capacity on a regular basis when new – as batteries age this

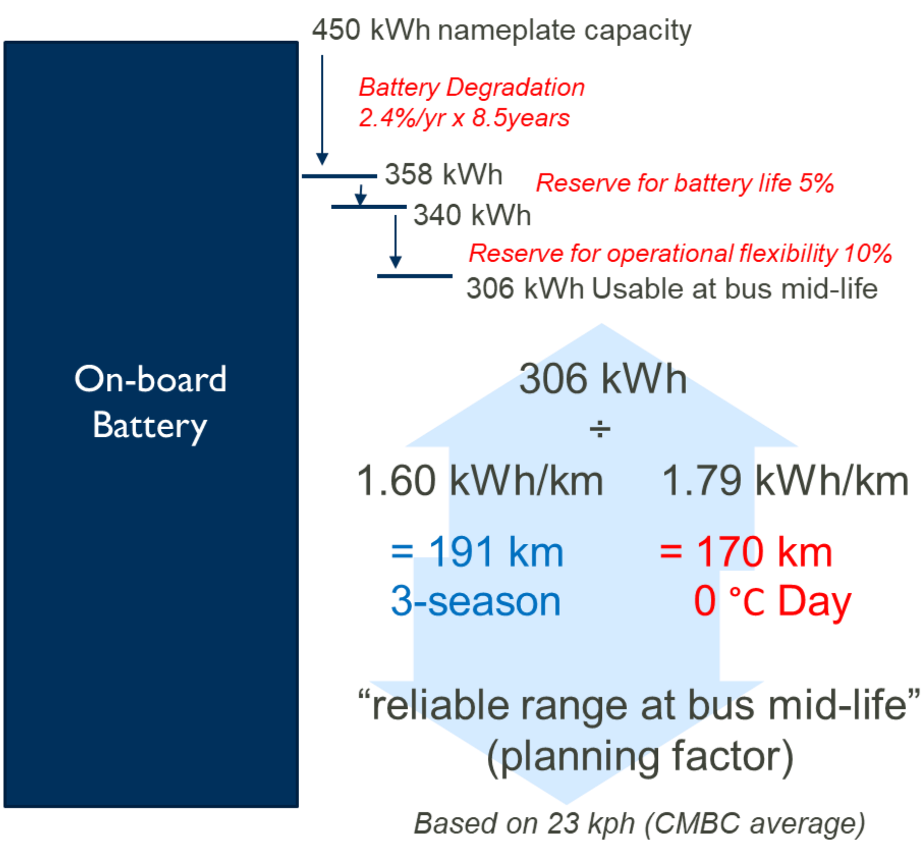
[53] The actual maximum capacity may be slightly higher than stated; some manufacturers publish figures that include a small safety margin.

discharge window can be opened, to allow discharge down to 5% of capacity near battery end-of life.

Even when not fully discharged batteries will lose capacity. Based on manufacturer warranties, MJB&A estimates that capacity loss could be as high as 2.4 percent per year – so that by the time a battery has been in service for 8.5 years (bus mid-life) it will only retain about 80 percent of its original capacity, and by bus end-of life at 17 years it will retain only 59 percent of its original capacity.

When planning for fleet electrification using depot charging, MJB&A recommends that transit agencies plan to replace electric bus batteries at bus mid-life, and that peak bus requirements be based on the “reliable” range (kilometers) that can be achieved just before the battery is replaced.

Figure C-3 Calculation of 40-ft Bus Reliable Range at Bus Mid-life



The calculation of reliable range should be based on projected average energy use (kWh/km) but should account for the fact that on any given day a given bus could use more than the average, based on factors such as traffic, passenger loading, and driver behavior; we recommend using 110% of the projected average to account for these factors. If the passenger cabin will be heated electrically, using energy from the battery, the calculation of reliable range should include energy used for cabin heating, and be based on the expected coldest day, not the annual average heat load. For buses that will use supplemental fuel heaters reliable range can be based on projected annual average energy use.

See Figure C-3 for an example of reliable range calculation, which accounts for both projected battery degradation and variability in daily energy use, using projected average energy use in CMBC service. As shown, with a 450-kWh battery, at bus mid-life only 306 kWh (68%) will be reliably available. Assuming average annual energy use of 1.6 kWh/km, from a planning perspective buses in average CMBC service can be assumed to have a reliable range of 191 kilometers per charge most of the year. However, unless supplemental fuel heating is used, range per charge in average CMBC service will fall to only 170 kilometers on the coldest winter days in Vancouver.

See Table C-1 for a summary of the projected reliable range per charge, at bus mid-life, of 40-ft depot-charged electric buses operating on routes assigned to the different CMBC transit centres[54].

With only electric heat, electric buses at the different transit centres will have a reliable range per charge at bus mid-life of 149 - 184 kilometers if equipped with a 450-kWh battery (industry norm), or 170 – 203 kilometers if equipped with a 660-kWh battery (industry best). If buses are equipped with supplemental fuel heat projected range per charge will increase by approximately 20 kilometers with a 450-kWh battery or 30 kilometers with a 660-kWh battery.

Currently, the maximum battery size available on 60-ft electric buses is 600 kWh. With this sized battery, 60-ft electric buses are projected to have similar range per charge in CMBC service as 40-ft buses with a 450-kWh battery: 150 – 185 km if equipped with only electric heat, and 173 – 205 km if equipped with supplemental diesel heat.

[54] In Table 8, data for transit centres other than VTC, BTC, and MTC are based on current operations. When MTC opens some routes will be moved between depots; the most affected depots will be BTC and VTC. The data in table 8 for VTC, BTC, and MTC is based on anticipated route assignments as of 2025.

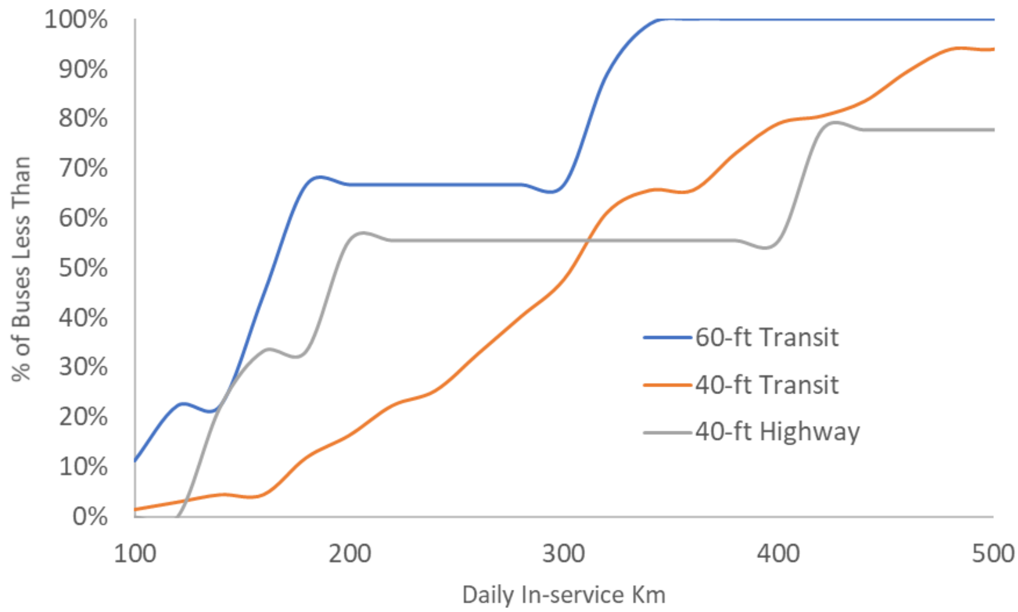
Table C-1 Projected Range per Charge of 40-ft Buses on CMBC Routes, at Bus Mid-life

Depot	AVG SPEED	AVG Energy Use (kWh/km)		Range Per Charge (km)			
				450 kWh Battery		660 kWh Battery	
	KPH	Annual AVG	Peak Day	Elec Heat	Fuel Heat	Elec Heat	Fuel Heat
HTC	22.7	1.61	1.80	170	190	250	278
PTC	27.1	1.51	1.67	184	203	269	297
RTC	24.2	1.57	1.75	175	194	257	285
STC	26.7	1.52	1.68	183	201	268	295
VTC	17.2	1.79	2.03	150	171	221	251
BTC	17.1	1.79	2.04	150	171	220	250
MTC	16.9	1.80	2.05	149	170	219	249

The average daily driving distance for 40-ft and 60-ft transit buses operated by CMBC ranges from 202 – 303 kilometers per day at the different transit centres. Highway buses average over 330 kilometers per day at all three locations from which they operate. While this is the average daily driving distance, a significant number of buses regularly exceed this value, due to the way CMBC schedules service. Typically, about 30 percent of buses leave the depot early in the morning and do not return until late afternoon or evening. Other buses leave the depot in the morning to cover the AM peak commuting period, then return to the depot at about 10 AM, since fewer buses operate mid-day. These same buses will likely then leave the depot again in mid-afternoon to provide additional service for the afternoon peak commuting period and return in the early evening.

See Figure C-4, which shows the distribution of mileage accumulated on a typical weekday by buses operating from the Port Coquitlam Transit Centre (PTC); other transit centres have similar distributions. Forty-foot transit buses at PTC average 314 kilometers per day, and about 50 percent of buses accumulate less mileage than this, but about 50 percent accumulate more mileage – with some buses driving more than 500 kilometers per day. Highway coaches at PTC have a similar distribution, but 60-ft buses do fewer miles. On average 60-ft buses at PTC only drive 200 kilometers per day, but still 30 percent of buses drive more than 300 kilometers per day.

Figure C-4 Distribution of Daily Bus Mileage at Port Coquitlam Transit Centre

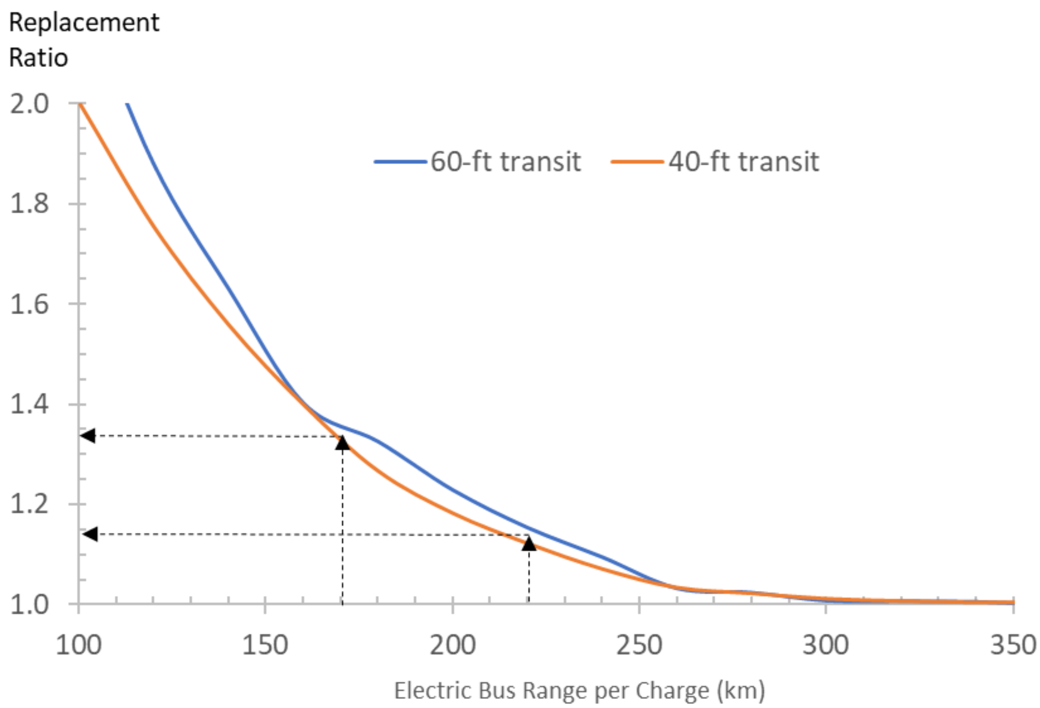


Given the projected range per charge values shown in Table C-1, to implement depot charging CMBC would need to change the way they schedule buses, to "break up" long daily bus assignments into shorter assignments that could be handled by an electric bus before needing to be re-charged. Doing this would increase the number of peak buses required, as discussed below.

To determine the number of depot-charged electric buses that would be required to maintain current service levels, MJB&A used the distribution of daily mileage at each transit centre and estimated electric bus range per charge at mid-life to calculate a "replacement ratio" for depot-charged electric buses in CMBC service[55]. The replacement ratio is the proportional number of electric buses that would be required to replace one diesel bus, due to limits on range per charge. A replacement ratio of 1.0 means that one electric bus can take the place of one diesel, hybrid-electric, or CNG bus. A replacement ratio of 1.2 indicates that 20 percent more electric buses would be required – i.e. every 100 diesel buses would need to be replaced with 120 electric buses due to the range restrictions of electric buses.

[55] For this calculation, all daily bus assignments less than estimated range per charge are assumed to have a replacement ratio of 1, and all daily bus assignments greater than estimated range per charge are assumed to have a replacement ratio calculated as daily miles divided by range per charge. A weighted average replacement ratio is then calculated for all daily bus assignments.

Figure C-5 Electric Bus Replacement Ratio versus Range per Charge at Marpole Transit Centre



See Figure C-5 for a plot of replacement ratio versus electric bus range per charge for 40-ft and 60-ft transit buses operating from Marpole Transit Centre (MTC)[56]. At MTC, if either a 40-ft or 60-ft electric bus had only 170 kilometers range per charge the replacement ratio would be about 1.35 – i.e. 35 percent more electric buses would be needed than diesel buses. If the electric buses had 220 kilometers range per charge only about 15 percent more buses would be required (1.15 replacement ratio). To be able to replace diesel, hybrid, or CNG buses one-for-one with electric buses at MTC, the electric bus range per charge would need to be greater than 300 kilometers.

See Table C-2 for a summary of projected replacement ratios for the different bus types operating from each CMBC transit centre. The replacement ratios in Table C-2 assume a 500-kWh battery pack for 40-ft buses and a 660-kWh battery pack for 60-ft buses; these are projected "industry norm" battery pack sizes for electric buses purchased in 2023 – 2026, accounting for projected further improvements in battery energy density. The values in Table C-2 also assume that buses will be equipped with supplemental fuel heaters, which will reduce battery energy demands on cold winter days, resulting in longer range.

[56] This is based on the routes projected to be assigned to MTC when it opens.

Table C-2 Projected Replacement Ratio for CMBC Depot Charging

Transit Centre	Bus Type		
	40-ft Transit	40-ft Highway	60-ft Transit
HTC	1.17	NA	1.21
PTC	1.43	1.36	1.15
RTC	1.33	1.37	1.22
STC	1.35	1.66	1.55
VTC	1.15	NA	1.13
BTC	1.15	NA	1.21
MTC	1.18	NA	1.13

As shown, the projected replacement ratio for depot-charged electric buses ranges from a low of 1.15 (40-ft transit buses at BTC and VTC) to a high of 1.66 (highway buses at STC). Projected depot charging replacement ratios for all bus types are significantly higher at PTC, RTC, and STC than at the other transit centres, due to higher average daily mileage accumulation at these depots. At all depots from which they operate highway buses have very high daily mileage and very high depot charge replacement ratios.

For buses not equipped with supplemental fuel heaters, projected range on cold winter days would be lower, and replacement ratios would be higher than that shown in Table 9 for all bus types at all transit centres; compared to electric buses with supplemental fuel heaters, about 10 percent more buses would be required if they were equipped with only electric heat.

The required increase in the bus fleet to implement depot charging has multiple effects:

- Capital costs will increase to purchase additional buses
- Capital costs will increase to purchase additional depot chargers
- Additional parking space will be required at CMBC depots
- Long daily bus assignments will need to be shortened, to turn buses back to the depot sooner than current practice. This will increase dead-head mileage.

C-2.2 Depot Charging Load & Electricity Cost

Currently, CMBC would be subject to local utility BC Hydro's Large General Service (LGS) rate for all electricity used to charge electric buses. This rate includes energy charges (dollars per kilowatt-hour, $/kWh) for all energy used, as well as demand charges (dollars per kilowatt, $/kW) based on monthly peak demand. BC Hydro has recently proposed to the British Columbia

Utilities Commission (BCUC) several options for special electric vehicle rates designed to incentivize electric vehicle adoption by lowering net electricity costs, especially for charging during "off-peak" periods.

See Table C-3 for a summary of the rate components of BC Hydro's LGS rate and the three proposed EV rates.

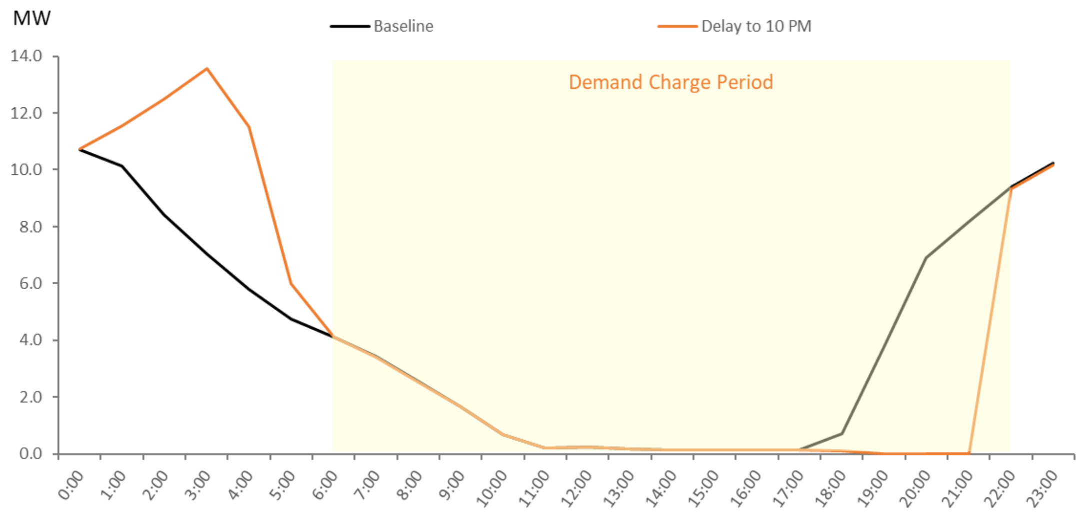
Table C-3 BC Hydro Electricity Rates

RATE	Demand Charge		Energy Charge ($/kWh)			
	$/KW	Period	11 PM – 7AM	7 AM – 4 PM	4 PM – 9 PM	9 PM -11 PM
LGS	$12.34	All-day	$0.061			
EV1	$12.34	6AM – 10 PM	$0.072			
EV2	$12.34	7AM – 10 PM	$0.060	$0.115	$0.147	$0.115
EV3[1]	$0	NA	$0.090			
[1] Applies only for the first five years, then will revert to LGS						
EV rates have been proposed but not yet approved						

BC Hydro's LGS rate applies the demand charge to the highest demand over any 15-minute period throughout the month, regardless of what time of day this peak happens, and energy charges are also the same regardless of when the energy is used. EV rates 1 and 2 keep the magnitude of demand charges the same as LGS ($12.34/kW), but they apply only to monthly peak demand during the time period 6 AM to 10 PM, or 7 AM – 10 PM. EV rate 2 additionally charges different energy rates by time of day, with the lowest rate between 11 PM and 7 AM, and the highest rate between 4 PM and 9 PM, which is typically the time of day when over-all regional electricity demand is highest. EV rate 3 has no demand charge, but the energy charge ($/kWh) is 50 percent higher than under the LGS rate.

See Figure C-7 for the projected weekday charging load at Marpole Transit Centre, assuming an average charge rate of 50 kW per bus. If charging at 50 kW, the average charge time will be between 5 and 7 hours per bus per day; there is enough time over-night to complete charging before buses need to pull out for morning peak service, and mid-day charging will not generally be required.

Figure C-7 Projected Weekday Charging Load for Depot Charging at MTC



The shape of the load curve will be similar for other transit centres, but the magnitude of the load (kW) will vary by location, in proportion to the number of daily peak buses. In Figure C-7 the baseline (black) load curve assumes that each bus will plug in and start to charge about one hour after returning to the transit centre in the afternoon or evening. The orange load curve shows the effect of delaying charge start for all buses to after 10 PM, to coincide with the time period of zero demand charges under BC Hydro's proposed EV rates. Baseline charging load peaks at about 10.5 megawatts (MW) at about midnight. If charge start is delayed to 10 PM peak charging load is shifted to about 3 AM, and also increases to 13.5 MW.

See Table C-4 for a summary of the projected average electricity cost for depot charging at CMBC transit centres under the different BC Hydro rates, based on the load profiles in Figure C-7. Under the baseline charging scenario electricity is projected to cost an average of approximately $0.12/kWh under all rates except EV3, where it would be $0.09/kWh for the first five years and $0.12/kWh in subsequent years.

If CMBC were to delay the start of depot charging until 10 PM, the average cost of electricity would go up to $0.13/kWh under the current Large General Services rate but would fall to approximately $0.09/kWh under all of the proposed EV rates. Note that average electricity costs could be as low as $0.07/kWh (under rate EV1) if there was no depot charging demand between 6 AM and 10 PM. However, this may not be feasible for CMBC bus operations; charging for a small number of late-returning night buses may need to take place either between 6 AM and 10 AM, or mid-day after morning peak service. The ability to finish charging these late returning buses before 6 AM would be enhanced if TransLink employed charging systems that provide three charge heads supplied by a single 150 kW inverter, such that in the early morning after most buses had finished charging these late-returning buses could charge at rates up to 150 kW each (see Section B-1).

Table C-4 Projected Depot Charging Electricity Cost

Charging Scenario	Rate			
	LSG	EV1	EV2	EV3
Baseline	$0.117	$0.115	$0.128	$0.090
Delay to 10 PM	$0.132	$0.094	$0.089	$0.090

Based on 1.6 kWh/km projected energy use, and an average electricity cost of $0.09/kWh (EV rates), energy costs for 40-ft depot-charged electric buses operated by CMBC are projected to average $0.144/km; this compares to average fuel costs of $0.623/km for CMBC diesel buses and $0.493/km for CMBC hybrid buses[57].

C-2.3 Depot Charging Infrastructure Design and Cost

As part of the Low Carbon Fleet Strategy development process AES Engineering developed conceptual designs for implementation of depot charging at two CMBC transit centres, the Burnaby Transit Centre (BTC) and the new Marpole Transit Centre (MTC). These locations were chosen because they were identified as the easiest locations to implement depot charging, due to lower daily mileage accumulation and lower electric bus replacement ratios on the routes which operate from these locations. BTC would represent a retrofit of an existing location, while MTC would represent a new depot designed for electric buses.

For each location AES evaluated four options for charging buses while parked overnight at the transit centre: 1) use of ground-mounted CCS corded chargers, 2) use of overhead-mounted CCS corded chargers, 3) use of overhead-mounted SAE J3105-1 conductive - pantograph chargers, and 4) use of wireless chargers.

For each option the following major assumptions were used:

- Nominal peak charging load of 50 kW or 75 kW per bus
- One charger provided at each bus parking space

[57] CMBC 40-ft diesel buses average 0.599 l/km and 40-ft hybrid buses average 0.474 l/km. CMBC currently pays a net cost of $1.04/l for diesel fuel.

- At BTC all bus parking is outdoors, uncovered; at MTC bus parking areas would be covered by an employee parking deck, due to site space constraints

The issues explored by AES in their conceptual designs included the lay-out and space claim of charging heads and power modules, required upgrades/expansion of building electrical systems to accommodate the new load, and distribution of power from the utility meter to the charging locations.

See Figures C-8 to C-10 for conceptual views of how each option would look at BTC. For ground-mounted corded chargers (Figure C-8), a new raised curb would need to be installed between every two bus parking lanes to hold the chargers, which would be in the middle of this lane toward the rear of each designated bus parking space.

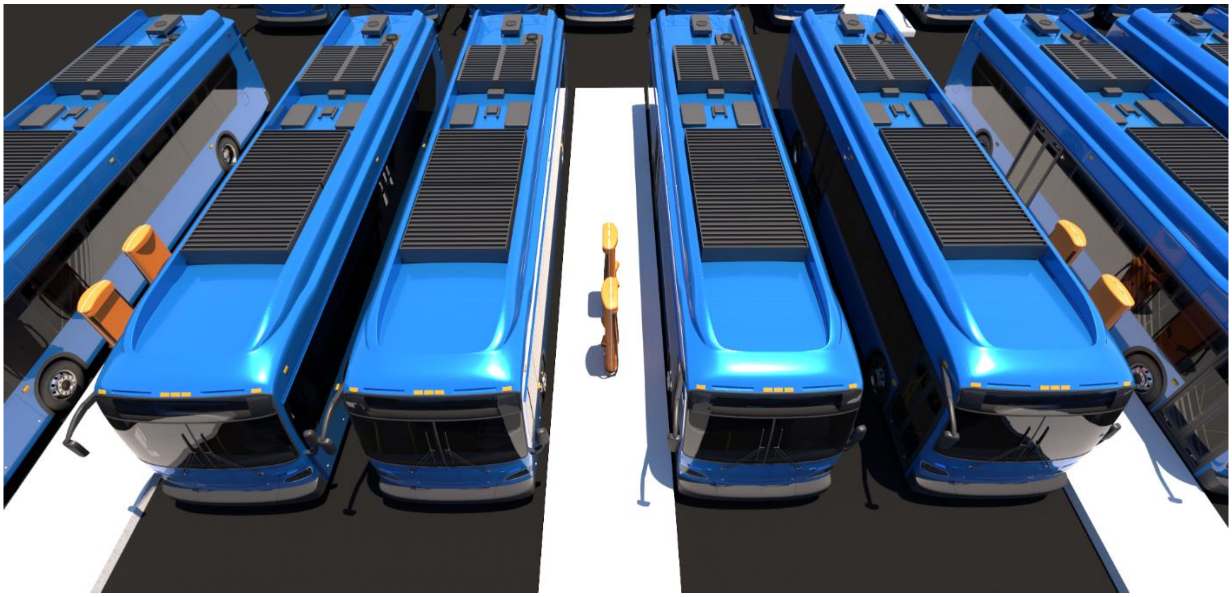
Buses would need to be equipped with two charge ports - on the rear curb-side and rear street-side of the bus – so that buses on each side of the charge lane could access a charger. Power would be distributed to each charger in underground conduit beneath each charger curb lane.

The new curbs required to hold chargers would reduce existing parking capacity by 20 - 25 percent, depending on charger manufacturer. BTC would be reduced from 129 40-ft parking spaces and 97 60-ft parking spaces to 102 – 111 and 81 – 85 parking spaces, respectively.[58] At MTC only 280 40-ft equivalent bus parking spaces could be provided at ground level, compared to the planned 300 spaces.

The main advantage of mounting chargers overhead, instead of on the ground, is that they would take up less space, since you would not need a new raised curb between every two parking lanes. However, because bus parking is outdoors, uncovered at BTC (and all of CMBC's current transit centres), over-head mounting of corded chargers would require a gantry structure to be installed across all parking lanes at each parking location (see Figure C-9). At BTC 25 gantries of varying lengths would be required; the chargers would be installed on the gantries. Power would be distributed to each charger in conduits running along each gantry. Under this scenario only one charging port would be required on each bus, but each charger would need to have an appropriate cable management system to ensure cords do not interfere with bus movements after disconnection.

[58] BTC includes two locations across the street from each other. BTC North has parking for 60-ft buses and BTC South has parking for 40-ft buses.

Figure C-8 Depot Charging with ground-mounted CCS corded chargers



Source: AES Engineering

Figure C-9 Depot Charging with overhead-mounted corded chargers

Source: AES Engineering

The new MTC has not yet been designed, but given the size of the available site, and planned capacity of 300 forty-foot equivalent buses, it has already been determined that employee parking will need to be located on a parking deck above the bus parking area. Under this scenario, overhead-mounted chargers could be hung from this parking structure, and a separate gantry structure would not be required.

If chargers were mounted overhead at BTC no current bus parking spaces would be lost[59]. At MTC, overhead mounting of chargers would also result in no loss of bus parking space compared to current plans, but the clearance below the employee parking deck would likely need to increase by two meters.

To use SAE J3105-1 conductive chargers for depot charging, instead of corded chargers, a pantograph must be installed overhead at each bus parking space. Under this scenario buses would not need to be plugged in and unplugged to charge - to initiate a charge the pantograph would move down to connect with charge rails installed on the roof or the bus, and then would move up when charging was complete. This is the same method used for in-route charging - see Appendix B.

See Figure C-10 for how this might look at BTC; the pantographs would be installed on overhead gantries, like overhead-mounted corded chargers. The power modules required to convert alternating current grid power to direct current for charging could also be installed on the gantries, or in a lane parallel to the bus parking lanes. At MTC the pantographs would be mounted to the underside of the overhead employee parking structure, and the power modules could either be located on the employee parking level, or on the bus parking level.

Each bus will need to be able to charge at an average rate of 50 kW. However, the system can be set up to have one 150 kW power module feeding three pantograph chargers. Under this scenario a given bus could charge at up to 150 kW, as long as the other two pantographs on the same module were not actively charging.

Overhead pantograph charging may reduce parking capacity at either BTC or MTC by up to 5 percent - to accommodate the space claim of required power modules. The main advantage of SAE J3105-1 pantograph chargers over corded chargers for depot charging is significantly reduced operational complexity, since buses will not need to be plugged in and unplugged each day. In addition, corded chargers are likely to suffer cord damage from bus movements, which will not be an issue with pantograph charging.

[59] The conceptual design of the gantry structure was optimized to reduce its impact on parking spaces.

Figure C-10 Depot Charging with SAE J3105-1 conductive pantograph chargers

Source: AES Engineering

Table C-5 Projected Cost of Depot Chargers at BTC and MTC

Transit Center	Metric	Corded Ground-mounted	Corded Overhead-mounted	SAE J3105 Overhead Pantograph
BTC	Bus Parking Spaces[1]	197	226	220
	Total Cost ($)	$18,124,000	$38,646,000	$66,660,000
	$/charger	$92,000	$171,000	$303,000
MTC	Bus Parking Spaces[1]	280	350[2]	340
	Total Cost ($)	$25,760,000	$36,400,000	$80,240,000
	$/charger	$92,000	$104,000	$236,000

[1] Maximum possible at ground level on existing (BTC) or planned (MTC) site
[2] Clearance below planned employee parking deck will need to be greater if overhead chargers installed

See Table C-5 for a summary of the estimated cost of installing depot charging infrastructure at BTC and MTC[60]. This includes all costs on the customer side of the meter to distribute the necessary power and install a charger at each bus parking space. This estimate includes 10 percent construction contingency but does not include the cost of design, permitting, project management, or financing costs.

As shown in Table C-5, ground-mounted corded chargers are projected to be the least expensive option at both depots, costing just over $90,000 per charger. Overhead mounting of corded chargers is estimated to add an additional $79,000 per charger at BTC, but only $12,000 at MTC; this is because a gantry structure would be required at BTC, but at MTC chargers could be hung from the already planned employee parking deck to be installed over the bus parking area.

Compared to overhead-mounted corded chargers, cordless conductive charging using pantographs is estimated to add $132,000 per charger at either depot, due to the additional purchase and installation costs of the pantographs[61].

For the other CMBC transit centres the cost of depot chargers is projected to be similar to costs at BTC, because these sites would require a similar design and have similar constraints.

Table C-6 BC Hydro Depot Charging Upgrade Costs

Transit Centre	BC Hydro Upgrade Cost	
	Total	Approx $/charger
BTC	$650,000	$2,600
HTC	$11,000,000	$55,000
PTC	$350,000	$1,500
RTC	$4,500,000	$20,000
STC	$1,000,000	$4,500
VTC	$3,900,000	$8,700
MTC	$2,400,000	$6,900

In addition to the costs shown in Table C-5, installation of depot chargers would require BC Hydro to provide additional electrical services. See Table C-6 for BC Hydro's estimate of the primary service upgrade cost at each CMBC transit centre. BC Hydro upgrade costs would add less than $10,000/charger at all transit centres except RTC and HTC. The very high costs at HTC result from insufficient capacity at the closest substation, which would require installation of a new 12-kilometer feeder cable to serve the load from the next closest substation with available capacity.

[60] These cost estimates were developed by AES Engineering, based on their conceptual charging designs for each site.

[61] Estimated costs for overhead pantograph connectors are based on current commercial offerings. There are reportedly efforts underway to reduce the cost of overhead pantograph connectors for depot-based charging, but there is insufficient information at this time to accurately project how pantograph costs may change in the future.

In addition to the cost of installing the chargers themselves, and upgrading the primary BC Hydro service, implementation of depot charging for a significant number of buses will require CMBC to acquire or build additional depot space, to accommodate both the space claim of the chargers and the need to purchase additional buses to maintain current service levels. As noted above, even overhead-mounted chargers (corded or pantograph) may result in up to 5 percent loss of bus parking spaces at both BTC and MTC. As discussed above, implementation of depot charging at BTC and MTC will also require approximately 15 percent more buses to maintain current service levels due to range restrictions of electric buses; at other depots even more buses would be needed - at least 30 percent more at PTC, RTC, and STC.

Implementation of depot charging with overhead chargers at BTC and MTC would require an additional 100 - 110 40-ft equivalent bus spaces somewhere in the system. Some options for accommodating this need include:

- Demolish an existing maintenance building at BTC North and expand bus parking into this space. This building houses fleet-wide support activities (office, shop, and warehouse space) that could be moved to another site without compromising functionality or increasing operating costs.
- Build a ninth transit center on a new site.

TransLink estimates that the cost of expanding bus parking at BTC North, including relocating existing functions, is in the range of $50 million. The cost of adding a ninth depot is unknown at this time.

C-3 In-route Charging Analysis

This section summarizes the analysis of cost and operational considerations for CMBC fleet electrification using in-route charging of electric buses. The analysis encompasses the estimated number and location of required in-route chargers (charging network); estimated charging time and effect on daily bus schedules; estimated daily charging load and electricity cost; and infrastructure costs for installing the necessary chargers along CMBC bus routes.

C-3.1 Required Charging Network

MJB&A analyzed the existing CMBC route network and service levels to develop a high-level conceptual design for the in-route charging network required to support fleet electrification using in-route charging. For each route, MJB&A analyzed one-way trip time (minutes), projected one-way trip energy use (kWh), and estimated charging time (minutes) to replenish the energy used, assuming 450 kW in-route chargers. This charging time was then compared to bus head-way (minutes between buses) to determine whether charging would be required on only one end of the route (one charge per round-trip), or on both ends of the route (one charge per one-way trip), and how many chargers would be required on the route in order to keep charging time less than bus headway and make sure that all buses could charge on every trip.

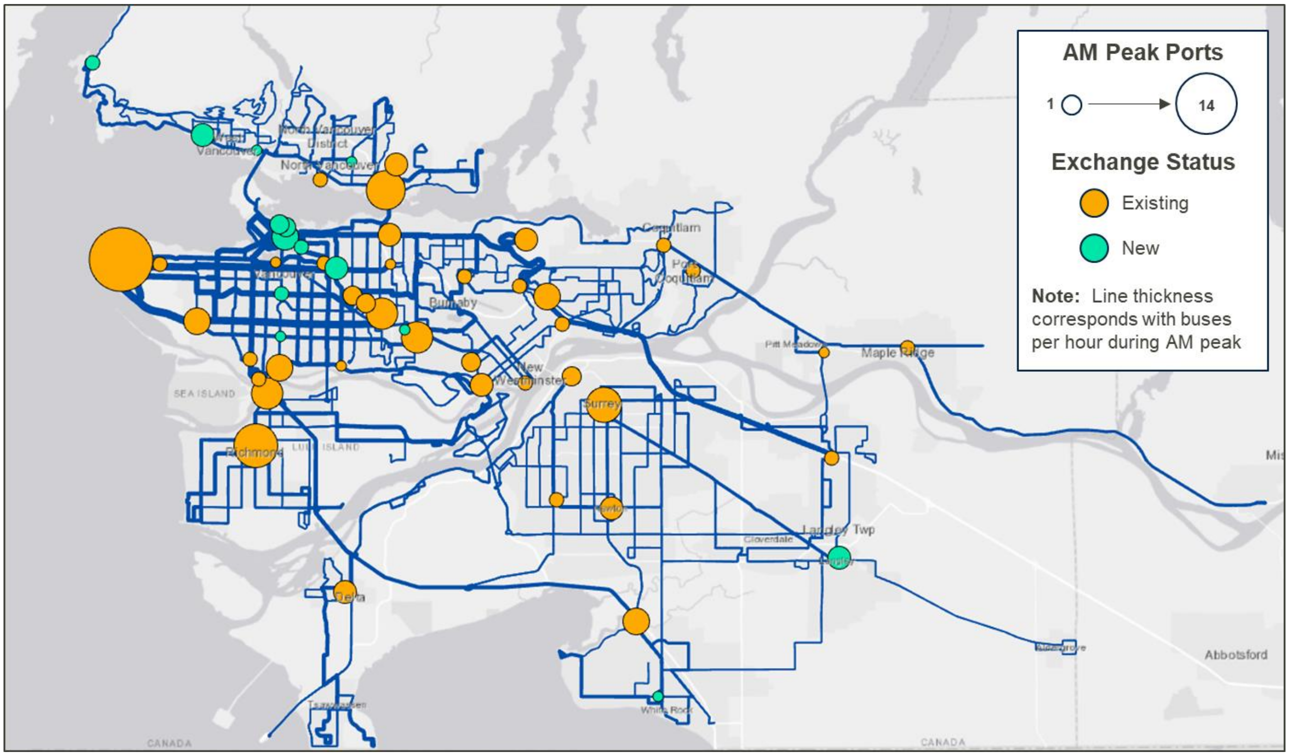
Next, MJB&A identified potential locations to locate in-route chargers. Considerations when identifying potential charging locations included:

- Minimize the total number of charging locations while also attempting to keep the number of chargers at any one location less than five
- Prioritize charging locations at route termini; only allow mid-route charging when no reasonable alternative exists
- Try to keep charging time at any charger less than six minutes; only allow longer charging time if it allows only one charge location on the route or allows travel all the way to the route terminus, and charge time is still less than route headway
- If possible, locate chargers at existing off-street bus exchanges. For necessary charging locations not at existing bus exchanges, locate at TransLink owned/controlled property if possible (i.e. SkyTrain Stations)

The existing off-street bus exchanges are generally located at route termini where several routes come together so that passengers can easily change between routes. The exchanges include marked bus bays where passengers load/unload and other bus parking spots for buses to lay-over between runs. Not every CMBC route has an off-street exchange. On some CMBC routes buses lay-over at designated locations on the street at the curb. Because the exchanges are already bus lay-over locations, and are located at route termini, they are ideal locations for in-route chargers.

See Figure C-10 for the resulting conceptual in-route charging network which would be required to serve all CMBC routes if every 40-ft and 60-ft bus (including current trolleys) was battery electric and all used in-route charging. This network is based on projected service levels in 2025, after the opening of the new Marpole Transit Center. This full network would require a total of 178 chargers at 53 different locations; this equates to one charger for approximately every seven peak buses (or one for every 8 total buses). Of the 53 locations identified as requiring chargers, 39 are existing off-street bus exchanges, and 14 are new locations. These new locations where chargers would be required are generally located at route termini.

Figure C-10 Conceptual In-route Charging Network for CMBC Service Area – Full System



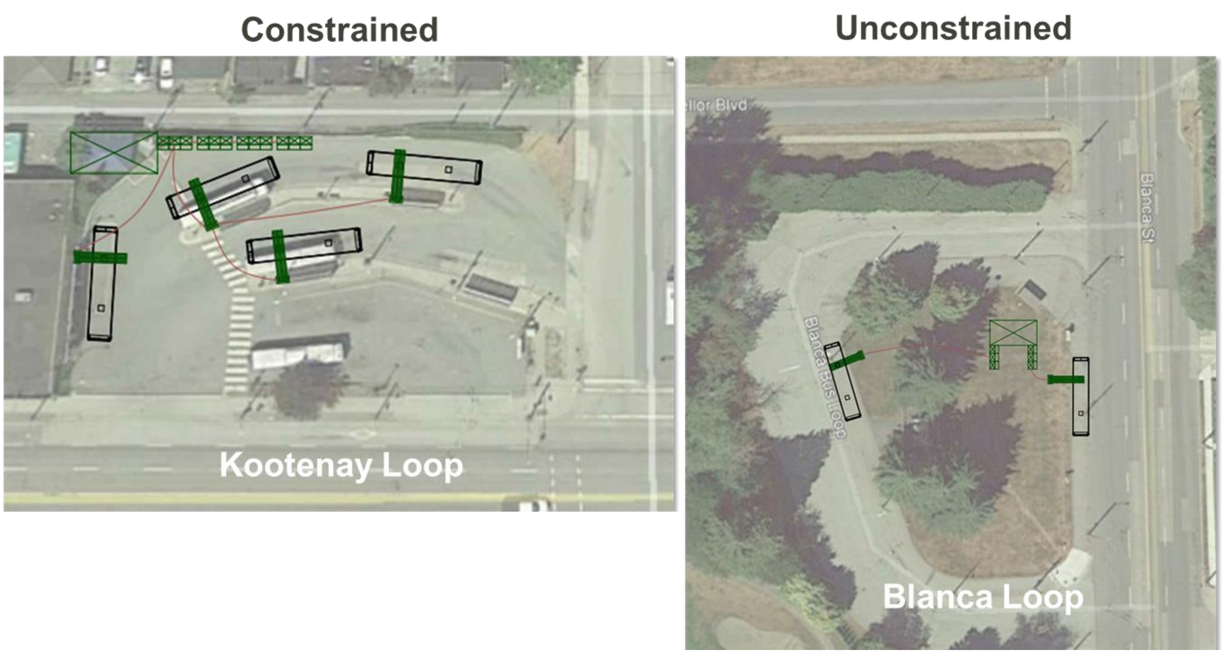
Of the potential charging locations shown in Figure C-10, twenty-six (49 percent) will require either one or two chargers, 20 locations (38 percent) will require 3 – 5 chargers each, and seven locations will require more than five chargers. The largest potential charging location is UBC Loop (the largest circle in Figure C-10, on the extreme left of the figure), which will require as many as 14 chargers. UBC Loop is a very large existing off-street bus exchange which serves ten different bus routes. Most of the routes served by UBC Loop also require charging at both route termini which means that the only way to reduce the required number of chargers there is to either use depot charging for some of these routes, or to do mid-route charging on these routes.

Note that the network designs shown in Figures C-10 is conceptual only and is intended to evaluate high-level feasibility and cost. Some of the specific charging locations identified may need to change due to site constraints. The local utility, BC Hydro, reviewed their power distribution system in the vicinity of all the potential charging sites shown in Figure C-10, to identify any power constraints; their review identified only three locations at which there was insufficient capacity to supply the estimated number of chargers required, at reasonable cost.

AES Engineering also did a high-level review of all these locations to evaluate available space for charging infrastructure and bus queuing, and ease of power access. Their review indicates that at about 35 percent of the sites installation of chargers would be relatively easy– there is enough space to install the necessary equipment and doing so will require no changes to existing pavements, curbs, or structures on the site. The remaining sites have some constraints that would make installation of the necessary chargers more difficult and costly. See Figure C-11 for an example of a constrained and unconstrained site.

Kootenay Loop is shown on the left in Figure C-11; this site could require up to four chargers, but there is insufficient space to do so. Installing four chargers at this location would require major changes to the existing site layout and/or acquisition of additional land. Blanca Loop is shown in the right of Figure C-11; this site would require up to two chargers and has enough space to do so without any changes to the existing site layout. See below for a discussion of how site constraints affect the cost of in-route charger installation.

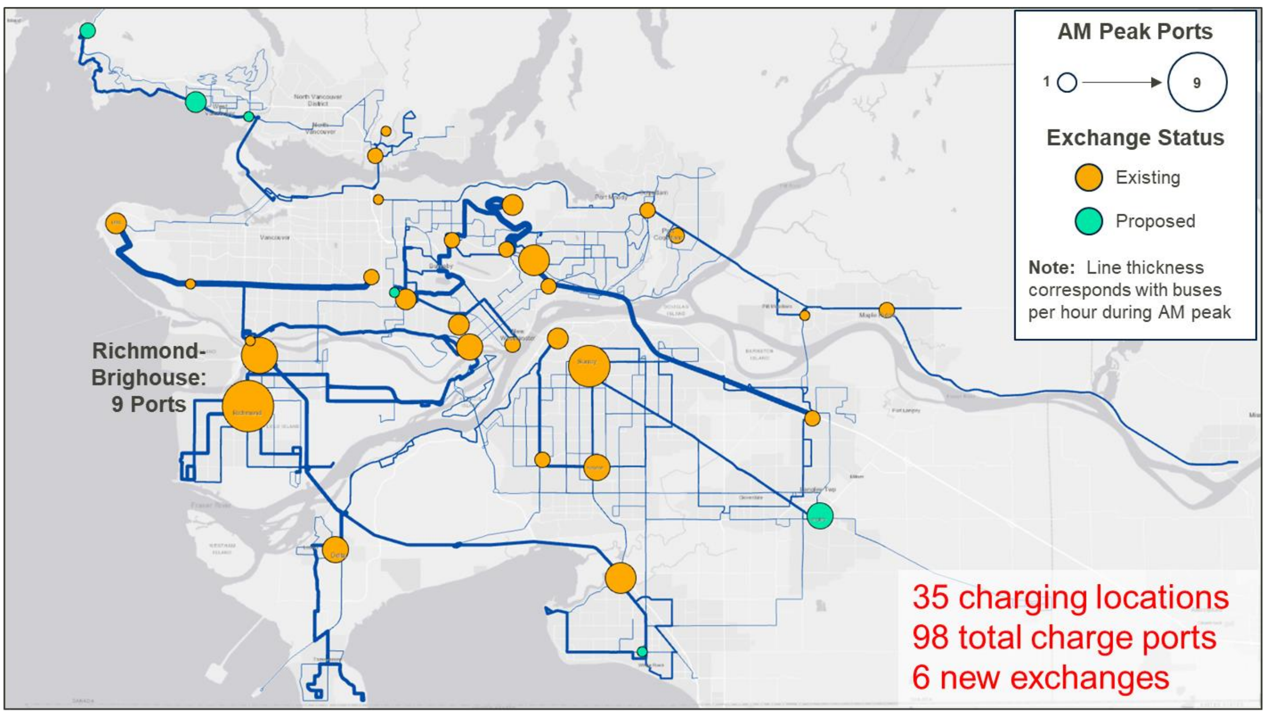
Figure C-11 Examples of Constrained and Unconstrained In-route Charging Locations



Also note that the conceptual charging network shown in Figure C-10 is for a full roll-out of in-route charging for all 40-ft and 60-ft buses operated by CMBC, including on routes that are currently trolley routes. If trolley routes continue as they are (no in-route charging required) the remaining 40-ft and 60-ft bus routes would require only 47 in-route charging locations with a total of 155 chargers. As discussed above the CMBC transit centres at which it would be easiest to implement depot charging are VTC (which is mostly trolleys), MTC, and BTC. If all three of these transit centres implemented depot charging, the in-route charge network required for the routes which operate from the remaining CMBC transit centres would include 98 chargers at 35 different locations, only six of which are new exchanges; see figure C-12.

Of these 35 potential charging locations only nine (26 percent) have space or power constraints that would make it more difficult and costly to install chargers. In addition, this network would require no chargers in downtown Vancouver, where space for bus lay-overs and charging is difficult and costly to develop. This reduced network also has fewer locations that would require a large number of chargers. In particular, the number of chargers at UBC Loop is reduced from 14 to three, the number at Phibbs Exchange is reduced from eight to two, the number at Joyce Station is reduced from six to two, and the number at Dunbar Loop is reduced from five to one. In this reduced network the location with potentially the largest number of required in-route chargers is Richmond-Brighouse station with nine in-route chargers.

Figure C-12 Conceptual In-route Charging Network for PTC, HTC, RTC and STC Service Areas

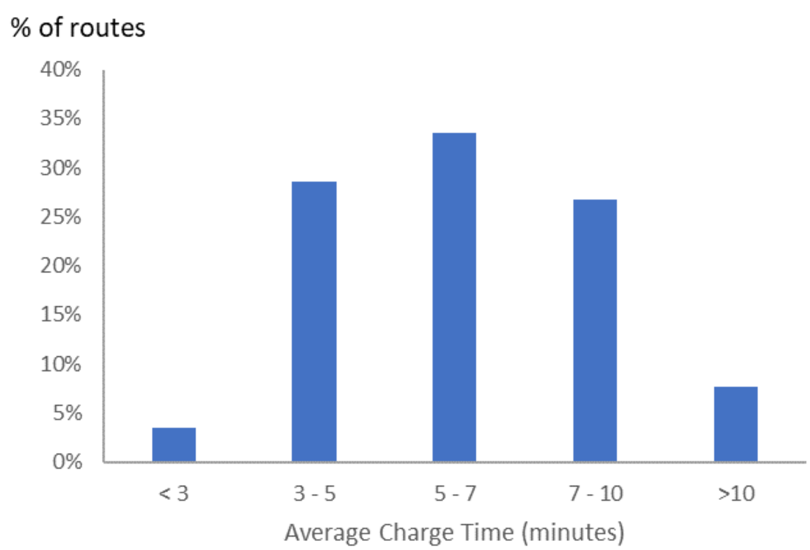


C-3.2 In-route Charging Time

See Figure C-13 for the distribution of in-route charge times that results from the conceptual in-route charge network shown in Figure C-10. This is the average charge time per charge event, to replenish the energy used since the last charge event, including one minute per event for bus movement in and out of charging position.

As shown, two thirds of routes will have charge times of less than 10 minutes per event; the weighted average charge time is 6 minutes per event across all routes. The routes with longer charge times are routes that have long headways; on all routes projected charge time is less than headway. The weighted average charge time across all routes is also 6 minutes per in-service hour; on average every bus will charge once per hour in service. CMBC buses average 11.4 to 17.3 hours per day in service, depending on bus type and transit centre; the weighted average in-service time for all 40-ft and 60-ft buses is 12.6 hours per day[62]. Total charge time for in-route charging will therefore average 1.26 hours per day per bus.

Figure C-13 Distribution of In-route Charge Times on CMBC Routes



Current CMBC bus schedules include lay-over time that averages approximately 9 minutes per hour. On average this is enough to cover the time required for in-route charging. However, in addition to providing a break for bus operators this lay-over time also serves as "recovery time" to keep buses on schedule throughout the day – i.e. if a bus is running late the normally scheduled lay-over time will be cut short, and the bus will leave on-time for the next run after dwelling at the exchange for a shorter period.

[62] This does not include highway coaches, which are in-service for a shorter time per day. Individual buses can be in service for a shorter or longer time on any given day.

As discussed above, in-route charging will happen during bus lay-overs – at bus exchanges or other lay-over locations. However, bus charging is a scheduled activity that must happen, even if a bus is running late on the route. As such, if existing lay-over time in bus schedules is used for charging it will not be able to function as recovery time.

An analysis of actual versus scheduled lay-over time over the last year shows that actual lay-over time was greater than 6 minutes per hour on 71 percent of all blocks operated[63], varying from 65 percent to 86 percent at different transit centres. Based on this data, existing lay-over time in current schedules should be able to cover at least 50 percent of required in-route charging time, without affecting on-time performance. A conservative estimate of the additional lay-over time that must be added to CMBC schedules to accommodate in-route charging is therefore 3 minutes per in-service hour. This additional time could be added during non-peak periods, so that the effect on the required number of peak buses would be minimal.

This analysis assumes that 450 kW in-route chargers will be used. MJB&A also evaluated the effect of using lower power chargers (300 kW). Lower power chargers will cost less to install, but daily charge time per bus will increase, and the amount of additional lay-over time required will also increase. Given that bus operators must be paid during lay-over time, the incremental cost of increased charging time would outweigh any savings on charger installation. Our analysis indicates that higher-power in-route charging is therefore less costly than charging at a lower rate.

C-3.3 In-route Charging Electricity Cost

MJB&A evaluated the average monthly demand (peak kW) and throughput (kWh) at CMBC in-route chargers and calculated projected monthly energy costs for in-route charging using the current BC Hydro Large General Service rate and the three EV rates recently proposed by BC Hydro (see section C-2.2 for a description of these rates).

For full implementation of in-route charging on a given route, average electricity costs under the current LGS rate are projected to be $0.116/kWh. This is slightly lower than projected average costs for depot charging under the LGS rate ($0.117/kWh) due to lower peak demand per bus[64]. For small pilot programs and during the transition to electric buses on a given route, the average electricity cost of in-route charging will be higher because monthly demand at each charger will be the same, but monthly through-put at each charger will be lower. If only one of every three

[63] A block is an assigned piece of work for a s specific bus, from the time it leaves the transit center until it returns.
[64] Peak demand per bus is lower for in-route charging than for dept charging because it is spread out over a longer period of time - the 12+ hours that a bus is in service, rather than the 6 – 8 hours that the bus is parked at the depot at night.

buses on a route was electric, the average cost of electricity for in-route charging could as high as $0.22/kWh.

Under two of the proposed EV rates, average electricity cost for in-route charging will be higher than under the current LGS rate; $0.127/kWh under proposed EV rate 1 and $0.176/kWh under proposed EV rate 2. These proposed rates are designed to provide discounts for charging during off-peak periods (10 PM – 7AM), but most in-route charging is during the peak period (7AM – 10 PM) when buses are in service, so these rates are not advantageous for in-route charging. Only proposed EV rate 3 – which charges a flat rate of $0.09/kWh and no demand charge – will be advantageous for in-route charging, particularly during the early years of transition when installed in-route chargers may not be fully utilized.

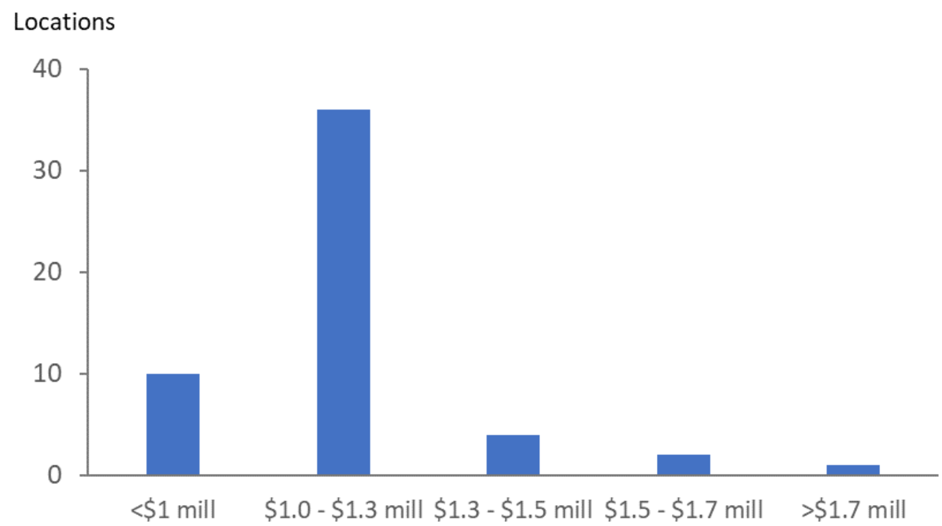
C-3.4 In-route Charging Infrastructure Cost

As part of the Low Carbon Fleet Strategy development process AES Engineering developed conceptual designs for implementation of in-route charging within the CMBC service area. This included a high-level review of all the potential in-route charging locations shown in Figure 18 to evaluate available space for charging infrastructure and bus queuing, and ease of power access (see Figure 19). The AES review indicates that only 27 percent of sites have significant challenges that would make charger installation difficult and costly. At most other sites there is enough space to install the necessary equipment and doing so will require few or no changes to existing pavements, curbs, or structures on the site.

AES estimates that the cost of in-route charger installation will range from $900,000 to $1.2 million per charger, depending on the extent of site modifications required. Approximately 40 percent of potential charger sites are judged to be at the low end of this cost range, 40 percent are judged to be in the middle of the range, and 20 percent are at the high end of the range. The weighted average cost for all sites is estimated to be $1.0 million per charger. This estimated cost includes purchase and installation of the power module and the pole-mounted pantograph, and all work on the customer side of the utility meter to distribute alternating current grid power to the power module and to distribute direct current from the power module to the pantograph charger. It also includes changes to roadway pavements, curbs, etc. to accommodate the installation, and 10 percent construction contingency. It does not include the cost of design, permitting, project management, or financing costs.

As with depot charging, installation of in-route chargers will require BC Hydro to upgrade the local power distribution system to provide the necessary power at each site. BC Hydro reviewed all of the potential charger sites in Figure C-10 to determine the cost of necessary upgrades. BC Hydro estimates that necessary upgrades to primary distribution will cost less than $50,000/charger at 25 percent of the sites, and less than $150,000/charger at 75 percent of the sites. A handful of locations will cost more – up to $800,000/charger at one location[65]. The weighted average upgrade cost for all potential charging sites is estimated to be $125,000/charger.

Figure C-14 Distribution of Projected Total In-route Charger Costs



See Figure C-14 for the distribution of projected total costs for in-route chargers in the CMBC service area, including both TransLink and BC Hydro costs. The cost at 85 percent of sites is projected to be less than $1.3 million/charger, and the weighted average for all sites is projected to be $1.1 million/charger[66].

[65] It is likely that this charging location could be moved to a location with lower upgrade costs.
[66] Not including the cost of design, permitting, project management, or financing costs.

Life-Cycle Cost Analysis

This section summarizes a life cycle cost analysis, which compares the cost of operating battery electric buses to the cost of operating current diesel, CNG, and hybrid-electric buses. Diesel, CNG, and hybrid bus costs are based on analysis of actual CMBC operating costs for the current fleet. Electric bus costs are based on the analysis described in section 4 and are specific to CMBC service. For all buses the life-cycle costs included in the analysis are:

- Bus purchase cost, including additional buses required due to range restrictions (depot charging) and in-route charge time (in-route charging)
- Purchase and installation cost of charging infrastructure (electric buses)
- Cost of depot expansion to accommodate depot-charged electric buses (additional buses, and additional space for chargers)
- 17 years of maintenance costs, including battery replacement at mid-life (for electric buses)
- 17 years of fuel costs
- 17 years of bus operator labor costs, including additional labor costs for electric buses due to increased lay-over time (in-route charging) or increased dead-head time (depot charging)
- 17 years of maintenance costs for bus chargers (electric buses)

The analysis uses estimates of general and fuel inflation over the 17-year life of buses consistent with assumptions used in TransLink financial plans.

Values are presented in both constant 2019 dollars and nominal dollars.

The major assumptions used in the cost analysis are shown in Table D-1.

Table D-1 Major 40-ft Bus Life-Cycle Cost Assumptions (2019$)

METRIC	DIESEL	HYBRID	Electric – Depot Charge	Electric - In Route Charge
Bus Cost	MY2020 $630,000 MY2040 $630,000	MY2020 $890,000 MY2040 $890,000	MY2020 $1,110,000 MY2040 $960,000	MY2020 $945,000 MY2040 $840,000
Battery Size	NA	MY2020 30 kWh MY2040 30 kWh	MY2020 450 kWh MY2040 550 kWh	MY2020 150 kWh MY2040 150 kWh
Replacement Ratio	1.00	1.00	MY2020 1.15 MY2040 1.05	1.00
Charger Cost[67]	NA	NA	$298,000/charger (50 kW panto)	$2.0 mill/charger (450 kW panto)
Chargers Required	NA	NA	1 per bus	1 per 8 buses
Fuel Cost	$1.04/liter	$1.04/liter	$0.09/kWh	$0.10/kWh
Fuel Use	0.60 l/km	0.47 l/km	1.4 kWh/km 0.02 l/km (fuel heat)	1.6 kWh/km
Maintenance Cost	$0.80/km	$0.80/km	MY2020 $0.80/km MY2040 $0.70/km	MY2020 $0.80/km MY2040 $0.70/km
Annual Mileage	68,000 km	68,000 km	68,000 km	68,000 km

D-1 Current Generation Buses (MY2020)

See Figure D-1 for a comparison of projected life-cycle costs (average $/mile) of model year 2019 40-ft diesel, hybrid, CNG and battery electric buses, operated in CMBC service.

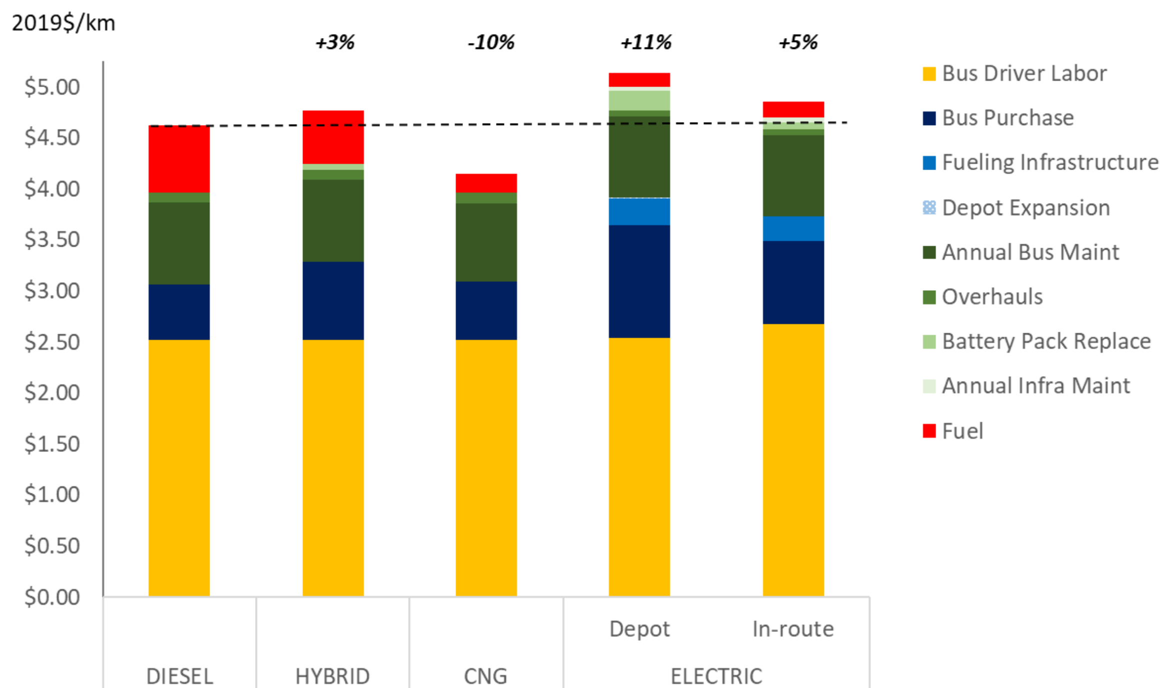
CMBC 40-ft diesel buses are projected to cost $4.62/km to operate over their life-time, hybrid buses are projected to cost $4.77/km, CNG buses are projected to cost $4.15/km, and battery buses are projected to cost between $4.86/km (in-route charging) and $5.14/km (depot charging). Over their life-time current battery buses are projected to cost 5 – 11 percent more to operate than diesel buses.

For all bus types the largest expense is bus operator labor. For diesel buses the second largest expense is maintenance, followed by fuel, then bus purchase cost. Hybrid buses are similar,

[67] These charger costs are fully burdened, including 10 percent construction contingency and costs for design, permitting, project management, and financing costs. In-route charger costs also include the cost of installing a small number of maintenance chargers at the depot.

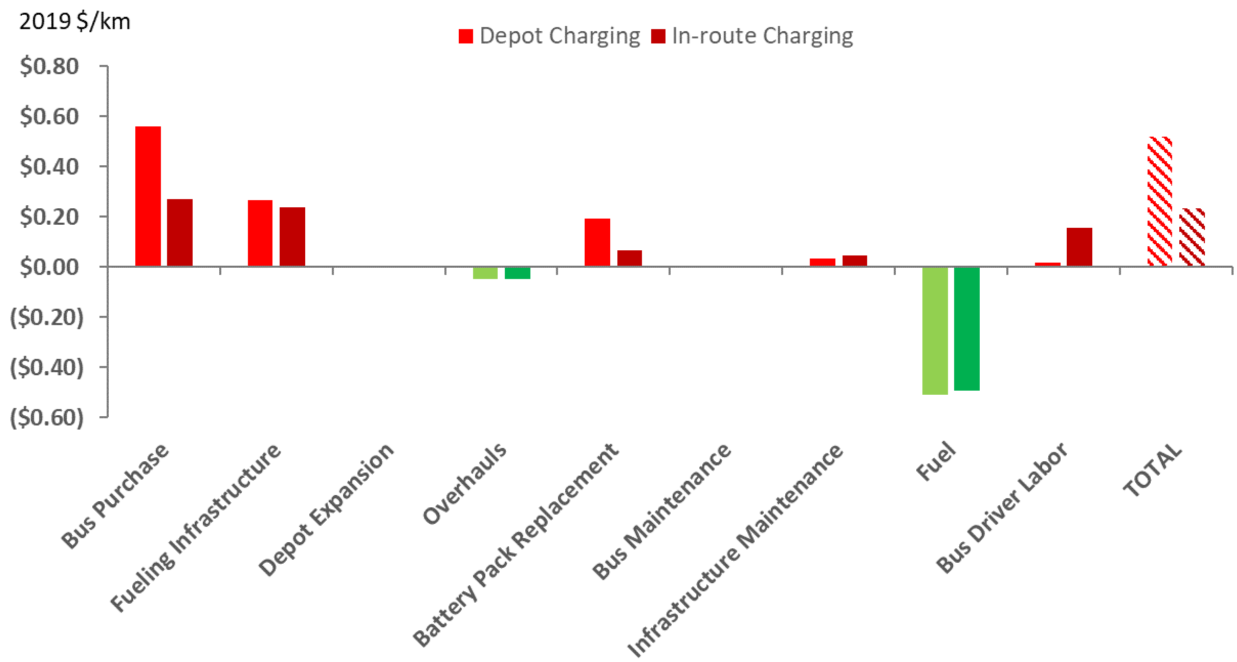
except that bus purchase is a bigger expense than fuel. For electric buses the second largest expense is bus purchase cost, which is significantly higher than for diesel buses, especially if the electric buses are depot charged. Electric buses also have increased costs relative to diesel for purchase and maintenance of the charging infrastructure and for mid-life battery replacement. However, electric buses have significantly lower fuel costs than diesel or hybrid buses.

Figure D-1 Projected Life Cycle Costs of 40-ft MY2019 Buses in CMBC Service



These cost relationships are shown more clearly in Figure D-2, which plots the difference in cost between diesel buses and electric buses. As shown in Figure 24, compared to diesel buses the purchase cost of current electric buses will add $0.27 - $0.56/km over their life, the cost of installing charging infrastructure will add $0.24 - $0.27/km, battery pack replacement will add $0.07 - $0.20/km, charger maintenance will add $0.03 - $0.05/km and bus operator labor costs will be $0.02 - $0.16/km higher. This will be balanced by a fuel cost savings of $0.49 - $0.51/km. Net costs will be $0.43 - $0.52/km higher for electric buses.

Figure D-2 Incremental Cost of MY2019 Electric Buses versus Diesel Buses (2019 $/km)



It is clear from Figures D-1 and D-2 that with current buses and charging infrastructure in-route charging is projected to be less expensive than depot charging for CMBC. Higher bus operator labor, charger maintenance, and fuel costs are more than offset by a significant savings in bus purchase, battery replacement, and charging infrastructure costs. This is primarily because depot charging requires significantly more buses (due to range restrictions) but also because the larger battery required for depot charging increases bus purchase and battery replacement costs per bus. Charging infrastructure costs are higher for depot charging than for in-route charging because the above analysis assumes SAE J3105 overhead pantograph charging at the depot, to eliminate the complications and cost of plugging and unplugging buses every day. If the analysis assumed the use of SAE J1772 corded chargers for depot charging, infrastructure costs would be significantly lower, but there would be additional operating costs for plugging and unplugging buses and for replacement of damaged charge cords.

D-2 Future Buses

The most significant reason why electric buses are projected to be more expensive to operate than diesel buses are the high cost of bus purchase and, for depot charging, the required increase in fleet size due to limits on battery size and resulting range limitations. Battery buses are more expensive to purchase than diesel buses due to high costs for both batteries and electric drive trains.

In the past 5 years the cost of bus batteries ($/kWh) has fallen by more than 40%, and most analysts predict that they will continue to fall – by 50 percent or more by 2035. Industry participants also project that the costs of electric drive trains will fall by as much as 50 percent over time as the technology matures and production volumes increase.

Analysts also predict that battery energy density will continue to increase, allowing for larger batteries and increased range, which will reduce the number of buses required for depot charging.

There are also opportunities for improved drive train and heating system efficiency, which will reduce energy use and fuel costs. Most analysts also project that over the next 20 years the price of diesel fuel will increase faster than the price of electricity, which will improve electric bus economics relative to diesel and hybrid buses.

Finally, there is reason to believe that electric bus maintenance cost will fall over time as the technology matures – this has been the experience with previous new technology introductions into transit (CNG, hybrid-electric).

See Figure D-3 for MJB&A's projection of CMBC bus life-cycle costs (2109 $/mi) for electric buses purchased between model years 2020 and 2050, compared to the current cost of diesel and hybrid buses. Life-cycle costs for electric buses that use in-route charging are projected to fall below the cost of hybrid buses after model year 2025, and to reach cost parity with diesel buses after about 2045.

Life-cycle costs of depot-charged electric buses are projected to fall below the cost of hybrid buses after model year 2035 but are still projected to be slightly higher than diesel bus costs through model year 2050.

Figure D-3 Projected Life Cycle Cost for Model Year 2020 – 2050 Buses