Battery Electric Bus and Facilities Analysis

FINAL REPORT

January 2020

Prepared for:

Milwaukee County Transit System

Prepared by:

MJB & A

M.J. Bradley & Associates LLC
(978) 369 5533 / www.mjbradley.com

Contents

Figures

Tables

Acknowledgements

Lead Authors: Dana Lowell, Dave Seamonds, and Luke Hellgren; M.J. Bradley & Associates
John Drayton and Daniel Quigg; Drayton Consulting
Mike Roller and Alain de Leon; IBC Engineering Services

This report was prepared for the Milwaukee Country Transit System (MCTS) by M.J. Bradley & Associates, LLC, with support from sub-consultants Drayton Consulting and IBC Engineering Services, Inc.

About MCTS

The Milwaukee County Transit System (MCTS) is owned by Milwaukee County and operated by Milwaukee Transport Services, Inc (MTS). MCTS operates fixed-route scheduled transit bus service on over 50 routes that cover the Milwaukee metro area and other municipalities within the county. The MCTS fleet of 391 40-ft diesel buses travels over 16 million miles annually, providing more than 140 million passenger-miles of transit service to county residents each year.

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

The Milwaukee County Transit System (MCTS) commissioned this analysis in order to help the agency prepare for the electrification of the County's fleet of 391 fixed-route transit buses, which are currently all diesel buses.

The county's adopted 2019 capital budget articulates the following fleet transition policy:

> *"Milwaukee County Transit System (MCTS) will initiate the transition of its vehicle fleet to battery-electric buses (BEBs) and away from fossil fuels to lessen exposure to volatile diesel fuel prices, achieve savings over the total lifecycle of the new vehicles, provide clean air and quieter operational benefits to the citizens and neighborhoods in which the County operates our transit fleet and the wider community".*

Milwaukee County's adopted 2019 Capital Budget also specifies that the new Bus Rapid Transit (BRT) route, currently in the planning stages and scheduled to start operating in 2022, will operate with battery electric buses.

To comply with these policies MCTS envisions purchasing a small fleet of up to 15 battery electric buses in the near term, which will both operate on the BRT route and be used as a pilot fleet to test the technology on other MCTS routes. This will be followed by future purchases of additional electric buses to replace retiring diesel buses, likely beginning in the 2025 timeframe.

For this project MJB&A was tasked to determine the financial and operational changes required for MCTS to transition to electric buses, to include:

- Evaluation of the capability of commercially available battery buses in MCTS service
- Determination of infrastructure requirements for battery bus charging
- Estimating the capital and operating costs associated with fleet transition,
- Identifying necessary changes to bus maintenance, bus scheduling, and other operating practices to accommodate electric buses, and
- Development of a *Fleet Electrification Business Plan* to guide the transition

Sections 1 – 5 of this document summarize the analysis conducted by MJB&A and our subconsultants Drayton Consulting and IBC Engineering, relative to the capital and operating requirements of battery electric buses in MCTS service. Section 6 provides a detailed business plan for fleet transition, to include required bus purchases and infrastructure investments, as well as required maintenance and operational changes to accommodate electric buses.

ELECTRIC BUS PILOT PROGRAM

MJBA& recommends that for the BRT route and electric bus pilot program MCTS procure a fleet of 15 battery electric buses, that can be used interchangeably on the BRT route and on select daily bus assignment blocks on all other MCTS routes. These fifteen buses will be supported by two 450-kW SAE J3105-1 overhead conductive pantograph chargers. One charger will be located at the western terminus of the BRT route, at the Watertown Plank Park & Ride lot. The other will be located at the depot which will house the electric buses.

Each weekday nine electric buses will be required on the BRT route, leaving up to six electric buses for use on other routes[1]. Buses operating on the BRT route will utilize in-route charging; every time a bus arrives at Watertown Plank Park & Ride it will charge for approximately 8 minutes, during normally scheduled lay-over time. This will allow buses to stay in service all day, while maintaining a consistent charge state in their on-board battery. Electric buses not required for BRT operations will be utilized on other MCTS routes and will be charged while stored overnight at the depot.

This configuration will provide maximum flexibility for deployment of the electric buses; it will ensure that the BRT route can continue to operate with electric buses even in the event of bus or charger problems, while also allowing MCTS to test electric bus and depot-based charging operations on other MCTS routes.

The pilot program will require $15.2 million in capital funding for purchase of the 15 electric buses and two chargers. It is expected that the pilot electric bus fleet will accumulate up to 675,000 annual miles in service, saving $150,000 annually on fuel costs compared to operating diesel buses.

FULL FLEET ELECTRIFICATION

Further electrification of the MCTS bus fleet could begin as early as 2025, with the entire fleet converted to battery electric buses as early as 2040. MJB&A recommends that MCTS implement in-route charging if pursuing full fleet electrification, which would require an

[1] MCTS maintains a 15 percent fleet spare factor to accommodate maintenance operations. On any given day 1 -2 electric buses may remain at the depot for maintenance activities.

additional $159 million in capital funding (nominal $) compared to continued replacement of retiring buses with new diesel buses, or an average of $10 million per year for aggressive electrification by 2040. Net operating cost savings are projected to be $1.7 million per year, or a total of $27million between 2025 and 2040.

Fleet electrification is projected to produce significant annual savings in bus maintenance and fuel costs, but these will be offset by additional costs for charger maintenance, mid-life battery pack replacements, and bus operator labor.

Fleet electrification using in-route charging is projected to be significantly less expensive than depot charging. Compared to in-route charging full fleet electrification using depot charging would require an additional $69 million in capital funding while producing an additional $13 million in operating cost savings between 2025 and 2040; between 2025 and 2040 net costs for electrifying the fleet using depot charging are projected to be $56 million higher than full fleet electrification using in-route charging. While in-route charging will incur higher capital costs for charging infrastructure, and higher incremental operating costs for charger maintenance, bus operator labor, and electricity (resulting in lower net fuel cost savings), there will be significantly lower capital costs for bus purchase, and lower operating costs for mid-life battery pack replacement.

Bus purchase costs for depot charging are projected to be higher than for in-route charging due to both more expensive buses (larger battery) and the need to purchase additional buses due to limitations on the size of on-board batteries and resulting limitations in daily range. The analysis projects that fleet electrification using depot charging will require the fleet to increase by 58 buses (+15%) and will also reduce bus parking space at the two existing depots by 111 buses to accommodate depot chargers. Full fleet electrification using depot charging will require MCTS to develop or acquire a third depot with the capacity for 170 buses.

If full electrification proceeds using in-route charging MCTS will not need to build a new depot but over time will need to install approximately 50 450-kW in-route chargers at up to 44 different locations throughout the MCTS service area. This will require acquisition/lease of land or usage rights, design, and permitting.

Fleet electrification will also require significant changes to bus operations to accommodate electric bus technology. Changes will be required to bus schedules, bus maintenance programs, and cold weather operations. MCTS will also need to develop completely new capabilities to regularly monitor bus charging activities, and to maintain and repair charging infrastructure. MCTS should also develop contingency plans to maintain bus charging in the event of loss of grid power at one or more charging locations.

The above discussion addresses estimated costs for an aggressive fleet electrification schedule. Fleet electrification with in-route charging could also proceed at a more measured pace, by converting individual routes to electric operation as funding becomes available. The most heavily used routes in the MCTS system are the Blue, Gold, Red, Green, and Purple express routes. Estimated incremental capital costs to electrify these routes using in-route charging range from $2.9 million (Blue route) to $5.6 million (Purple Route) per route, including the cost of required in-route chargers and the incremental cost of electric buses compared to new diesel buses.

If fleet electrification proceeds at a modest pace, over the next ten years MCTS will need to replace some retiring diesel buses with new buses that are not battery buses. A complementary approach to consider is replacement of these retiring buses with hybrid-electric buses, until funding is available to commit to 100 percent replacement of diesel buses with battery-electric buses. Hybrid electric buses do not reduce GHG emissions as dramatically as battery electric buses, but they are also less costly to implement. In MCTS service hybrid-electric buses are projected to use at least 17 percent less fuel than diesel buses and to emit 17 percent fewer greenhouse gas (GHG) emissions. Average life-cycle costs of hybrid-electric buses are projected to be 6 percent higher than life-cycle costs for diesel buses, including both capital and operating costs. Replacement of some retiring diesel buses with hybrid-electric buses is a potential complementary interim strategy to full fleet electrification.

1 Background - MCTS Fleet, Facilities, and Service Profile

This section briefly summarizes the current MCTS diesel bus fleet, existing bus garages from which the fleet operates, and the routes on which the buses operate.

1.1 Bus Fleet and Maintenance Facilities

The MCTS fleet includes 391 40-ft diesel transit buses, which range in age from 2 years (model year 2017) to 16 years (model year 2003). Twenty eight percent of the fleet is less than five years old, 36 percent is between five and ten years old, and 36 percent is greater than 10 years old. In order to maintain the fleet in good working order, MCTS has a long-term need to purchase an average of 25 – 30 new buses per year, so that they can retire the oldest buses when they have reached the end of their useful life[2].

These buses are housed at and operate from two bus garages, Fond du Lac Garage and Kinnickinnic Garage. MCTS also operates a centralized Fleet Maintenance facility which is used for major repairs. MCTS owns a third garage property – Fiebrantz Garage – which is no longer used and is currently vacant.

See table 1 for a summary of the size and assigned number of buses at each MCTS bus facility.

Table 1 MCTS Bus Facilities

FACILITY	MAINTENANCE [SF]	BUS PARKING [SF]	TOTAL [SF]	BUS CAPACITY [buses]	Pits/Hoists in Maintenance Area	Assigned Buses
Fond du Lac	48,800	160,700	209,500	229	22	216
Kinnickinnic	47,400	126,700	174,100	177	18	175
Fleet Maintenance	204,600	0	204,600	NA	42	NA
Fiebrantz	28,800	58,000	86,800	100	11	VACANT

Each MCTS garage site includes separate enclosed buildings which house maintenance operations, bus parking areas, and the bus wash and diesel fueling station. All buses are parked in doors. All three MCTS bus garages are highly constrained, with little to no extra space within

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

the fence line - and no vacant adjacent properties – that could be used for expansion. All of these facilities are 40 years old or older. Building construction details, and ceiling height in the bus parking area, varies from site to site, and in the case of Fond du Lac Garage from building to building[3].

1.2 Bus Routes and Service Profile

MCTS operates 30 different "fixed" routes on which service is provided approximately 20 hours per day (generally 4 AM – 1 AM). These routes generally run north-south or east-west. On these routes bus headway (minutes between buses) ranges from 12 to 60 minutes during peak morning (6 AM – 9 AM) and afternoon (3 PM – 6 PM) commuting times, with longer headways mid-day and in the late evening/early morning.

MCTS also runs a number of limited service routes which operate only during morning and afternoon peak periods, providing additional service to specific destinations with heavy commuting traffic. These include Ubus routes to local universities, Flyer routes to downtown Milwaukee, and shuttle routes to/from Park and Ride lots. MCTS also uses their transit buses to operate a limited number of school routes to bring children between home and local elementary schools in the morning and afternoon. See Figure 1 for a summary of the MCTS route network.

MCTS buses on fixed and Ubus routes average 13 – 15 hours per day in service, accumulating an average of 180 – 200 miles per day, at an average in-service speed of about 13 miles per hour[4]. MCTS buses operating on non-fixed routes average 4 – 5 hours per day in service, accumulating an average of 70– 95 miles per day, at an average in-service speed of 18 - 20 miles per hour[5]. Buses are not permanently assigned to a given route or type of route; an individual bus might operate on a fixed and on a non-fixed route on successive days.

1.3 New BRT Route

The new BRT route, currently being planned, will operate east-west between the waterfront in downtown Milwaukee and the Watertown Plank Park and Ride lot in Wauwatosa, primarily along Wisconsin Avenue and Bluemound Road (see Figure 2). Approximately nine miles from end to end, the route is currently projected to include 20 stops, with one-way travel time of approximately 37 minutes end-to-end (14.6 MPH average in-service speed).

[3] This facility includes of a series of adjacent bus parking buildings that were constructed at different times.

[4] On any given day individual buses may be in service from 4 to 22 hours and may accumulate from 70 to 300 miles in service.

[5] On any given day individual buses may be in service from 2 to 9 hours and may accumulate from 40 to 200 miles in service.

Figure 1 MCTS Bus Routes

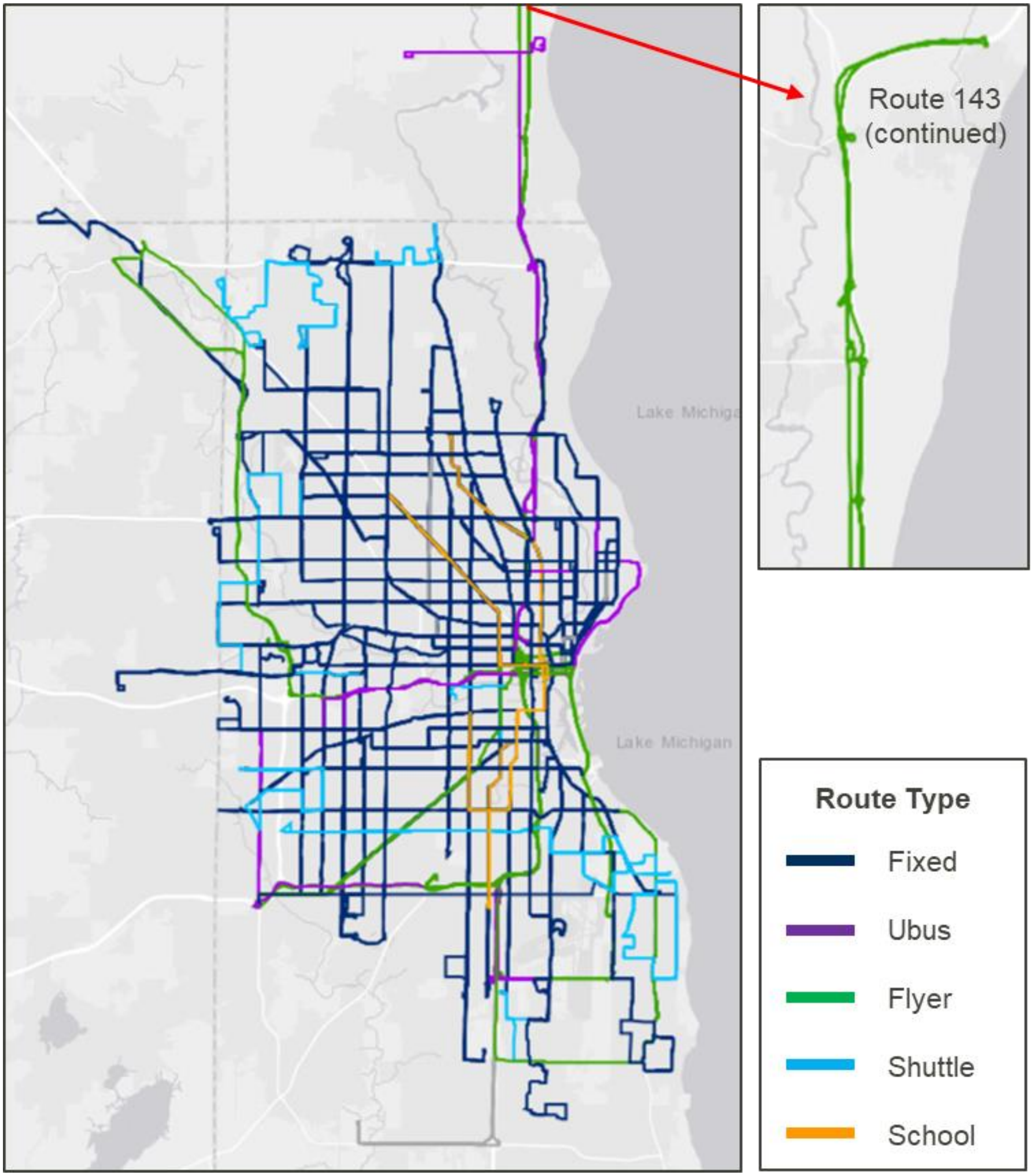
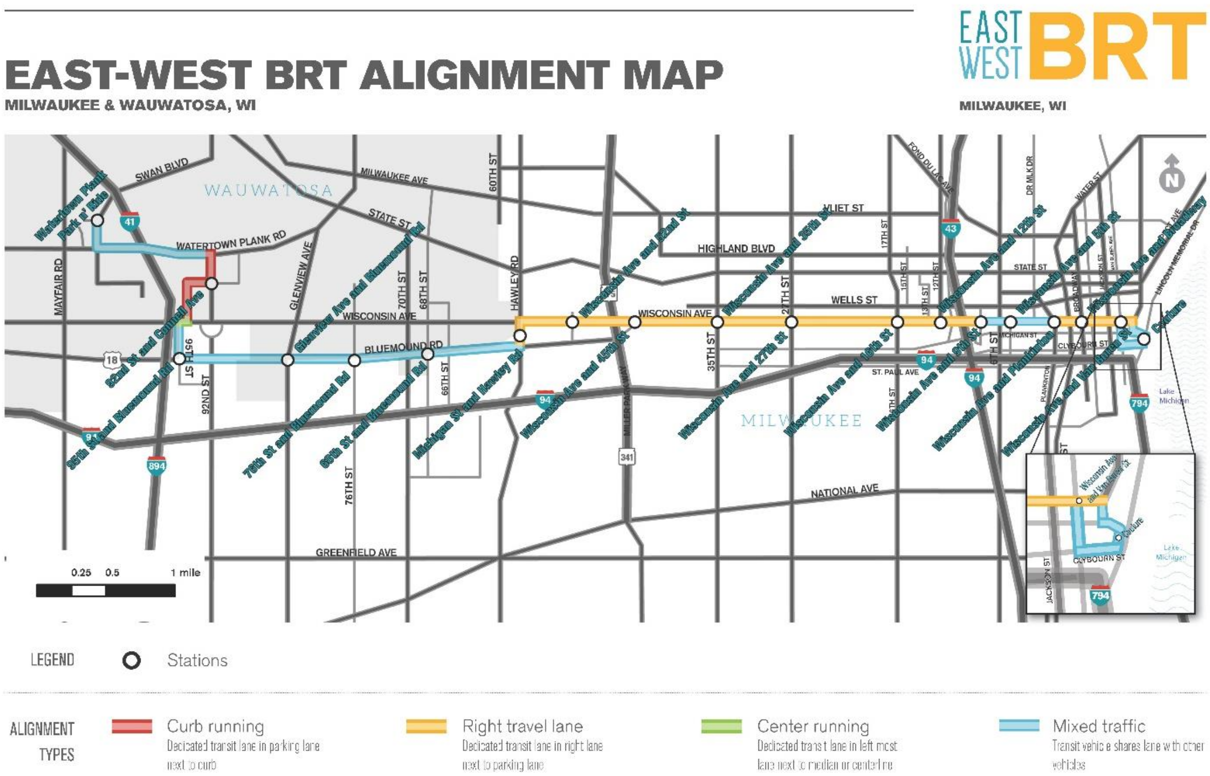


Figure 2 Proposed BRT Route



The BRT route is currently projected to operate with six buses per hour each direction between 7 AM and 5 PM daily, and with three buses per hour each direction at other times.

2 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.

2.1 Electric Buses In-service and on Order

Full-sized[6] battery electric transit buses have been in limited operation in the U.S. 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

[6] 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.

of more than 550 battery electric buses, with 70 percent of them entering service since 2016[7]. 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[8]. When these buses have been delivered, approximately 6 percent of U.S. 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.[9]

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 (30); Minneapolis Metro (27); SEPTA in Philadelphia (25); Chicago Transit Authority (30), and Montreal, Canada (40).

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[10]. This regulation requires all transit agencies in California to phase in purchasing of “zero-emission” buses[11] 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.

2.2 Electric Bus Manufacturers

See Table 2 for a summary of the manufacturers that currently offer battery electric 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

[7] 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
[8] Based on news articles and press releases from various sources, and bus manufacturer websites
[9] Personal communication with J. Gibson, New Flyer of America
[10] *https://ww2.arb.ca.gov/news/california-transitioning-all-electric-public-bus-fleet-2040*
[11] Zero emission buses include battery-electric buses and hydrogen fuel cell buses

systems. Complete coach works remanufactures old diesel buses with a new electric propulsion system.

Table 2 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

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.

2.3 Available Electric Bus Models

Table 3 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.

Table 3 Commercially Available 40-ft Battery Buses

Parameter	BYD	Gillig	New Flyer	Nova	Proterra
Length (in)	482	501	492	490	512
Wheelbase (in)	240	279	284	243	296
Height (in)	134	134	130	130	134
Front Overhang (in) [1]	101	101	87	120	104
GVWR (lb)	43,431	45,000	44,308	43,000	43,650
Curb Weight (lb) [2]	32,920	29,650/33,750	30,134/32,920	32,000	26,649/33,149
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	62.5 MPH	No Data	No Data	No Data	65 MPH
Energy Use [5]	1.99 kWh/mi (2014 - CBD)	No Data	1.75 kWh/mi (2014 - CDB)	1.94 kWh/mi (2018 – OCC)	2.01 kWh/mi (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 150 lb/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.

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 2,000 – 3,000 lb lower curb weight than other electric buses with the same sized batteries.

PHYSICAL DIMENSIONS

All electric buses have similar dimensions (height, length, wheelbase) as CNG and hybrid-electric buses on the market[12]. 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 87 inches to 120 inches.

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

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

are them 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 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 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 of 43,000 – 45,000 pounds, and curb weight of 26,650 – 33,750 pounds, depending on manufacturer and installed battery capacity. The curb weight of 40-ft diesel buses is typically in the range of 26,000 – 28,000 lbs, so electric buses with the largest available battery, appropriate for overnight depot charging, will typically weigh 4,000 – 6,000 pounds more than a similar diesel bus, with 2,500 – 3,800 pounds more on the rear axle. In-route charged electric buses, with a smaller battery, will typically weight 1,000 – 2,500 pounds more than a diesel bus, with 600-1,600 pounds 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 150 pounds 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 DC charging, using a charge port compatible with an SAE J1772 CCS-Type 1 connector[13]. 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.[14] With AC charging the inverters installed on the bus convert incoming 480-volt

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

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.

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 forthcoming SAE J3105-1 charging standard, which is still a work in progress but is scheduled to be published by the end of 2019[15]. All manufacturers install the J3105-1 charge port 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.

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.

[15] 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.

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 32 °F and 70 °F. 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 generally temperate summer environment in Milwaukee hot weather operation is not expected to be problematic for MCTS battery electric buses. While winter temperatures in Milwaukee routinely fall below 20 °F cold weather operation is also not expected to be overly difficult for MCTS because all buses are stored indoors in heated space. Battery packs have high thermal mass (they cool off slowly) and also generate heat as they are dis-charged over the day while buses are in service. As such, daily operation on cold days is not expected to be a significant problem, if the battery packs are sufficiently warm to start the day. Winter operation in Milwaukee will reduce bus range for buses charged overnight at the depot, due to the energy required to heat both the battery pack and the passenger cabin. See Section 4 below.

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 and the APTA Public Transportation Vehicle Database indicates that between 2017 and 2019 different agencies have paid between $650,000 and $1.2 million per bus for battery-electric buses; the weighted average price of electric buses listed in the APTA database is $889,000 per bus[16]. 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

[16] 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 year built between 2017 and 2022 (some are on order but not yet delivered). These buses were manufactured by Proterra, BYD, and New Flyer.

low end the purchase price was reduced by the agency's decision to lease the bus batteries rather than buying them outright.

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. Current public pricing data from Proterra's battery leasing program implies that costs have fallen into the range of $450/kWh, at least for Proterra.

Based on the totality of available information, MJB&A estimates that electric buses purchased in volume (30+ buses) over the next few years will cost in the range of $850,0000 - $900,000 per bus for depot-charged buses with a large battery (450 kWh) and in the range of $720,000 - $780,000 per bus for in-route charged buses with a smaller battery (150-220 kWh). Prices for a smaller number of buses (5 – 15) could likely be higher.

This compares to the approximately $510,000 purchase price for MCTS diesel buses (most recent purchase), which is similar to the price paid by most other transit agencies, per the APTA database[17].

3 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.

3.1 Depot Charging

Depot charging is analogous to home charging for personal electric vehicles; 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. Charging rates of 50 – 75 kW are required, to complete the necessary charging in the available 6- to 8-hour overnight window.

The most common way to implement depot charging is to use direct current chargers equipped with an SAE J1772 CCS-Type 1 connector (CCS charger); the standard connector is plugged into a compatible port on the bus, and power is transferred from the charger to the bus via an electrical cord. There are several appropriately sized chargers on the market (50 kW – 62 kW), which are also used for "fast-charging" electric cars. See figure 3 for several examples of commercially

[17] The APTA database lists almost 2,500 diesel buses (37-43 ft; year built 2017 – 2022) and the weighted average price paid for these buses was $504,000, with 85 percent of buses less than $575,000/bus.

available chargers. See Figure 4 for the configuration of the SAE J1772 connector and on-bus charge port.

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 20 percent, depending on whether they are mounted on the ground or overhead. While overhead mounting may reduce the space requirements it will add cost, due to the need to add overhead structure to carry the weight of the chargers. In existing buildings, such as the MCTS garages, there also may not be enough overhead clearance to mount chargers overhead.

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 3.2. While operationally simpler, this method of depot charging is typically more expensive than using SAE J1772 corded chargers, due to the cost of the overhead pantograph used to connect the charger to the bus.

Figure 3 Commercially Available SAE J1772 Compatible Chargers

Figure 4 SAE J1772 Connector

Several companies also sell wireless inductive chargers that could be used for depot charging. With a wireless charger a power source 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 source, power is transferred across the air gap via magnetic fields generated by magnetic coils in the source and receiver. Wireless charging is reported by the manufacturers to be as efficient as wired and conductive charging, with a similar cost for purchase and installation of the necessary equipment. However, the power receiver on the bus must be actively cooled during charging, which requires a higher level of integration than the other charging methods; none of the bus models listed in Table 3 offer wireless charging as a standard option. In addition, this is an infant technology with only a handful of installations in North America, less than 3 years of in-use experience, and a small and potentially fragile manufacturing base.

The biggest issue associated with depot charging – regardless of the type of charger used - 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 MCTS 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.

3.2 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 Section 4.3, in-route charging would require one charger for approximately every 8 buses on MCTS fixed routes and one charger for every 3.4 buses on the other MCTS routes that operate only during peak periods.

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 30 – 60 minutes per day per bus.

In-route charging is typically done using overhead conductive chargers. See Figure 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.

There are two 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, or 450 kW.

Figure 5 Typical In-route Charger Installation

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.

While in-route charging eliminates the range restrictions of depot-charged buses, time will likely need to be added to bus schedules to accommodate the periodic charging. In addition, MCTS will need to procure easements or other agreements to install the necessary chargers on public or private land across the service area. Prior experience has shown that the process of siting and permitting in-route chargers can be time-consuming and may take two years or more per site.

4 MCTS Operational Analysis

This section summarizes the analysis of MCTS bus operations, and implications for transition to electric buses. The subjects covered include projected energy use on MCTS 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 IBC Engineering, and are specific to MCTS facilities.

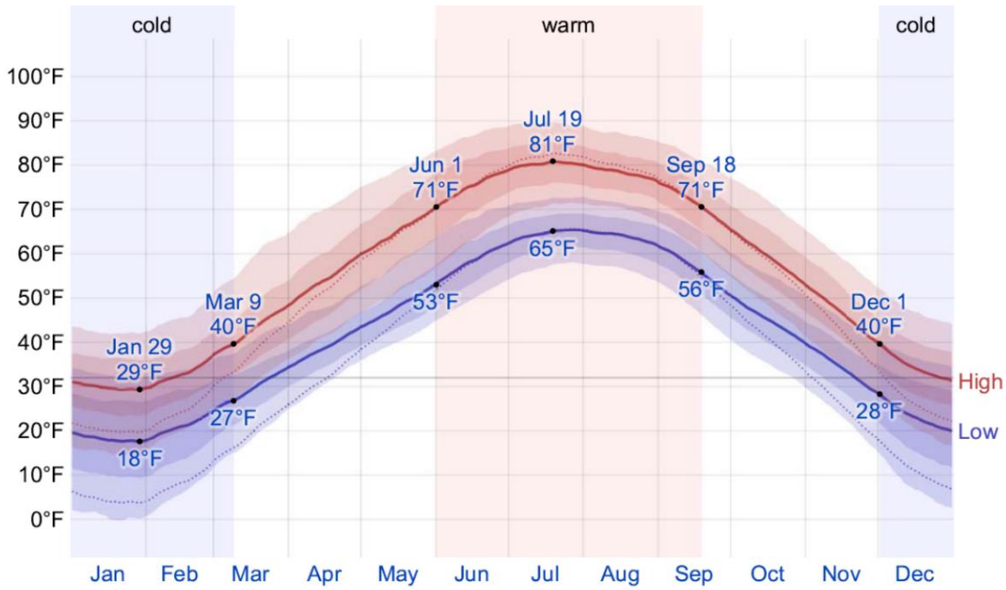
4.1 Projected Electric Bus Energy Use

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 speed on the route – the lower the speed the more energy required (kWh/mi), primarily because lower speed correlates to more stops.

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 kW when ambient temperature is 80 ° F, while the average daily heating load could be as high as 14 kW (electric resistance heating) when the ambient temperature is 0 ° F.

See figure 6 for the historical average daily high and low temperature in Wisconsin. Historically the annual average high temperature is 81° F (in July), but could reach 90° F or higher. The annual average low temperature is 18° F (in February), but could fall below 0° F.

Figure 6 Average High and Low Temperature, Milwaukee, WI

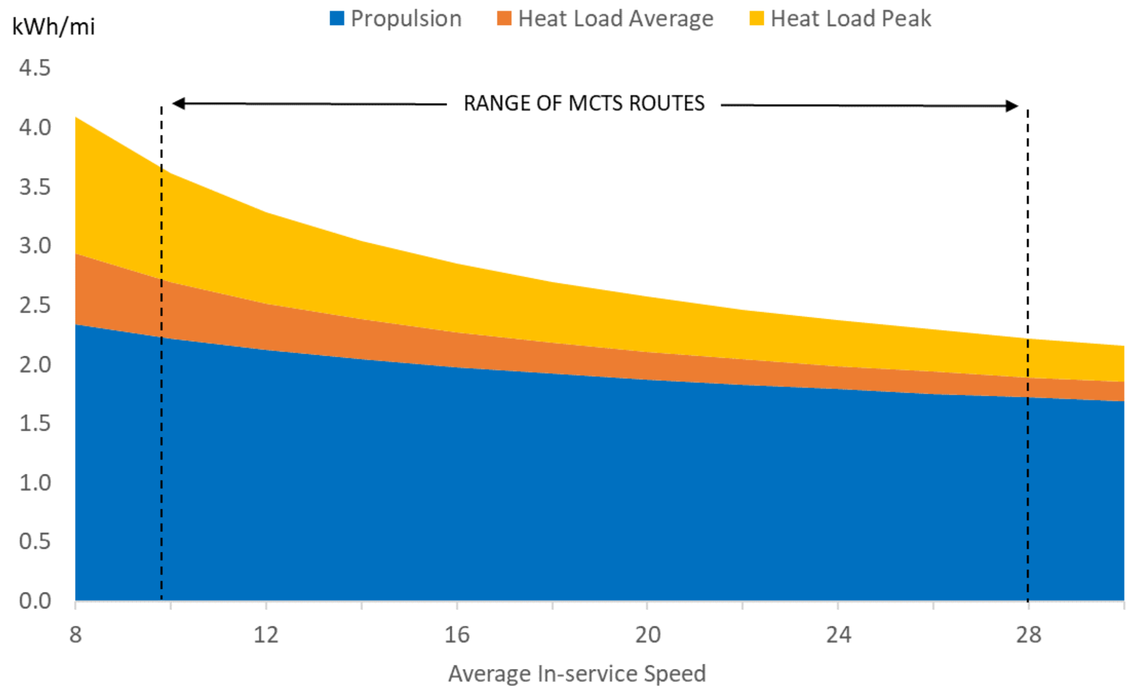


The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures.

See figure 7 for a summary of the estimated energy use by electric buses in service on MCTS routes. The average in-service speed of the different MCTS routes ranges from 10 MPH to 28 MPH. As such, the estimated energy required for propulsion will range from 1.7 - 2.2 kWh/mi, depending on the route. On the coldest winter day (0° F), the additional energy required for cabin heating will add 0.5 – 1.4 kWh/mi, for a total load of 2.2 – 3.6 kWh/mi. Across the entire year, average energy use is projected to total 1.9 – 2.7 kWh/mi for the different routes, including both propulsion and heating/cooling.

The new BRT route is projected to have an average in-service speed of 14.6 MPH. Total electric bus energy use on this route is projected to average 2.4 kWh/mi across the year, but to be 3.0 kWh/mi on the coldest winter day.

Figure 7 Projected Electric Bus Energy Use in MCTS Service



4.2 Depot Charging Analysis

This section summarizes the analysis of cost and operational considerations for MCTS fleet electrification using over-night depot charging of electric buses. The analysis encompasses estimated range per charge on different MCTS 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 MCTS depots.

4.2.1 Range per Charge & Replacement Ratio

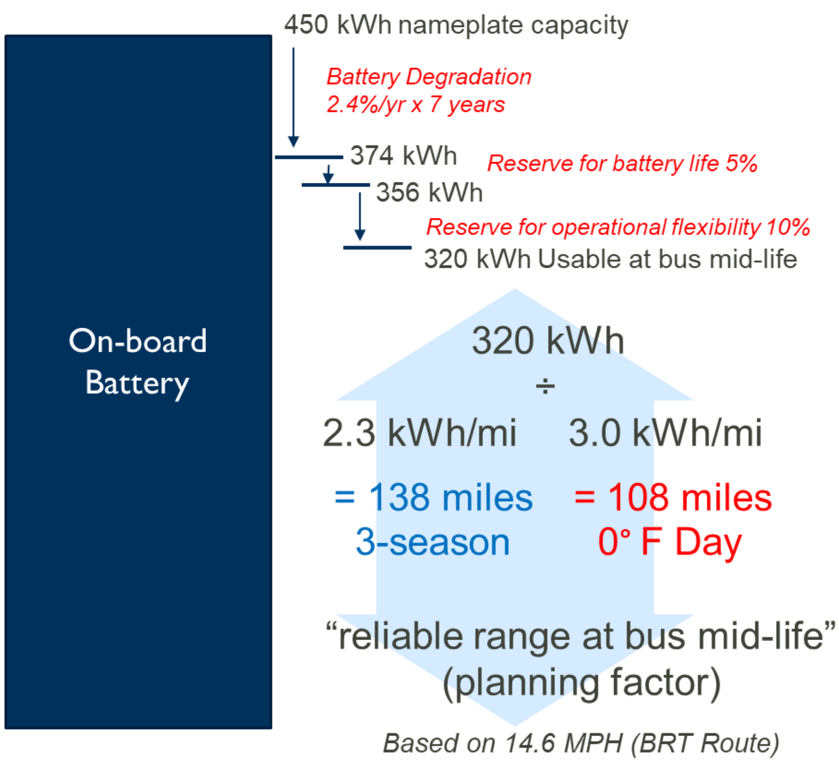
As discussed in section 2.3, for most manufacturers the nameplate energy capacity of the largest battery currently available on 40-ft buses is 450 kWh; the exception is Proterra which offers battery packs as large as 660 kWh. This is the theoretical capacity when the battery pack is new, but not all 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 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 7 years (bus mid-life) it will only retain about 83 percent of its original capacity, and by bus end-of life at 14 years it will retain only 66 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 (miles) that can be achieved just before the battery is replaced.

The calculation of reliable range should be based on projected average energy use (kWh/mi) 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.

Figure 8 Calculation of Reliable Range at Bus Mid-life



See Figure 8 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 on the new MCTS BRT route. As shown, with a 450-kWh battery, at bus mid-life only 320 kWh (71%) will be reliably available. Assuming average annual energy use of 2.4 kWh/mi, from a planning perspective buses on the BRT route can be assumed to have a reliable range of 138 miles per charge most of the year. However, unless supplemental fuel heating is used, range per charge on the route will fall to only 108 miles on the coldest winter days in Milwaukee.

For a Proterra bus with a 660-kWh battery (largest available in the industry), available energy at bus mid-life would be 469 kWh, and reliable range per charge on the BRT route would be 202 miles with supplemental fuel heat, and 159 miles with only electric heat.

Table 4 Projected Range per Charge on MCTS Routes, at Bus Mid-life

Depot	Routes	AVG SPEED	AVG Energy Use (kWh/mi)		Range Per Charge (miles)			
					450 kWh Battery		660 kWh Battery	
		MPH	Peak Day	Annual AVG	Elec Heat	Fuel Heat	Elec Heat	Fuel Heat
KK	Fixed & Ubus	13.2	3.1	2.4	103	133	152	195
KK	Flyer& Shuttle	18.5	2.7	2.2	122	150	178	219
FD	Fixed & Ubus	12.7	3.2	2.5	101	131	148	192
FD	Flyer& Shuttle	20.2	2.6	2.1	126	154	185	226
BRT	BRT	14.6	3.0	2.3	108	138	159	202

See Table 4 for a summary of the projected reliable range per charge, at bus mid-life, of depot-charged electric buses on the different MCTS routes. Fixed and Ubus routes have lower average speed, higher projected energy use, and lower projected range per charge than Flyer and Shuttle routes.

With only electric heat, electric buses on MCTS fixed routes will have a reliable range per charge of approximately 100 miles if equipped with a 450-kWh battery (industry norm), or approximately 150 miles if equipped with a 660-kWh battery (industry best). If buses on these routes are equipped with supplemental fuel heat projected range per charge will increase to approximately 133 miles (450-kWh) or 195 miles (660-kWh).

With only electric heat, electric buses on MCTS Flyer and Shuttle routes will have a reliable range per charge of approximately 120 miles if equipped with a 450-kWh battery (industry norm), or approximately 180 miles if equipped with a 660-kWh battery (industry best). If buses on these routes are equipped with supplemental fuel heat projected range per charge will increase to approximately 150 miles (450-kWh) or 220 miles (660-kWh).

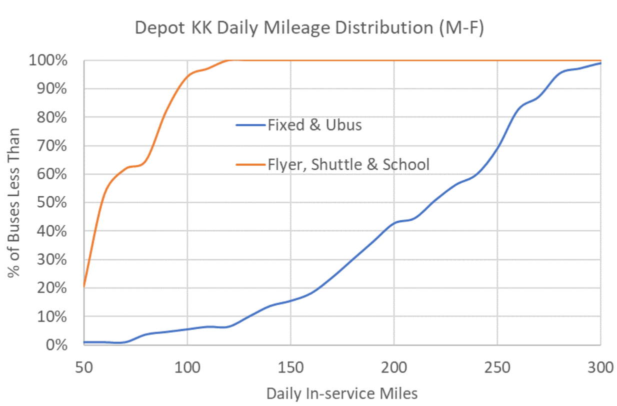
Given the way that MCTS currently schedules service, many buses – particularly those on Fixed routes – accumulate more miles per day than the projected reliable range per charge for depot-charged electric buses. Given this, to implement depot charging MCTS would need to change the way they schedule buses, 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.

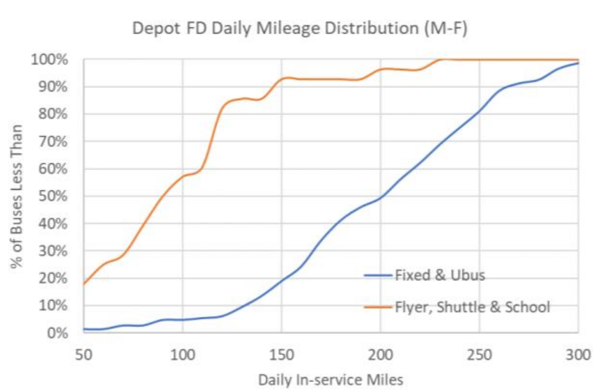
See Figure 9, which shows the distribution of mileage accumulated on a typical weekday by MCTS buses. The chart on the left summarizes buses operating from Kinnickinnic garage and the chart on the right summarizes buses operating from Fond du Lac garage. In both charts the blue line represents buses on Fixed and Ubus routes, and the orange line represents buses on Flyer, Shuttle, and school routes.

Buses on fixed routes operating from both garages average about 200 miles per day, and on any given day 50 percent of buses accumulate less mileage than this, some as little as 50 miles. However, 50 percent of buses travel more than 200 miles per day – some as many as 300 miles per day.

Buses operating on Shuttle, Flyer, and school routes do not travel as far. These buses average less than 100 miles per day at both garages, and in fact no bus on these routes out of Kinnickinnic accumulates more than 120 miles per day. However, about 10% of the buses on Shuttle and Flyer routes out of Fond du Lac travel more than 150 miles per day, with some accumulating over 200 miles per day.

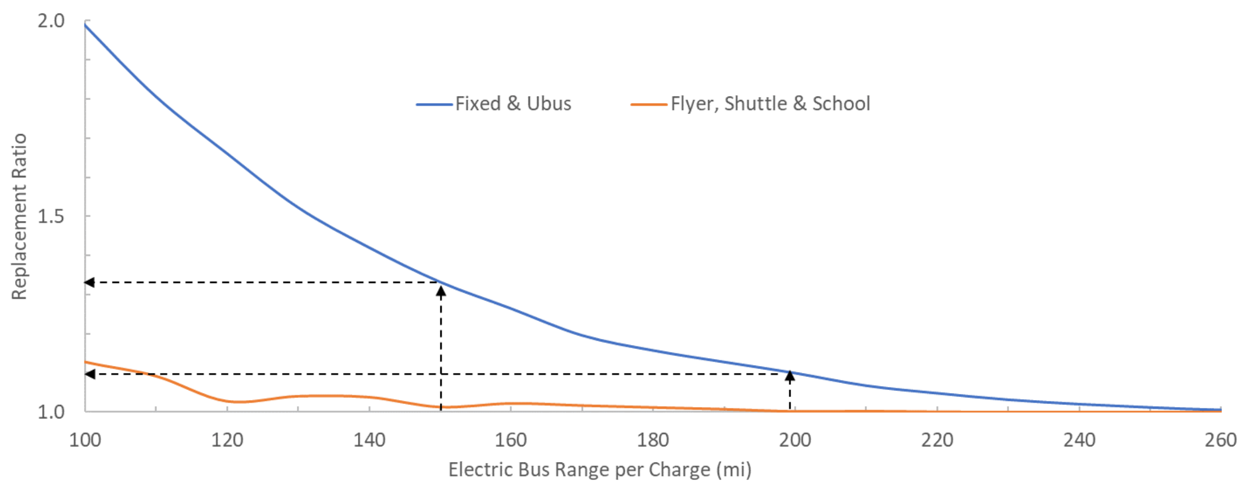
Figure 9 Distribution of MCTS Daily Bus Miles





MJB&A used the data in Figure 9 to calculate a "replacement ratio" for depot-charged electric buses in MCTS service. 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 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.

Figure 10 Electric Bus Replacement Ratio versus Range per Charge – Fond du Lac Garage



See Figure 10 for a plot of replacement ratio versus electric bus range per charge at Fond du Lac depot. For fixed and Ubus routes out of this depot, if an electric bus had only 150 miles range per charge the replacement ratio would by about 1.3 – i.e. 30 percent more electric buses would be needed than diesel buses. If the electric buses had 200 miles range per charge only about 10 percent more buses would be required (1.1 replacement ratio). To be able to replace diesel buses one-for-one with electric buses on Fixed routes out of Fond du Lac, the electric bus range per charge would need to be greater than 260 miles.

Due to lower daily mileage accumulation on Flyer and shuttle routes the replacement ratio for these routes is lower. With 150 miles range per charge the electric bus replacement ratio on these routes would be very close to 1.0.

Using the data in Table 4 and Figure 10, MJB&A calculated the projected electric bus replacement ratio for MCTS bus routes; this data is summarized in Table 5.

The projected electric bus replacement ratio for MCTS Shuttle and Flyer routes is close to 1.0, even with the industry typical 450 kWh battery size, and even if electric heat is used. Very few, if any additional buses will be required to implement depot charging for buses operating on these routes.

Table 5 Projected Replacement Ratio for MCTS Depot Charging

Depot	Routes	AVG Miles per Bus per Day	Electric Bus Replacement Ratio			
			450 kWh Battery		660 kWh Battery	
			Elec Heat	Fuel Heat	Elec Heat	Fuel Heat
KK	Fixed & Ubus	212	2.09	1.61	1.41	1.15
KK	Flyer& Shuttle	66	1.00	1.00	1.00	1.00
FD	Fixed & Ubus	197	1.99	1.52	1.33	1.12
FD	Flyer& Shuttle	95	1.03	1.01	1.00	1.00
BRT	BRT	195	1.81	1.42	1.26	1.10

The same is not true of MCTS fixed routes. Due to much higher mileage accumulation on these routes, the limitations of battery size and range per charge will require significantly more electric buses than diesel buses on these routes, even when using electric buses with the largest available battery (660 kWh), and especially if only electric heating is used. As shown in Table 5, if using electric buses with 450 kWh batteries and only electric heat, about twice as many electric buses would be required compared to the current diesel fleet. If supplemental fuel heaters were used on these buses the replacement ratio would fall to about 1.5 (50% more buses required).

Even when using electric buses with the largest battery available on the market (660 kWh) and supplemental diesel heat about 12 percent more electric buses will be required on fixed routes to implement depot charging.

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 MCTS 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.

4.2.2 Depot Charging Load & Electricity Cost

If implementing depot charging, MCTS would be subject to the local utility's (WE Energies) CG3, general secondary rate for electricity. This rate includes:

- A facility charge (per meter) of $1.12/day
- Energy charges of $0.078/kWh for energy used during peak periods, and $0.056/kWh for energy used during non-peak periods, and
- A demand charge of $13.80/kW-month, applied to the maximum demand seem during the month during peak hours

The peak period is 9 AM to 9 PM on weekdays. Demand is measured based on average throughput (kWh/hr) over 15-minute intervals throughout the month.

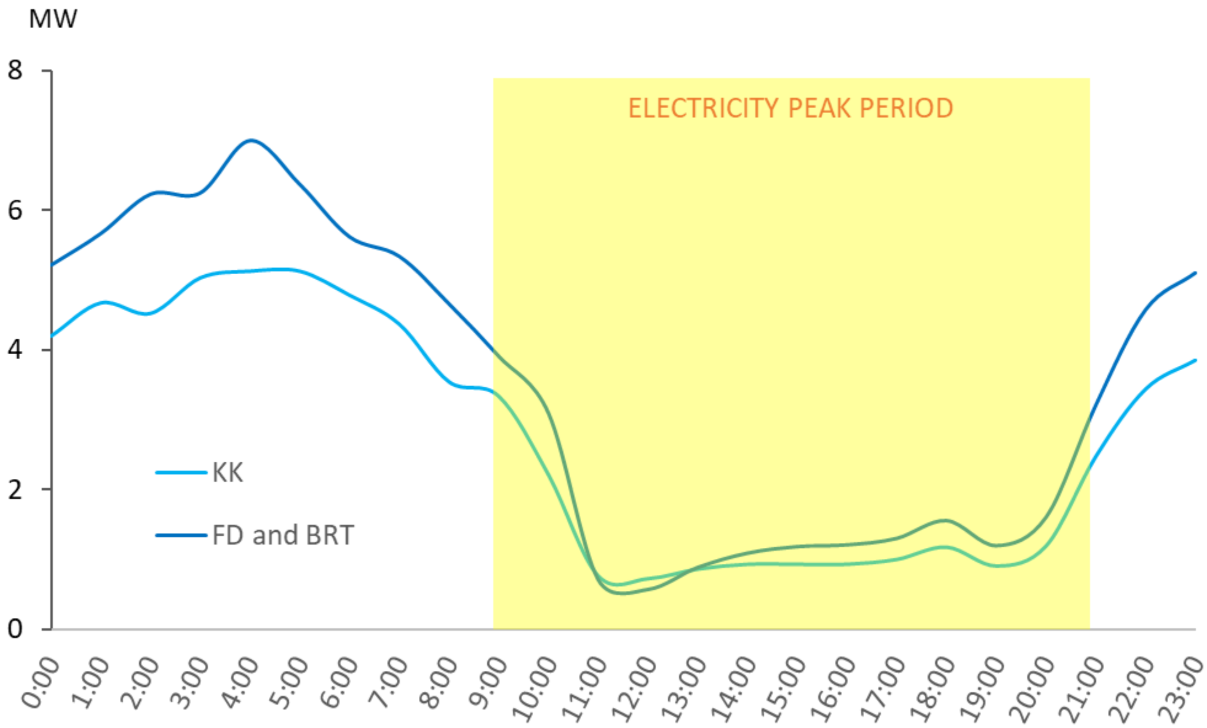
See Table 6 for the projected daily charge time and load, monthly energy use, and average electricity cost for MCTS depot charging, assuming 50 kW depot chargers. As shown, MCTS buses on fixed routes are projected to use almost 9,000 kWh/month/bus, while buses on Shuttle and Flyer routes will use less than half as much energy due to lower daily mileage. Buses on the new BRT route are projected to use 9,600 kWh/bus/ month. The average electricity cost for depot charging is projected to be about $0.09/kWh. This compares to an average electricity cost in Wisconsin of $0.144/kWh for residential customers and $0.109/kWh for commercial customers[18]. The projected electricity cost for depot charging will be lower than electricity costs for other commercial customers because a greater percentage of energy use is in non-peak hours, which reduces both demand and energy charges.

Table 6 projected Demand, Throughput and Electricity Cost for MCTS Depot Charging

DEPOT - Routes	Average per Bus			Average Electricity Cost
	Charge Time [hr/day]	Peak Load [kW]	Energy Use [kWh/month]	[$/kWh]
KK-fixed	6.4	21.8	8,774	$0.095
KK-other	5.0	6.6	2,738	$0.094
FD-fixed	6.4	19.3	8,899	$0.090
FD-other	7.1	6.3	3,847	$0.082
BRT	6.9	19.3	9,623	$0.088

[18] U.S. Energy Information Administration, *State Electricity Profiles, Wisconsin*, 2017, https://www.eia.gov/electricity/state/wisconsin/

Figure 11 Projected Weekday Charging Load, MCTS Depot Charging



See Figure 11, which shows projected weekday charging demand (MW) for the MCTS depots, if all buses were depot-charged. For this analysis, MJB&A assumed that for each bus charging will start 1 – 2 hours after it returns to the depot from PM peak service, to allow time for bus cleaning and fare box servicing, as well as to push the start of most charging after the 9 PM start of the non-peak electricity period. To further avoid higher demand and energy charges during peak periods, we also assumed no charging mid-day, even though a significant number of buses are typically at the depot during this time.

As shown in Table 6, 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. Also note that while the maximum charge rate per bus is assumed to be 50 kW, the average peak load is only about 20 kW/bus, because not all buses will be charging at the same time.

As shown in Figure 11, under the modeled scenario projected peak load occurs at about 4 AM, and load is relatively low during the peak electricity period from 9 AM – 9 PM. Given current service levels and timing, it is not possible to avoid all demand charges by restricting charging to the 9 PM – 9AM non-peak period, even if charging at higher rates. Some buses will need to start charging before 9 PM, and/or will not complete their charging by 9 AM.

4.2.3 Depot Charging Infrastructure Cost

IBC Engineering (IBC) reviewed both the Fond du Lac and Kinnickinnic depot and developed conceptual designs for implementing bus charging at each location. These conceptual designs were for a full roll-out of depot charging at each facility, with a charger at each bus parking space, capable of providing 50 kW to each connected bus.

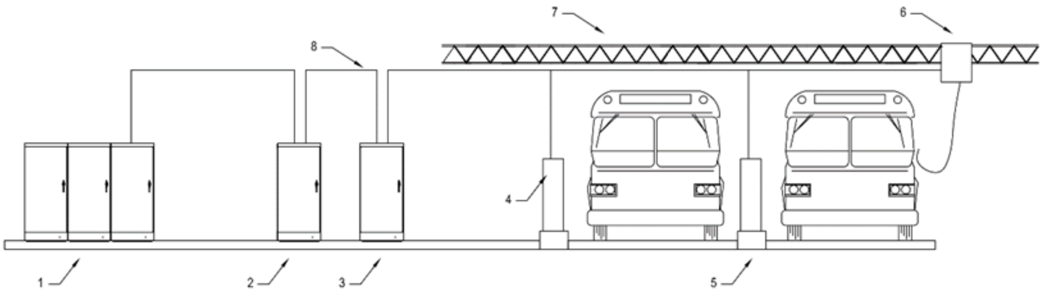
IBC used ABB's family of slow chargers as the technology basis for estimating the cost of electrical construction, along with the RSMeans 2016 estimating tool, IBC Engineers' project and product experience, and manufacturers' budget quotations for significant equipment.

See figure 12 for the main components of electrical infrastructure required for depot charging buses. Note that IBC evaluated costs for both overhead mounting and ground-mounting of charge heads; both options are shown in Figure 12, but only one option would be implemented at each location. Also note that for both depots, IBC assumes that the incoming utility service will be primary voltage, which will require that MCTS install, own and maintain a new medium voltage substation (item 1 in Figure 12). As a primary voltage customer, the utility will charge MCTS a lower power rate ($/kWh), and the savings between this rate and that charged to customers taking power at secondary voltage will recoup the cost of the customer-owned substation within 5 years.

The IBC conceptual design also includes provisions for providing mobile back-up power for bus charging if the depot loses grid power. Each power panel, which supports 9 – 12 charging units, includes a mobile generator connection. This scenario allows a 750kW mobile generator to energize the charging system of one lane. It also allows multiple generators to charge multiple lanes. Smaller generators can also be used to charge a smaller number of buses. The cost of these mobile generators is not included in IBC's cost estimate.

In order to provide a location to mount charge heads on the ground, or to provide a clear space so that the cables from chargers mounted overhead will not interfere with bus movements, the IBC conceptual design includes a 2-ft buffer space between each bus parking lane. For ground-mounted chargers a curb would be installed in this buffer space to protect the charge heads from damage by bus movements. For overhead mounting a cable management system would be required to retract bus cables when not in use. Overhead mounting would also require an additional overhead support structure to hold the weight of the charge heads. This is shown in Figure 13.

Figure 12 Main Components of Depot Charging Electrical Infrastructure



1. Medium Voltage Substation
2. Power Distribution Panelboard with mobile generator connection
3. Power Unit
4. Pedestal Charging Unit
5. Lane Curb
6. Overhead Charging Unit
7. Overhead Support
8. Raceway/Conduits

Figure 13 Ground and Overhead Mounting Options for Depot Chargers

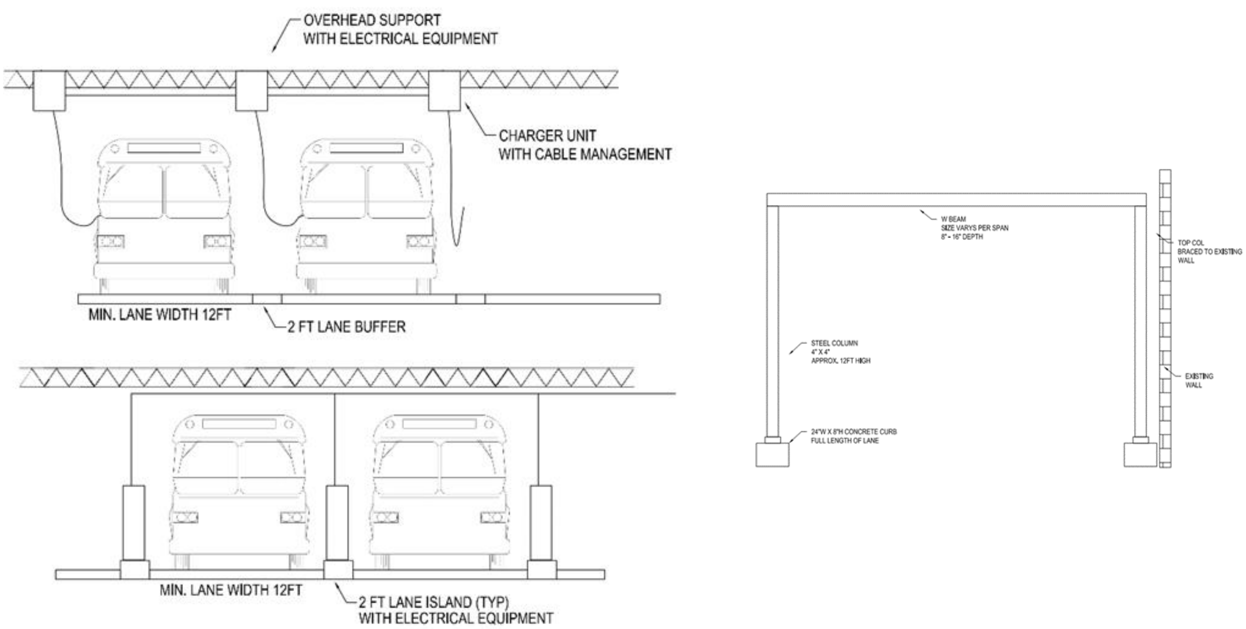


Figure 14 Conceptual Layout of Depot Chargers at Kinnickinnic Depot

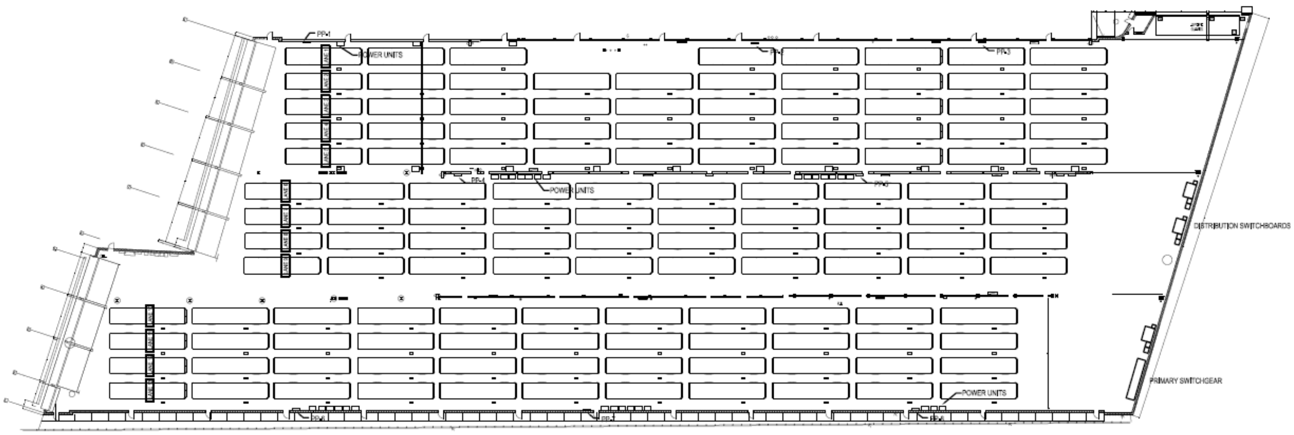


Figure 15 Depot Charging Conceptual Design Cost Estimates

DEPOT CHARGING

	FD	**KK**
Electrical	$9,743,657	$7,975,767
Civil/Struictural	$581,370	$419,301
Architectural	$350,000	$350,000
Remote Monitoring	$250,000	$250,000
sub-total	*$10,925,027*	*$8,995,068*
Contingency (20%)	$2,185,005	$1,799,014
sub-total	*$13,110,033*	*$10,794,082*
Design	$439,000	$359,000
Utility service [1]	$0	$0
TOTAL	**$13,549,033**	**$11,153,082**
Number of buses	148	132
Average per bus	**$91,548**	**$84,493**

[1] *The design assumes primary service with customer owned substation; these costs included in electrical*

The required buffer space between bus parking lanes would reduce the number of buses that could be parked in each depot. IBC estimates that Fond du Lac depot can house 148 depot-charged buses (compared to current assignment of 216 buses) and Kinnickinnic depot can house

132 depot-charged buses (compared to current assignment of 175 buses). See Figure 14 for the conceptual layout of overhead-mounted depot chargers at Kinnickinnic depot.

IBC's conceptual cost estimates for implementing depot charging at Fond du Lac and Kinnickinnic depots are summarized in Figure 15.

Total estimated charging infrastructure cost is $13.5 million to implement depot charging for 148 buses at Fond du Lac and $11.2 million to implement depot charging for 132 buses at Kinnickinnic. This includes a 20 percent construction contingency, design costs, and a system to remotely monitor charging status of each charger. This equates to an average of $85,000 - $92,000 per bus charging infrastructure cost to implement depot charging.

4.3 In-route Charging Analysis

This section summarizes the analysis of cost and operational considerations for MCTS 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 MCTS bus routes.

4.3.1 Required Charging Network

MJB&A analyzed the existing MCTS 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. The starting point for the analysis was an assumption that chargers would preferentially be placed at or near existing bus lay-over locations, which are typically at both ends of each route (route termini). MCTS has a contractual obligation to provide 7 percent of bus driving time as lay-over time, to provide a break for drivers. On most routes, current practice is to provide minimum lay-over of 4 minutes every time the bus completes a one-way trip on each route (i.e. 4 minutes at each end of route on each trip); depending on the length of the route the lay-over could longer, up to 6 minutes per one-way trip.

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), in order to keep charging time less than bus headway.

Many MCTS routes have lay-over locations dedicated to only that route, while some share lay-over locations with other routes, at least on one end. In order to minimize the number of charging locations, and minimize the number of total chargers, MJB&A preferentially identified as charging locations lay-overs shared by more than one route, and evaluated opportunities to share chargers among routes, on routes with long head-way. For routes that required charging on only one end of the route we also preferentially identified as the preferred charging location lay-overs located at park and ride lots or at other locations with large parking lots (i.e. Mall, big-box store), as opposed to lay-overs at the curb on public streets.

See Figure 16 for the resulting conceptual in-route charging network. Table 6 also lists the potential in-route charging locations shown in Figure 16. The total network to serve all MCTS routes would require a total of 51 chargers at 44 different locations; this equates to one charger for every 6.3 peak buses (or one for every 7.9 total buses). Most locations would require only a single charger; only five locations would require two chargers and only one location would require three chargers. Also note that most routes require charging at only one end, not both ends, so only slightly more than half of existing lay-over locations are designated as charging locations.

The fixed and Ubus routes would require a total of 33 chargers at 28 locations (one charger per 7.8 buses), while the Flyer, Shuttle, and school routes would require a total of 18 chargers and 18 different locations (one charger per 3.4 buses), and the BRT route will require only one charger, designated to be at the Watertown Plank Park & Ride lot at the western terminus of the route[19].

[19] The number of locations and chargers for a full system roll-out are smaller than the totals for fixed versus other routes separately, due to sharing of a few locations/chargers by fixed and other routes.

Figure 16 Conceptual In-route Charging Network for MCTS Service Area

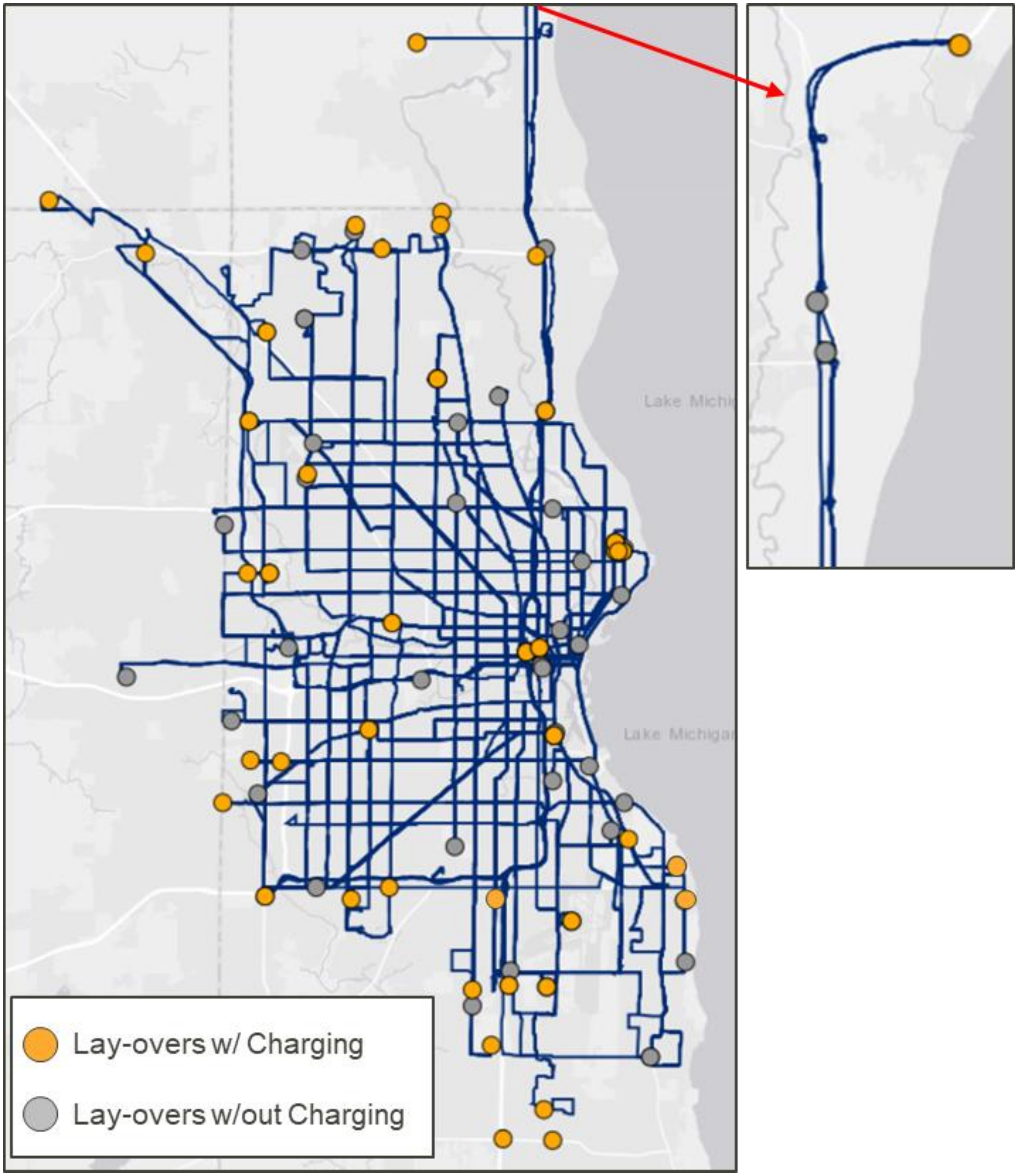


Table 7 Potential In-route Charging Locations

Lay-over Location	Latitude	Longitude	Route(s) Served (Type)	Number of 450 kW Chargers
Watertown Plank Park & Ride	43.046	-88.044	BRT (BRT)	1
Bayshore Town Center	43.123	-87.915	14 (Fixed), 15 (Fixed), GreenLine (Fixed)	3
1st & Maple	43.012	-87.911	17 (Shuttle), 52 (Fixed), 54 (Fixed), 56 (Fixed)	2
Hartford & Maryland	43.078	-87.882	30 (Fixed), GoldLine (Fixed)	2
Mayfair Mall	43.067	-88.045	21 (Fixed), 31 (Fixed), 60 (Fixed)	2
Park Place & Liberty	43.150	-88.047	223 (Shuttle), BlueLine (Fixed)	2
Zellman Court	42.925	-87.932	19 (Fixed), 219 (Shuttle)	2
43rd & Mill	43.134	-87.966	30 (Fixed), 35 (Fixed)	1
Vliet & 60th	43.050	-87.988	33 (Fixed), 64 (Fixed)	1
69th & National	43.014	-87.999	23 (Fixed), BlueLine (Fixed)	1
74th & Holmes	74th	-88.006	76 (Fixed)	1
92nd & Glendale	43.101	-88.027	12 (Fixed)	1
Brown Deer East Park & Ride Lot	43.176	-87.920	49U (Ubus)	1
Centennial & Target	42.883	-87.916	80 (Fixed)	1
Cherrywood Lane Access Road & Green Bay Road	43.191	-87.964	12 (Fixed)	1
Germantown Walmart	43.195	-88.149	57 (Fixed)	1
Hales Corners Park & Ride	42.956	-88.047	28 (Fixed), 55 (Fixed)	1
IKEA	42.905	-87.941	PurpleLine (Fixed)	1
Kenwood & Maryland	43.075	-87.883	40U (Ubus), 44U (Ubus)	1
Kenwood & Prospect	43.075	-87.881	RedLine (Fixed)	1
Kenwood & Stowell	43.075	-87.879	21 (Fixed), 22 (Fixed), 60 (Fixed)	1
Lincoln & 114th	43.003	-88.054	53 (Fixed)	1
Lovers Lane & Silver Spring	43.119	-88.055	28 (Fixed), 63 (Fixed)	1
MATC North Campus	43.249	-87.976	42U (Ubus)	1
MATC South Campus	42.925	-87.915	40U (Ubus), 80 (Fixed)	1
Mitchell International Airport	42.948	-87.903	GreenLine (Fixed)	1
Northridge	43.186	-88.005	67 (Fixed)	1
Oklahoma & 124th	42.988	-88.067	51 (Fixed)	1
Walmart on Sycamore & 27th	42.924	-87.950	PurpleLine (Fixed)	1
Pilgrim Road P&R Lot	43.177	-88.104	79 (Flyer)	1
Port Washington Park & Ride Lot	43.411	-87.870	143 (Flyer)	1
Ryan & Howell	42.872	-87.912	48 (Flyer)	1
Ryan P&R Lot	42.873	-87.935	40 (Flyer)	1
102nd & Lincoln	43.002	-88.040	87 (Shuttle)	1
Center & 114th	43.067	-88.055	85 (Shuttle)	1
Cudahy High School	42.955	-87.850	88 (Shuttle)	1
Kilbourn & 6th	43.042	-87.918	44 (Flyer), 49 (Flyer), 79 (Flyer)	1
Kinnickinnic & Crawford	42.976	-87.876	50 (Shuttle)	1
Layton & 60th	42.959	-87.989	46 (Flyer)	1
Park Plaza & Brown Deer	43.179	-87.992	276 (Shuttle)	1
S20 & Halsey	42.955	-87.939	RR1 (School), RR2 (School), RR3 (School)	1
Schroeder & Green Bay	43.187	-87.965	49 (Flyer)	1
St. Francis High School	42.967	-87.853	89 (Shuttle)	1
Wells & 10th	43.040	-87.925	40 (Flyer), 43 (Flyer), 46 (Flyer), 48 (Flyer)	1
				51

Note that the network design shown in Figure 16 and Table 6 is conceptual only and was intended to evaluate high-level feasibility and cost. The scope of this project did not allow for a full evaluation of site constraints at every identified charging location. However, note that the vast majority of MCTS routes require charging at only one terminus, so only slightly more than half of existing lay-over locations are designated as charging locations. Given this, if charging is not feasible or practical at some of the locations shown in Figure 16 and Table 6, in most cases charging could be moved to the other route terminus without increasing the total number of locations or chargers.

There may also be opportunities to further rationalize the network shown in Figure 16, to reduce the total number of required charging locations and/or the total number of required chargers. In particular, the required network would be smaller and less expensive if charging locations for most Flyer and Shuttle routes could be consolidated with charging locations for fixed routes. However, this would likely entail adding dead-head time to the Shuttle and Flyer routes to be able to access fixed route charging locations.

4.3.2 In-route Charging Time

See Figure 17 for the distribution of in-route charge times that results from the conceptual in-route charge network shown in Figure 16, and Table 7 for average charge times by depot and route type. In Figure 17 the chart on the left is average charge time across the year, while the figure on the right is required charge time on the coldest winter day – these charge times are longer due to the additional energy used for cabin heating.

Figure 17 Distribution of In-route Charge Times on MCTS Routes

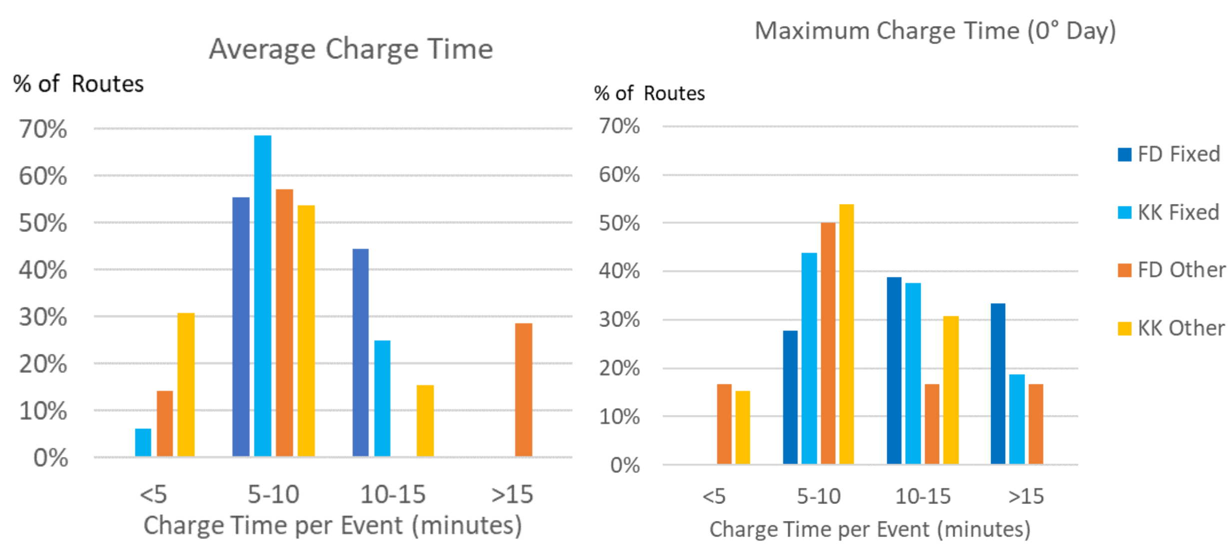


Table 8 Average In-route Charge Time by Depot and Route Type

	Average Charge Time per Event (minutes)				
	FD-Fixed	FD-Other	KK-fixed	KK-other	BRT
Avg Day	10.5	7.2	8.3	6.5	6.6
Peak Day	13.0	8.5	10.3	7.7	8.1

As shown, most routes will have charge times of less than 10 minutes per event, while a handful will have longer charge times. The routes with longer charge times are routes that have long headways; on all routes projected charge time is less than headway. To replenish all the energy used over the day during in-route charging, charging time on very cold days will need to be about 2 minutes longer per charge event than charging on warmer days, due to the additional energy required for cabin heating.

Note that the above charging times are based on charging only once per round-trip on most routes. If charging was done at both route termini the above charging times per event would be cut in half, but total charge time across the day would stay the same, since there would also be twice as many charging events per day.

Required charging time for in-route charging ranges from 5 to 20 minutes per round trip on different routes, while existing lay-over time ranges from 5 to 13 minutes. On some routes the required charging can be accommodated within the existing lay-over time, while on other routes it cannot, and additional lay-over time would need to be added to schedules to accommodate in-route charging. The fact that buses currently lay over at the end of each one-way trip, and charging is only required once every round trip on most routes increases the amount of additional lay-over time that will need to be added for charging. If the current policy to lay over after each one-way trip is maintained, 23 – 35 minutes per day per peak bus will need to be added to all fixed-route schedules, to accommodate charging. If, however, current lay-over time were consolidated to happen once every round-trip (at the charging location) only 8 – 9 minutes per day per peak bus will need to be added to fixed route schedules to accommodate charging.

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 charging is therefore less costly than charging at a lower rate.

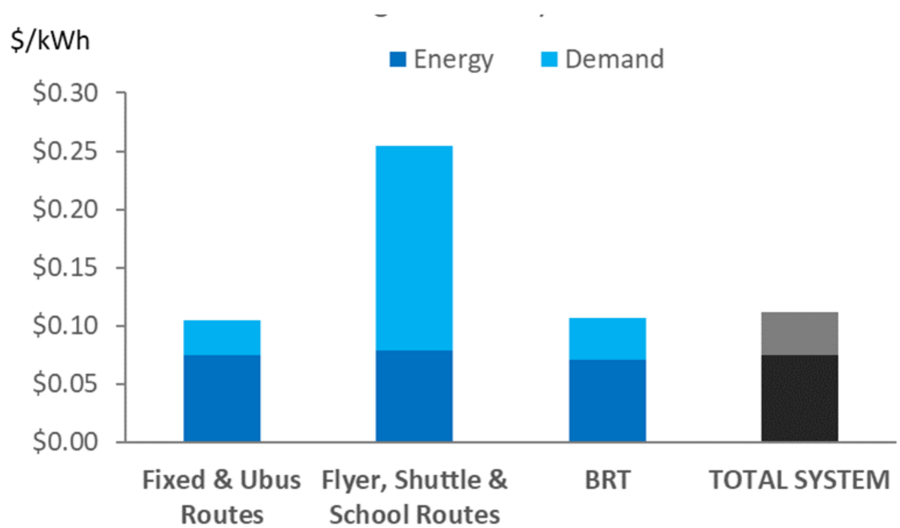
4.3.3 In-route Charging Electricity Cost

MJB&A evaluated the monthly demand (peak kW) and monthly throughput (kWh) at each of the proposed charging locations shown in Figure 16 and calculated projected monthly energy costs using the WE Energies CG3 rate (see Section 4.2.2). The results of this analysis are shown in Figure 18. Average in-route charging electricity cost for Fixed and Ubus routes, and the BRT route, is projected to be a little over $0.10/kWh, about $0.01/kWh higher than costs for depot charging. Electricity costs for in-route charging on these routes is higher than for depot charging because peak demand occurs during the daily peak period, resulting in higher demand charges. In addition, more energy use is during the peak period, which results in higher energy costs.

Average electricity cost for in-route charging on Flyer and Shuttle routes is projected to be much higher, at over $0.25/kWh. This is because peak demand, and therefore the magnitude of demand charges ($/month) will be similar at chargers on all routes, but throughput (kWh/month) will be much lower at chargers on Flyer and Shuttle routes than at chargers on Fixed routes – this results in higher average demand charges ($/kWh), as shown in Figure 18.

For the over-all system, including both Fixed and other routes, the average electricity cost of in-route charging is projected to be just over $0.11/kWh, about $0.02/kWh higher than electricity costs for depot charging, but in line with electricity costs for other commercial customers.

Figure 18 Projected Average Electricity Cost for MCTS In-route Charging



4.3.4 In-route Charging Infrastructure Cost

IBC Engineering (IBC) reviewed the potential in-route charging locations shown in Figure 16 and developed a conceptual electrical design for implementing in-route bus charging at these locations. These conceptual designs are based on a 450-kW charger with pole-mounted pantograph, compliant with SAE J3105-1. IBC also reviewed the configuration of select locations to identify potential siting/layout of necessary electrical equipment. IBC did not conduct a detailed review or develop a specific conceptual layout for every potential in-route charging location shown in Figure 16.

IBC used ABB's family of fast chargers as the technology basis for estimating the cost of electrical construction, along with the RSMeans 2016 estimating tool, IBC Engineers' project and product experience, and manufacturers' budget quotations for significant equipment.

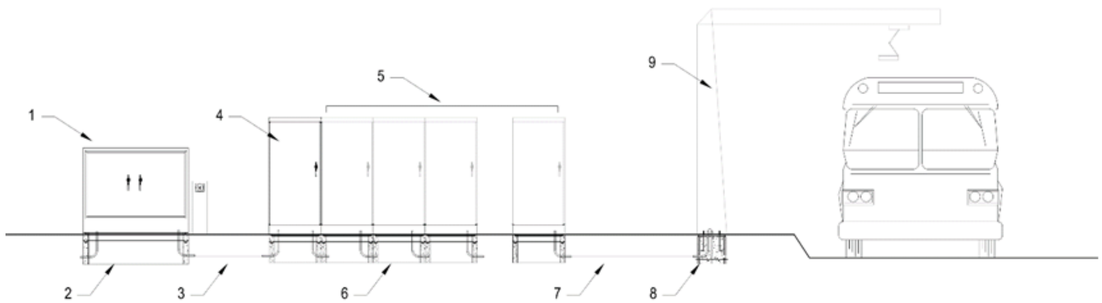
See Figure 19 for the main components of electrical infrastructure required for in-route chargers. Item 1 and 2 in Figure 19 (service transformer and pad) would be supplied by the local utility, WeEnergies, and are not included in IBC's cost estimate.

The IBC conceptual design includes provisions for a mobile generator connection at each distribution panel. A mobile 450kW diesel generator could energize one charging pole if the charger loses grid power. Route locations with more than one charging pole will selectively only energize one pole. Upon return of power, the system will be manually reset, and the mobile generator will be removed from the site. The cost of these mobile generators is not included in IBC's cost estimate.

See Figure 20 for conceptual equipment lay-outs at three potential charging locations, which would require one, two, and three chargers respectively for a full system-wide roll-out of in-route charging. For each charger the charging pole would be installed near the roadway, with the pantograph extended over the bus travel lane. To charge, a bus will pull under the charger and stop when the pantograph is above the on-bus charge rails. The pantograph would then move down to contact the charging rails on the bus. When charging is complete the pantograph will retract, allowing the bus to proceed on its route. The other equipment shown in Figure 19 could be located up to 100 feet away from the charge pole; power is transferred from this equipment to the charge pole via underground conduit.

WeEnergies reviewed their distribution system in the vicinity of each potential in-route charging location, to determine whether there is enough excess capacity in existing service transformers to serve the projected in-route charging load, and if not, the cost to upgrade/replace transformers to serve the load. Their analysis indicates that upgrade costs will be less than $50,000 per charger at 50 percent of locations, less than $125,000 per charger at 25 percent of locations, and up to $250,000 per charger at 25 percent of locations. The average estimated upgrade cost is approximately $100,000 per charger.

Figure 19 Main Components of In-route Charger



1. *Main Service Transformer with Metering.*
2. *Transformer Pad*
3. Underground Service Lateral Feeder
4. Main Distribution Switchboard with mobile generator connection
5. Power/Charging Units
6. Charging Unit Concrete Pad
7. DC Cables to Charging Pole
8. Charging Pole Base
9. Charging Pole with Control Cabinet and Pantograph Charger

Figure 20 Conceptual In-route Charger Layout at Three Potential Charging Locations

The conceptual cost estimate for implementing in-route charging for the MCTS system is summarized in Figure 21.

Figure 21 Conceptual In-route Charger Cost Estimate

	In-route 450 kW
Charger Installation	$481,488
Site Work	$100,000
Remote Monitoring	$25,000
sub-total	*$606,488*
Contingency (20%)	$121,298
sub-total	*$727,785*
Design	$22,000
Utility service	$100,000
TOTAL	**$849,785**
Total Chargers	51
Total Buses	402
Average $/bus	**$107,809**

Total estimated cost is an average of $850,000 per charger. This includes purchase and installation of electrical equipment per IBC's conceptual design, an estimated $100,000 per charger for site work (i.e. modifications to roadways, curbs, and other structures on site to accommodate equipment installation and to create bus charging positions), a remote monitoring system, design costs, 20 percent construction contingency, and We Energies costs to provide primary service. One in-route charger would be required for approximately every eight buses; this equates to an average cost of $108,000/bus.

Implementing in-route charging on every MCTS route would require 51 in-route chargers at a total cost of $43.3 million.

5 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 buses. Diesel bus costs are based on an analysis of MCTS actual operating costs conducted by MJB&A in 2017 for a previous project. Electric bus costs are based on the analysis described in section 4 and are specific to MCTS service. For both diesel and electric buses, the life-cycle costs included in the analysis are:

- Bus purchase cost, including additional buses required when depot charging electric buses
- 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)
- 14 years of maintenance costs, including battery replacement at mid-life (for electric buses)
- 14 years of fuel costs
- 14 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)
- 14 years of maintenance costs for bus chargers (electric buses)

The analysis uses estimates from the Energy Information Administration for general and fuel inflation over the 14-year life of the bus[20].

All values presented in this section are in constant 2019 dollars, for easy comparison to current costs. Actual costs in nominal dollars would be higher due to inflation.

The major assumptions used in the cost analysis are shown in Table 8.

Table 9 Major Life-Cycle Cost Assumptions

METRIC	MY2020 Buses		
	DIESEL	Electric – Depot Charge	Electric -In Route Charge
Bus Cost	$508,000	$900,000 (450 kWh)	$750,000 (150 kWh)
Replacement Ratio	1.00	1.35 Fixed Routes 1.00 Other Routes	1.00
Charger Cost	NA	$88,000/charger (50 kW)	$850,000/charger (450 kW)

[20] U.S. Energy Information Administration, *2019 Annual Energy Outlook*, reference case

Chargers Required	NA	1:1 bus (Fixed route) 1:2 bus (other route)	1:7.8 bus (Fixed route) 1:3.4 bus (other route)
Fuel Cost	$2.63/gal	$0.09/kWh	$0.11/kWh
Fuel Use	5.5 MPG	2.05 kWh/mi 0.01 gal/mi (fuel heat)	$2.39 kWh/mi
Maintenance Cost	$0.83/mile	$0.83/mile	$0.83/mile
Battery Replacement	NA	Mid-life $169,000	Mid-life $56,000
Annual Miles/bus	47,984	47,984	47,984

5.1 Current Generation Buses (MY2020)

See Figure 22 for a comparison of projected life-cycle costs (average $/mile) of model year 2020 diesel and electric buses, operated in MCTS service.

Diesel buses are projected to cost $4.89/mile to operate over their life-time, while depot-charged electric buses are projected to cost $6.00/mile (23% more than diesel) and in-route charged buses are projected to cost $5.39/mile (10% more than diesel).

For both types of bus, the largest expense is bus operator labor. For diesel buses the second largest expense is maintenance, followed by bus purchase cost, then 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 buses.

These cost relationships are shown more clearly in Figure 23, which plots the difference in cost between diesel buses electric buses.

Figure 22 Projected Life Cycle Costs of MY2020 Buses (2018$/mile)

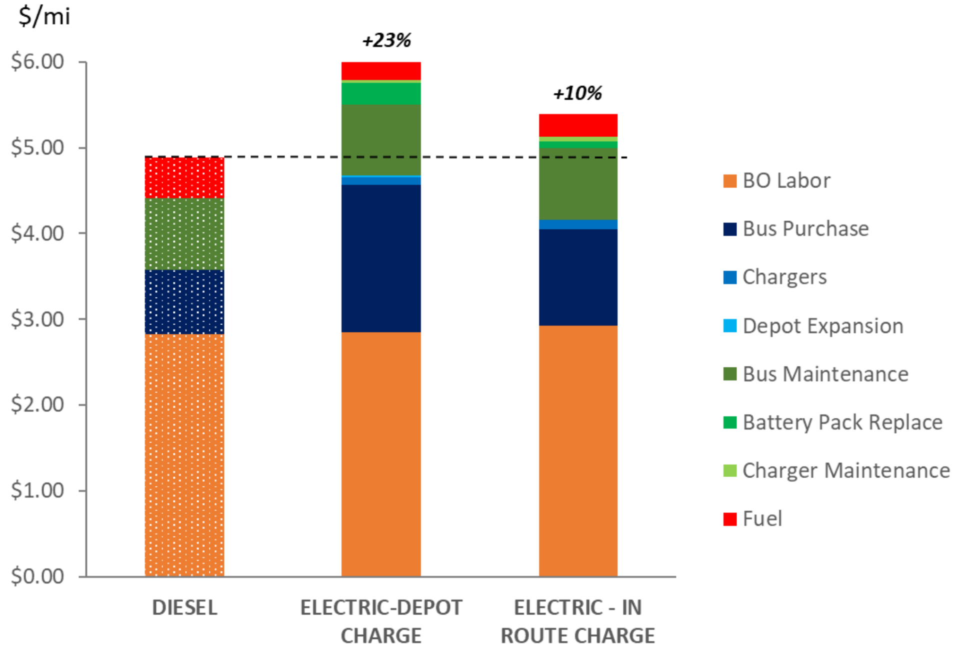
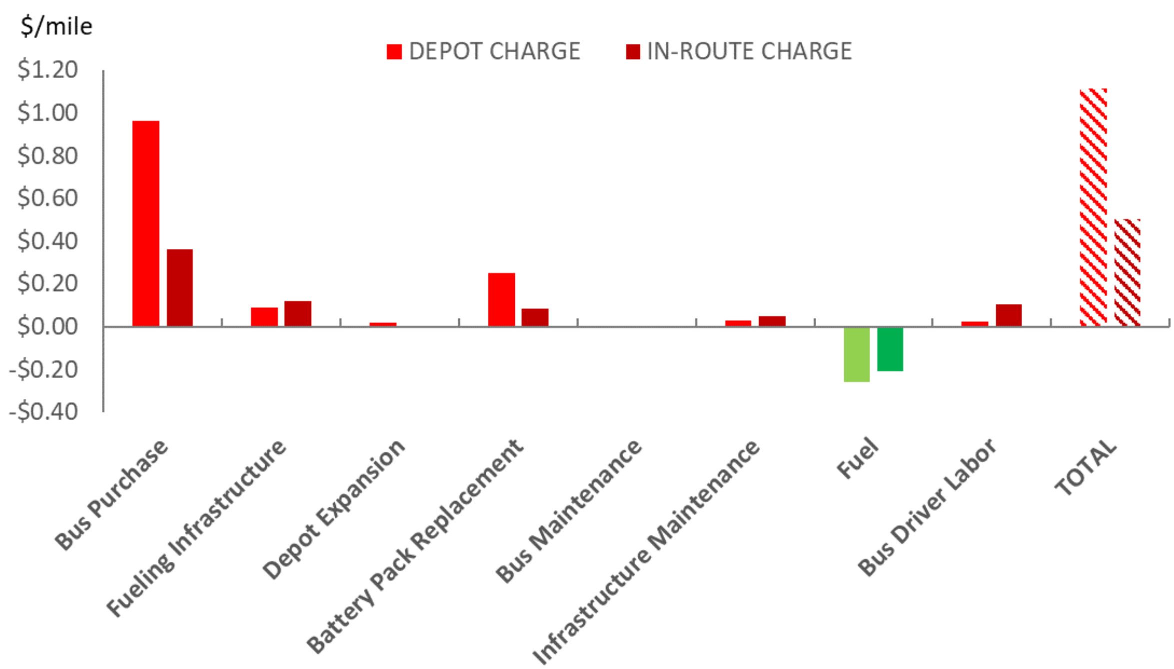
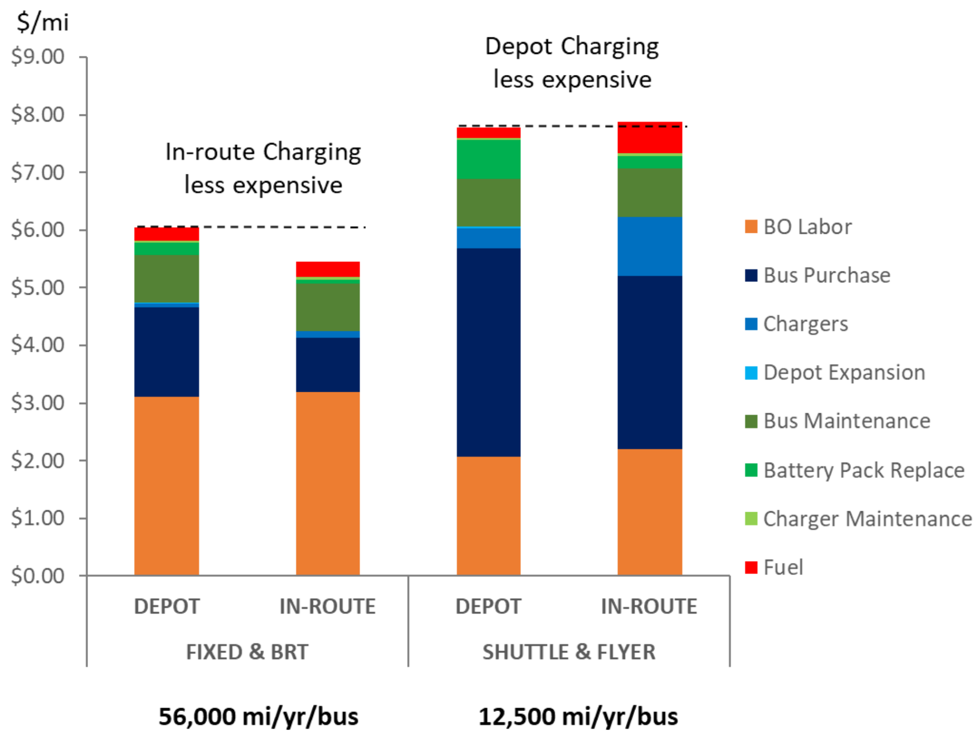


Figure 23 Incremental Cost of Electric Buses versus Diesel Buses ($/mile)



As shown in Figure 23, compared to diesel buses the purchase cost of electric buses will add $0.36 - $0.96/mile over their life, the cost of installing charging infrastructure will add $0.09 - $0.12/mile, battery pack replacement will add $0.08 - $0.25/mile, charger maintenance will add $0.03 - $0.05/mile and bus operator labor costs will be $0.02 - $0.10/mile higher. This will be balanced by a fuel cost savings of $0.21 - $0.26/mile. Net costs will be $0.50 - $1.11/mile higher for electric buses.

Figure 24 Comparison of Charging Options for Different Route Types



It is clear from Figures 22 and 23 that in-route charging is projected to be less expensive than depot charging for MCTS. Higher charger costs and slightly higher labor and electricity costs for in-route charging are more than offset by a significant savings in bus purchase and battery replacement 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.

However, when costs for the different types of routes operated by MCTS are separated, the results are slightly different. See Figure 24, which compares depot and in-route charging costs for MCTS Fixed routes versus Shuttle and Flyer routes. As shown, the cost of electric bus operation ($/mile) is significantly higher on Flyer and Shuttle routes than on Fixed routes, regardless of how the buses are charged. However, for Flyer and Shuttle routes depot charging is less expensive than in-route charging because daily mileage accumulation on these routes is so low. The low daily mileage accumulation means that, unlike on fixed routes, depot charged electric buses can replace diesel buses one-for-one on these routes. Also, as noted in section 4.3.3, electricity costs for in-route charging on Flyer and Shuttle routes is high due to low monthly throughput at in-route chargers on these routes.

The financial analysis indicates that the lowest cost solution for fleet electrification at MCTS would be to use in-route charging on Fixed, UBus and the BRT routes, and depot charging for Shuttle, Flyer, and school routes. However, this would require different bus types (battery size and charge port type) that would not be inter-changeable and would result in a significant imbalance in annual mileage accumulation.

Currently MCTS diesel buses are interchangeable, and a given bus may operate on a fixed route one day and a shuttle route the next. Average mileage accumulation is about 48,000 miles per year per bus, and 670,000 miles over the life of the bus (14 years). If separate bus types were operated on fixed versus Shuttle/Flyer routes – due to use of a different charging methodology – the buses on fixed routes would accumulate about 56,000 miles per year, while buses on Flyer and Shuttle routes would only accumulate about 12,500 miles per year. Retiring fixed route buses after 12 years instead of 14 would maintain current life-time mileage, but even if Shuttle/Flyer route buses were kept in service for 20 years they would only accumulate 250,000 miles over their life.

5.2 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 than diesel buses due to high costs for both batteries and electric drive trains.

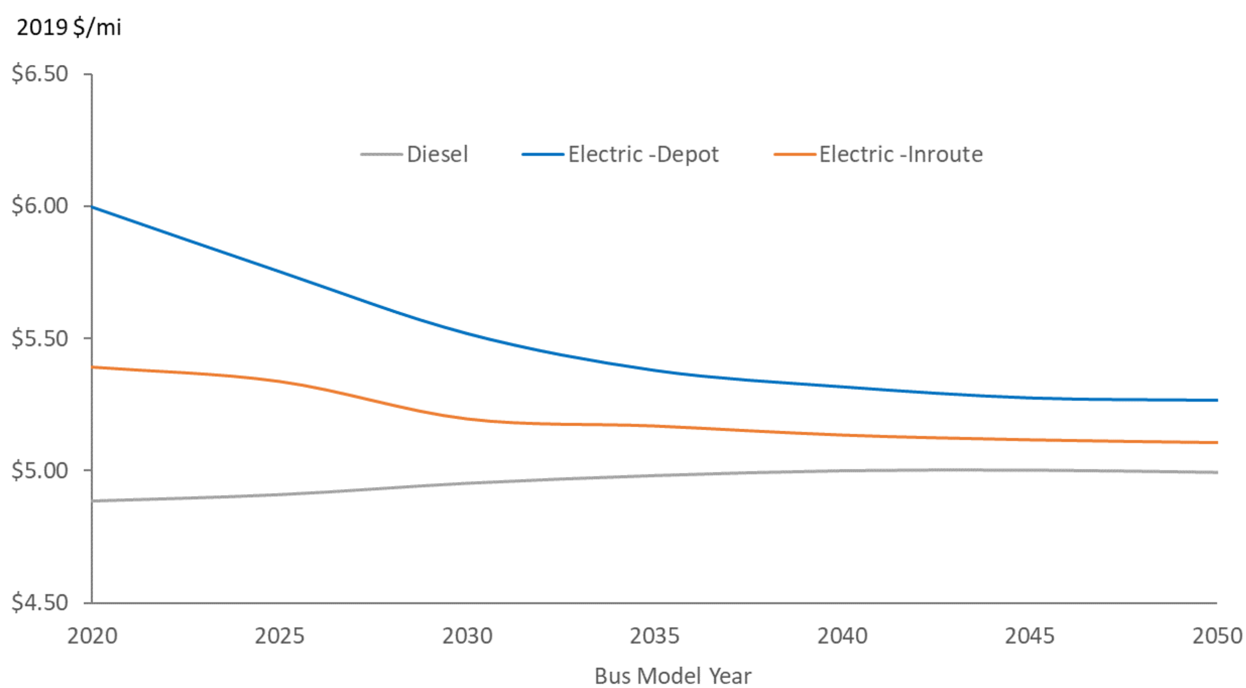
In the past 5 years the cost of bus batteries ($/kWh) has fallen by more than 40%, and most analysts predict that they will continue to fall – by as much as another 50 – 70 percent by 2035. Industry participants also project that the costs of electric drive trains will fall by as much as 50 percent over 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. The Energy Information Administration also projects 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 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 introduction into transit (CNG, hybrid-electric).

Figure 25 Projected Life Cycle Cost for Model Year 2020 – 2050 Buses



See Figure 25 for MJB&A's projection of MCTS life-cycle costs (2109 $/mi) for diesel and electric buses purchased between model year 2020 and 2050. Over their life, average costs for electric buses purchased in 2020 are projected to be $5.61 - $5.99/mile, an increase of $0.73 - $1.11/mile compared to diesel buses. By model year 2030 the incremental cost over their life of electric buses compared to diesel buses is projected to fall to $0.24 - $0.57/mile, and by 2050 it is projected to fall to only $0.11 - $0.27/mile.

Also note that over time the cost difference between depot charging and in-route charging will narrow, because reductions in battery costs and increases in battery size have a greater positive effect on the economics of depot charging than in-route charging. For buses purchased after model year 2040 depot charging could be less than \$0.20/mile more costly than in-route charging for MCTS.

6 Emissions Analysis

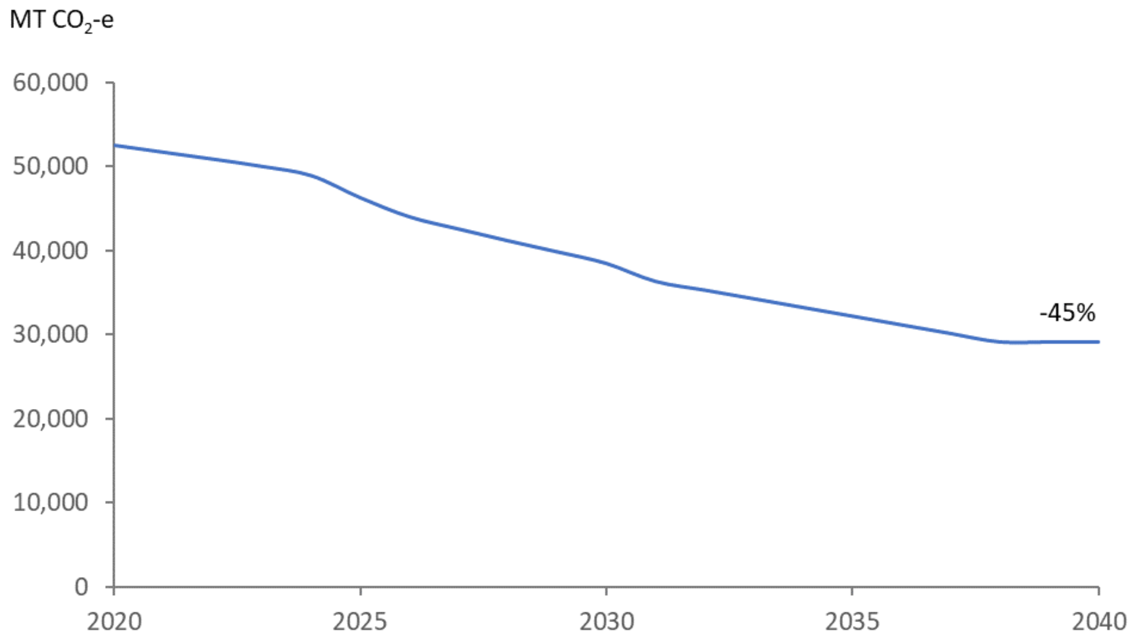
This section summarizes an estimate of annual fleet emissions of greenhouse gases (GHG), nitrogen oxides (NOx), and particulate matter (PM), under an aggressive electrification scenario which assumes that after 2025 MCTS will purchase only battery electric buses, to replace retiring diesel buses. This scenario results in full fleet electrification by 2038.

GHG emissions are a major contributor to global climate change, and the transportation sector is the largest contributor to total GHG emissions in the United States. NOx and PM are the two pollutants emitted by internal combustion engines of most significant concern. NOx combines in the atmosphere with volatile organic hydrocarbon, in the presence of sunlight, to produce ground level ozone - also known as smog - which is a respiratory irritant that can contribute to or exacerbate lung and breathing problems. NOx also contributes to the formation of secondary PM particles in the atmosphere. Atmospheric PM – both directly emitted and secondary PM - has been shown to cause or exacerbate respiratory and cardiac disease and has been linked to an increased incidence of lung cancer and premature mortality.

Estimated total annual greenhouse gas (GHG) emissions from the MCTS bus fleet are shown in Figure 26. For diesel buses in the fleet this figure includes both tail-pipe emissions and upstream emissions from production and transport of diesel fuel. For electric buses in the fleet it includes emissions associated with generating the electricity used to charge the buses. Total GHGs plotted in Figure 26 include emissions of carbon dioxide (CO_2), as well as emissions of methane (CH_4) and nitrous oxide (N_2O) converted to CO_2-equivalent emissions using their global warming potential over 100 years (GWP_{100}).

As shown, the current MCTS diesel bus fleet is estimated to emit 52,500 metric tons (MT) of GHGs per year. Once the fleet is converted to all electric buses annual GHG emissions will fall to 29,100 MT, a reduction of 45 percent. This estimate is based on the current electric generation mix; if the electric grid in Wisconsin is further de-carbonized by replacing coal and natural gas generation with renewable sources (solar, wind), total GHG emissions associated with MCTS electric buses will be even lower.

Figure 26 Projected MCTS Fleet GHG Emissions with Electrification



See Figure 27 and Figure 28 for estimated annual MCTS fleet emissions of NOx and PM, respectively. These figures only include local diesel bus tail-pipe emissions within the MCTS service area[21].

As shown, the current MCTS diesel bus fleet is estimated to emit 12.8 tons of NOx and 0.38 tons of PM per year in the Milwaukee metro area. Since electric buses have no tailpipe emissions, annual fleet NOx and PM emissions will fall to zero as the MCTS fleet is electrified. As such, MCTS fleet electrification could contribute to improvements in local air quality in Milwaukee, with associated reductions in negative health effects.

[21] Most upstream emissions from production and transport of diesel fuel are not local to Milwaukee or Wisconsin.

Figure 27 Projected MCTS Fleet NOx Emissions with Electrification

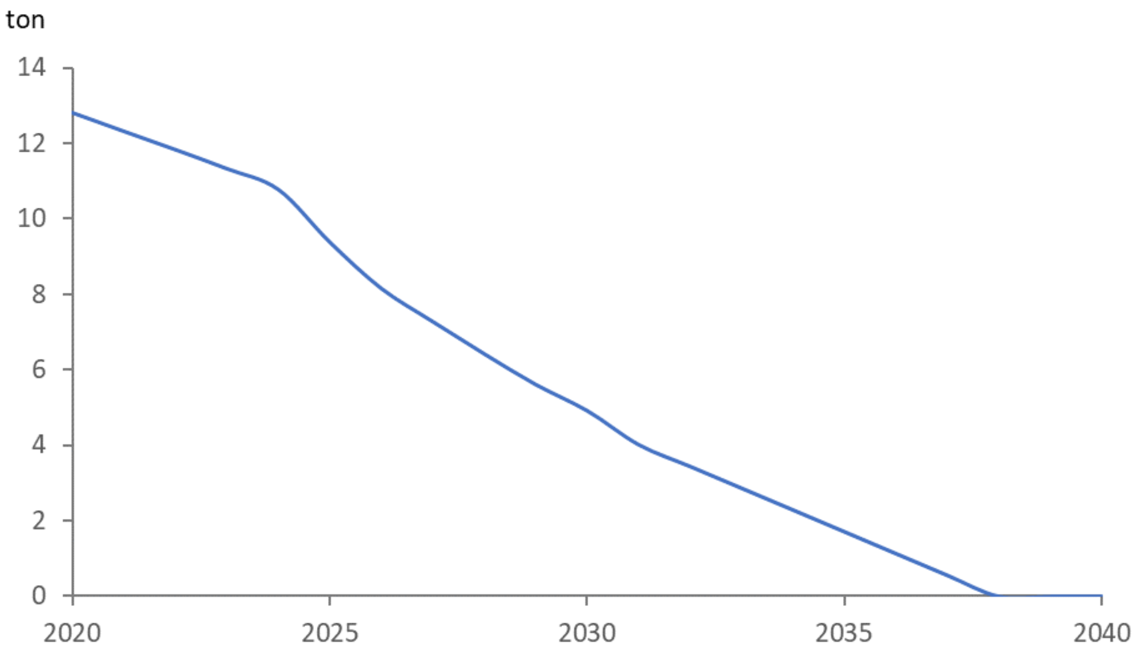
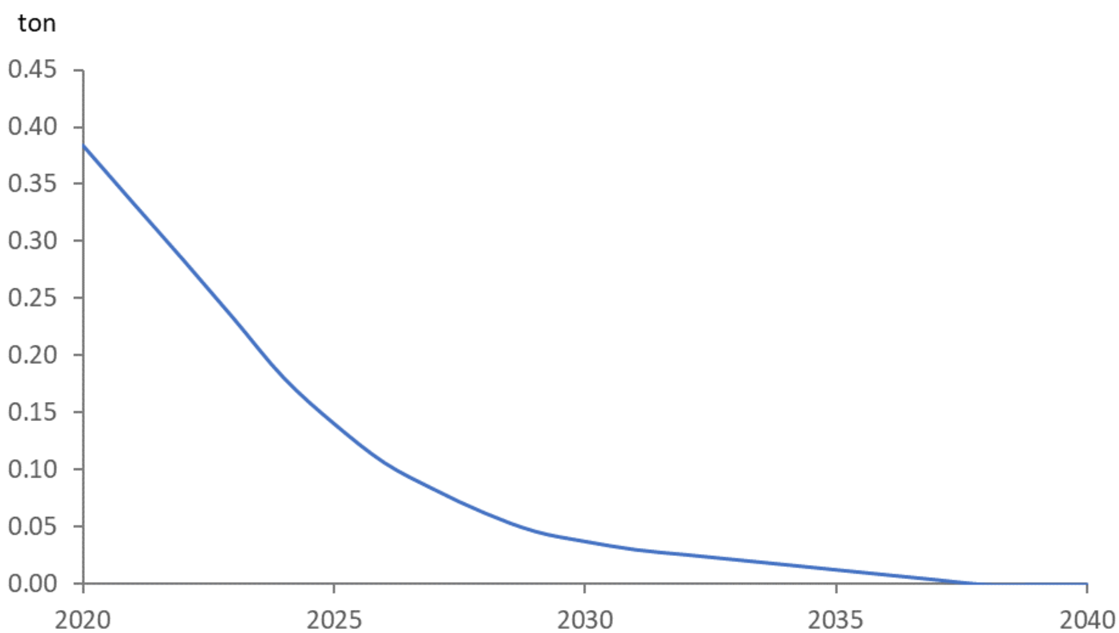


Figure 28 Projected MCTS Fleet PM Emissions with Electrification



7 Fleet Electrification Business Plan

Section 7.1 summarizes recommendations for MCTS's proposed electric bus pilot program, to include operation of electric buses on the new BRT route.

Section 7.2 summarizes the investments that would be required to transition the entire MCTS fleet to electric buses, and projected operating cost savings that would result.

Section 7.3 summarizes operational changes that must be implemented by MCTS to accommodate full fleet electrification.

7.1 Pilot Program and BRT Route Business Plan

MCTS has proposed the purchase of 15 electric buses in 2020, to include eleven buses for the new BRT route and four buses to be deployed on other MCTS routes. This electric bus fleet will serve as a pilot program to allow MCTS to test the technology in revenue service, and to refine plans for further fleet electrification.

Given bus and infrastructure procurement schedules, the electric buses purchased for the pilot program are expected to enter service in late 2021 or early 2022.

This section summarizes recommendations related to this pilot program.

7.1.1 Equipment and Charging Strategy

MJB&A recommends that electrification of the BRT route be implemented using in-route charging. If using in-route charging nine peak buses will be required to operate planned week-day service; an additional two spare buses (11 total) will be required to accommodate maintenance operations. A single 450 kW in-route charger, located at the Watertown Plank Park & Ride, will be required to serve this route.

It would not be practical or cost-effective to use in-route charging for the remaining four electric buses in the pilot fleet. These buses will need to be charged over night at the assigned depot; this will allow them to be used across the system on virtually any route, to fully test the technology across all MCTS operations.

In order to maintain maximum flexibility in how the electric bus pilot fleet can be deployed, MJB&A recommends that all 15 buses be identical, equipped with a large 450 kWh battery and SAE J3105-1 conductive charge rails on the roof of the bus, compatible with an overhead pantograph charger. This will allow all electric buses to be used on the BRT route or on any other route. For depot charging those buses not used on the BRT route, one 450 kW pantograph charger will be required at the depot, rather than individual corded chargers for each bus. Charge time for each bus charged at the depot will be less than one hour per day, so there is enough time to charge the four buses while parked at the depot overnight, using a single charger. The charger can be identical to the charger at Watertown Plank, and can be installed next to the bus storage building (outside) at either Fond du Lac or Kinnickinnic depot. This charger can also provide back-up charging capability for the buses on the BRT route, if the Watertown Plank charger is out of service.

See Table 9 for a summary of recommended specifications for the pilot electric buses, and Table 10 for a summary of capital investments required to implement the pilot program.

Table 10 Recommended Electric Bus Specifications – BRT & Pilot Program

METRIC	RECOMMENDATION
Battery Capacity	450 kWh (nominal)
Charge Port/Location	SAE J3105-1 / On bus roof
Heating System	Supplemental fuel heater included

Table 11 Electric Bus Pilot Program Investments

	Number	Unit Cost	Total Cost
Electric buses	15	$900,000	$13,500,000
Chargers	2	$850,000	$1,700,000
TOTAL			**$15,200,000**

The electric bus pilot program will require $15.2 million in capital funding, for purchase of buses and charging infrastructure. This is $7.5 million more than it would cost MCTS to purchase 11 new diesel buses for the new BRT route, and to purchase four new diesel buses to replace retiring fleet buses.

The electric buses in the pilot program are projected to accumulate approximately 45,000 miles per bus per year (a total of 675,000 electric miles annually) and to use 1,620 MWh of electricity annually, at a cost of $172,000. Fuel for a diesel bus fleet operating the same mileage would cost at least $323,000[22] per year. The electric bus pilot fleet is therefore projected to save approximately $150,000 per year in fuel costs.

[22] 5.5 MPG; $2.63/gallon

7.1.2 Electric Bus Pilot Program Operational Considerations

To implement the proposed electric bus pilot program, MCTS must:

- PURCHASE ELECTRIC BUSES: as a follow-on effort to this analysis, MJB&A is developing an electric bus technical specification, which is consistent with the draft *Standard Bus Procurement Guidelines – Electric Bus,* issued by the American Public Transportation Association in August 2019, but also incorporates MCTS-specific requirements. This specification will be ready to utilize in an MCTS procurement no later than January 2020. Based on prior experience it will likely take at least six months to complete the procurement process, with bus contract award sometime in the second quarter 2020. With current order back-logs bus delivery will likely take at least 12 months, with buses delivered and entering service sometime in the second or third quarter 2021.
- PURCHASE AND INSTALL CHARGERS: To charge the electric bus pilot fleet, MCTS will need to install two 450-kW pole-mounted overhead conductive pantograph chargers. One will be installed at the Watertown Plank Park & Ride lot, to support in-route charging of electric buses operated on the new BRT route. The other will be installed at the depot which houses the electric bus fleet, to provide back-up for the Watertown Plank charger, and to charge the other four electric buses overnight at the depot. MCTS should initiate a final design process for these chargers as soon as possible and start the procurement process for purchase and installation concurrent with the purchase of electric buses.
- CONTRACT FOR CHARGER MAINTENANCE: MJB&A recommends that for this pilot program MCTS contract with the charger manufacturer, the installer, or another third party to provide regular scheduled maintenance (per manufacturer recommendations) and failure maintenance for the overhead chargers. It is particularly critical that a contract mechanism be put in place to allow expeditious repair of charger failures (less than 4 hours response time, less than 12 hours/24 hours repair time for minor/major repairs).
- INCLUDE CHARGING TIME IN BRT SCHEDULES: To replenish the energy used on route, buses on the BRT route are projected to require up to 8 minutes of charge time each time they arrive at the Watertown Plank charging location[23]. All bus blocks for the BRT route should include a minimum 10-minute lay-over period at the Watertown Plank Park & Ride on each trip, to allow for charging.

[23] This is projected charge time on peak winter days with high cabin heating load. It includes one minute for moving the bus in and out of the charger.

- MANAGE DEPLOYMENT OF NON-BRT ELETRIC BUSES: With a 450-kWh battery pack, the electric buses are projected to have a reliable range of 130 miles per charge (approximately 10 hours in-service). Daily bus assignments must be managed to ensure that electric buses are not assigned to longer blocks, or they will run out of energy and need to return to the depot before completing the daily assignment. Electric buses could be assigned to a morning peak block and a second afternoon peak block that together add to more than 130 miles, if charged after returning to the depot from the morning block. However, this would increase average electricity cost for charging buses, due to higher peak-period demand charges.
- MANAGE CHARGING DEMAND: If not using mid-day depot charging to extend the daily range of non-BRT electric buses, the start time of over-night depot charging should be delayed until after 9 PM. This will significantly reduce average electricity costs for depot charging by avoiding peak demand and energy charges. If mid-day depot charging is used, this charging will incur peak demand charges, and overnight charging could start at any time without incurring additional demand charges.

7.2 Full Fleet Transition Business Plan

As discussed above, the electric bus pilot fleet is projected to enter revenue service in late 2021 or early 2022. It would be preferable for MCTS to get two full years of service from this fleet before continuing with fleet electrification. It would be realistic for MCTS to target additional electric bus awards starting in 2025, with a potential to turn over the entire fleet to electric buses as early as 2040.

With this schedule in mind, this section summarizes the capital investments that would be required to achieve full fleet electrification by 2040, as well as projected changes in annual operating costs over that time period.

The projected cost of full fleet electrification is based on the MCTS operational analysis and conceptual charging designs discussed in Section 4. All costs used in the analysis reflect inflation assumptions from the Energy Information Administration's 2019 Annual Energy Outlook reference case. The EIA projects average general inflation of approximately 2.5 percent annually through 2025 and 2.2 percent annually from 2025 – 2040; these values were applied to bus purchase, charging infrastructure, maintenance, and bus operator labor costs. EIA also projects that annual increases in diesel and electricity prices will average 3.5 percent and 2.7 percent, respectively, between 2020 and 2040.

Projected electric bus purchase costs also reflect expected continued evolution of electric drivetrain and battery technology, which will result in bus and battery cost reductions (in constant dollars, not including inflation) as well as increases in maximum battery size for depot-charged buses. The analysis assumes that in constant dollars depot-charged battery buses purchased in 2040 will cost 15 percent less than current buses, despite having a 30 percent larger battery pack and 30 percent greater range. In-route charged battery buses purchased in 2040 are assumed to cost 10 percent less than current buses[24]. Mid-life battery replacements for buses purchased in 2040 are projected to be 15 percent and 36 percent less expensive than for buses purchased today, for depot-charged and in-route charged buses, respectively.

The analysis also assumes that propulsion system maintenance costs for electric buses will fall over time as the technology matures, reaching a 25 percent reduction compared to diesel buses after 2035[25].

The analysis assumes that MCTS will continue to retire existing buses after 14 years in service and will therefore need to purchase an average of 28 new buses every year to replace retiring buses.

Table 12 Total Incremental Costs for MCTS Fleet Electrification

nom$ millions	TOTAL 2025 - 2040		AVERAGE ANNUAL	
	Depot Charging	In-route Charging	Depot Charging	In-route Charging
Bus Purchase	$174.7	$102.5	$10.9	$6.4
Charging Infrastructure	$53.0	$56.0	$3.3	$3.5
sub-total Capital	***$227.7***	***$158.5***	***$14.2***	***$9.9***
Bus Maintenance	($16.7)	($16.7)	($1.0)	($1.0)
Charger Maintenance	$9.0	$12.0	$0.6	$0.8
Battery Pack Replacement	$71.3	$17.7	$4.5	$1.1
Bus Operator Labor	$2.6	$27.3	$0.2	$1.7
Fuel	($93.7)	($80.5)	($5.9)	($5.0)
sub-total operating	**($27.5)**	**($40.2)**	**($1.7)**	**($2.5)**
TOTAL	**$200.1**	**$118.3**	**$12.5**	**$7.4**

[24] Projected significant reductions in battery costs have less effect on the price of in-route charged buses due to their much smaller battery.
[25] This results in a 12.5 percent reduction in total maintenance costs, since about 60 percent of bus maintenance costs are for non-propulsion systems and will not change for electric buses.

See Table 11 for a summary of projected incremental costs to convert the MCTS fleet to 100 percent electric buses between 2025 and 2040. The projected costs are incremental to continued use of diesel buses in the MCTS fleet, and are in nominal dollars, including projected inflation.

As shown, fleet electrification is projected to require $159 - $228 million more in capital funding (nominal $) than continued replacement of retiring buses with new diesel buses, or an average of $10 - $14 million per year. Net operating cost savings are projected to be $1.7 - $2.5 million per year, or a total of $27 - $40 million between 2025 and 2040.

Fleet electrification will produce significant annual savings in bus maintenance and fuel costs, but these will be offset by additional costs for charger maintenance, mid-life battery pack replacements, and bus operator labor.

Based on the cost projections shown in Table 11, MJB&A recommends that MCTS pursue fleet electrification using in-route charging, as this approach is projected to be significantly less expensive than depot charging. While in-route charging will incur higher capital costs for charging infrastructure, and higher incremental operating costs for charger maintenance, bus operator labor, and electricity (resulting in lower net fuel cost savings), there will be significantly lower capital costs for bus purchase, and lower operating costs for mid-life battery pack replacement.

Bus purchase costs for depot charging are projected to be higher than for in-route charging due to both more expensive buses (larger battery) and the need to purchase additional buses due to range restrictions. The analysis projects that fleet electrification using depot charging will require the fleet to increase by 58 buses (+15%).

See Figures 26 and 27 for a summary of the cumulative costs of fleet electrification over time for depot and in-route charging, respectively.

Figure 29 Cumulative Incremental Costs of Fleet Electrification – Depot Charging

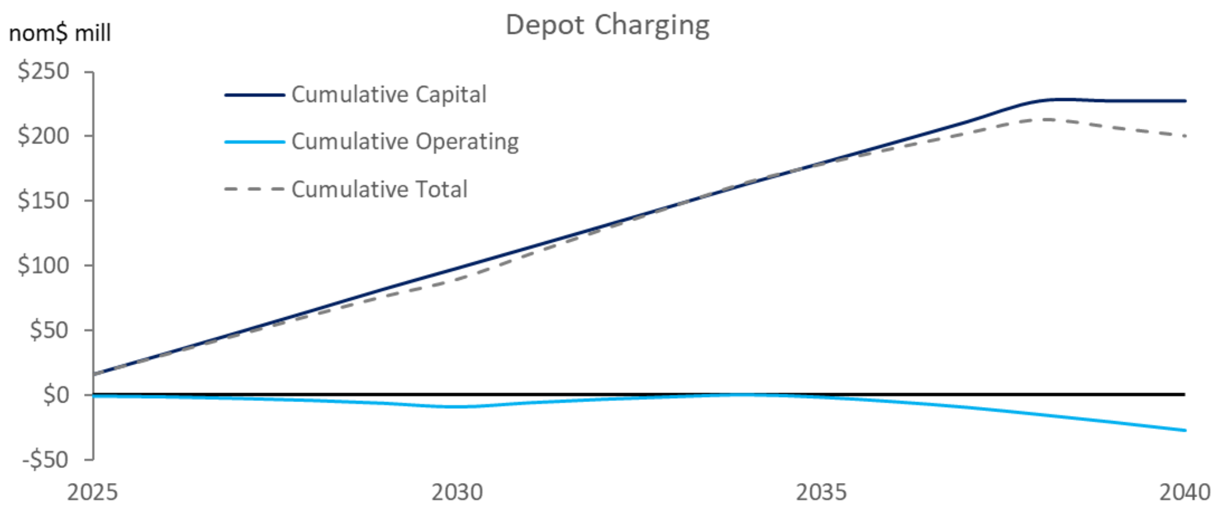
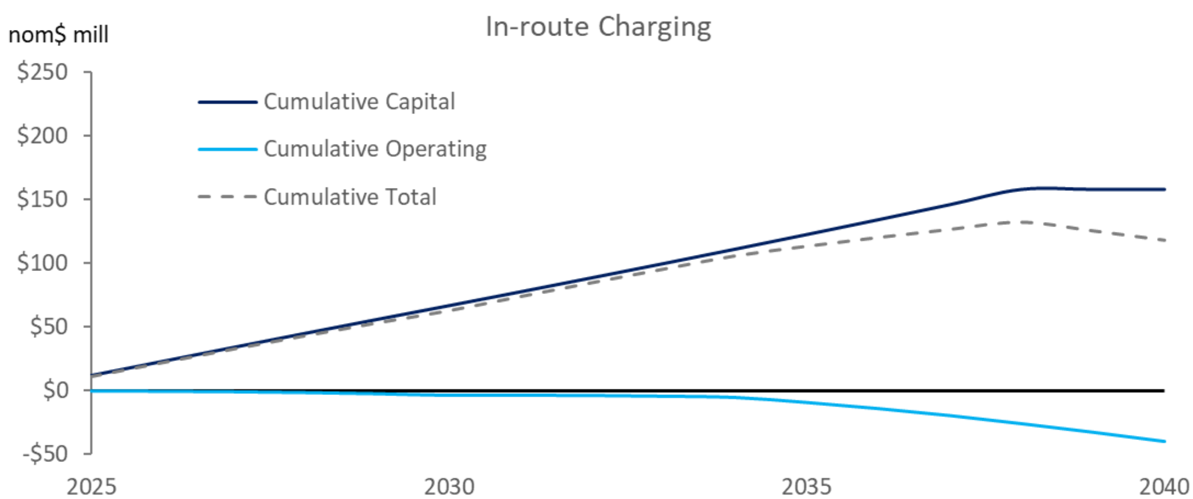


Figure 30 Cumulative Incremental Costs of Fleet Electrification – In-route Charging



In these figures cumulative incremental capital costs are blotted in dark blue, cumulative incremental operating costs savings are plotted in light blue, and cumulative net costs (capital minus operating savings) are shown by the dashed grey line. Under either scenario net operating cost savings are modest through 2035, after which they start to accelerate, and begin to pay back the upfront capital investment for fleet electrification. Under the in-route charging scenario annual net costs for an electric fleet reach parity with costs for a diesel fleet after 2040; in future years annual operating cost savings from operating electric buses will completely off-set the annual incremental capital costs of bus replacement. Under the depot charging scenario, however, annual incremental capital costs for purchase of new electric buses continue to exceed annual operating cost savings after 2040.

Conversion of the fleet to electric buses using depot charging would require fleet size to increase by 58 buses. In addition, as discussed in section 4.3.3 the installation of charging infrastructure at the Fond du Lac and Kinnickinnic depots will reduce available bus parking space by up to 111 buses. Implementing depot charging for the entire fleet will therefore require MCTS to create new depot capacity for up to 170 buses.

To implement depot charging, in the short term likely the easiest option would be to re-open the Fiebrantz depot and to shift 100 existing diesel buses from Fond du Lac to operate from that location. This would open swing space at Fond du Lac to allow installation of charging infrastructure with minimal disruption to depot operations. It would also provide enough additional space to accommodate complete conversion of Fond du Lac to full depot charging operations. However, to convert Kinnickinnic to depot-charged electric buses space for an additional 70 buses would be required. Likely the best option would be to construct an entirely new depot built from scratch to accommodate 170 electric buses, with this depot required to open in 2030 or 2031. After the new depot opened Fiebrantz could be closed permanently and charging infrastructure could be installed at Kinnickinnic. The costs associated with this required depot expansion are unknown and are not included in Table 11.

If implementing depot charging all existing bus blocks would eventually need to be reconfigured, to be no longer than approximately 10 hours or 130 miles. This change would not need to take place all at once; rather the block schedule for portions of the systems would need to be revised every year as additional depot-charged electric buses were added to the fleet.

If electrification were to proceed using in-route charging MCTS would not need to re-open Fiebrantz or build a new depot. However, MCTS would over time need to install approximately 50 450-kW in-route chargers at up to 44 different locations throughout the MCTS service area, or approximately three per year between 2025 and 2040 as electric buses were delivered. This would require acquisition/lease of land or usage rights, design, and permitting. Some locations may also require extensive modifications to pavements and/or curbs to accommodate bus charging.

If implementing in-route charging lay-over times would need to be adjusted as routes are converted to electric operation, to ensure enough charging time at in-route charging locations. In addition to adding time at some lay-overs, it will be advisable to consolidate lay-overs at only one end of the route on most routes, at the charging location. Current practice is to include lay overs at each route terminus. This change will not reduce total lay-over time but will create one long lay-over after each round trip, rather than a shorter lay-over after each one-way trip.

The above discussion highlights the most significant trade-offs between depot and in-route charging. Fleet electrification using depot charging will require MCTS to acquire additional depot space. In-route charging will not require a new depot but will require MCTS to find space to install charging infrastructure at/near the termini of all routes. Optimal development of an in-route charging network may also require modification of some routes, based on constraints related to charger placement.

The above discussion also assumes an aggressive fleet electrification schedule to achieve complete turn-over to electric buses by 2040. Fleet electrification could also proceed at a more measured pace, in line with available funding. Electrification using in-route charging could proceed on a route-by-route basis, with relatively modest investments required for conversion of each route. The most heavily used routes in the MCTS system are the Blue, Gold, Red, Green, and Purple express routes. The Blue route requires seven peak buses on weekdays, while the other express routes require between 11 and 13 peak buses each. Other MCTS fixed routes require between two and 15 peak buses each on weekdays, with an average of seven. Including spare buses, the express routes each require 8 -15 total buses, while on average other fixed routes each require eight. The Green and Purple routes would each require two chargers to support in-route charging on the route, while most other fixed routes only require one charger each.

The estimated incremental capital costs to electrify the express routes using in-route charging are $2.9 million for the Blue route, $4.2 million each for the Gold and Red routes, $5.4 million for the Green Route, and $5.6 million for the Purple Route. This includes the cost of required in-route chargers and the incremental cost of required electric buses compared to new diesel buses. The average incremental capital cost to electrify other MCTS fixed routes is $2.9 million per route. As noted, most routes will require only a single in-route charger at a single location, so conversion of individual routes to in-route charging will require modest effort to develop the necessary charging infrastructure.

If fleet electrification proceeds at a modest pace, over the next ten years MCTS will need to replace some retiring diesel buses with new buses that are not battery buses. A complementary approach to consider is replacement of these retiring buses with hybrid-electric buses, until funding is available to commit to 100 percent replacement of diesel buses with battery-electric buses.

Hybrid electric buses currently cost approximately $260,000 per bus more than diesel buses[26], but do not require any investments in charging infrastructure. They also have no range

[26] Based on 2019 APTA Transit vehicle database. This database includes 2,297 diesel buses and 456 hybrid-electric buses with bus length between 37-ft and 42-ft, and build year between 2017 and 2021, for which purchase price is

restrictions so can be used on any MCTS routes without changes to schedules or bus blocks. In MCTS service hybrid-electric buses are projected to use at least 17 percent less fuel than diesel buses and to emit 17 percent fewer greenhouse gas (GHG) emissions. In MCTS service average life-cycle costs of hybrid-electric buses are projected to be 6 percent higher than life-cycle costs for diesel buses (+$0.44/mile), including both capital and operating costs[27].

Hybrid electric buses do not reduce GHG emissions as dramatically as battery electric buses, but they are also less costly to implement. Replacement of some retiring diesel buses with hybrid-electric buses is a complementary interim strategy to full fleet electrification.

7.3 Fleet Electrification – Operational Changes

This section summarizes the major changes to MCTS bus fleet operations that will be required to accommodate full transition of diesel buses to battery electric buses. Changes will be required to bus schedules, bus maintenance programs, and cold weather operations. MCTS will also need to develop completely new capabilities to regularly monitor bus charging activities, and to maintain and repair charging infrastructure. MCTS should also develop contingency plans to maintain bus charging in the event of loss of grid power at one or more charging locations.

7.3.1 Bus Scheduling

Depot charged buses have limited in-service range before needing to be re-charged. On Fixed and Flyer routes current scheduling policies result in some daily bus assignments (blocks) that are too long for depot-charged buses to handle on a single charge.

Assuming nominal battery pack capacity of 480 kWh (for buses purchased in 2025) all daily bus blocks will need to be limited to no more than 10 hours or 140 miles between the bus leaving and returning to the depot, if depot charging will be used[28]. This limitation is projected to increase peak bus requirements for MCTS fixed routes by 27 percent on average for buses purchased in 2025[29], and to increase dead-head mileage; these increases are accounted for in

---

listed. The weighted average price of these diesel buses is $504,000 and the weighted average price of these hybrid buses is $767,000.

[27] This estimate is based on a 2016 Alternative Fuel Bus study conducted for MCTS by MJB&A, but with bus purchase and fuel costs updated to current assumptions.

[28] 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. Maximum battery pack size is also expected to increase over time for all manufacturers – as it does range will increase and the noted daily block length limitation can increase for newly acquired buses, but not for existing buses in the fleet.

[29] For buses purchased in later years the increase in peak bus requirements will be lower, based on expected increases in maximum battery capacity. The projected increase in peak bus requirements is projected to fall to 19 percent for buses purchased in 2030 and 10 percent for buses purchased in 2035.

the bus purchase and charging infrastructure investments, and in the projection of incremental operating costs, detailed in section 6.2.

Required charging time for in-route charging ranges from 5 to 20 minutes per round trip on different routes, while existing lay-over time ranges from 5 to 13 minutes. On some routes the required charging can be accommodated within the existing lay-over time, while on other routes it cannot, and additional lay-over time would need to be added to some schedules to accommodate in-route charging. The fact that buses currently lay over at the end of each one-way trip, and charging is only required once every round trip on most routes increases the amount of additional lay-over time that will need to be added for charging. If the current policy to lay over after each one-way trip is maintained, 23 – 35 minutes per day per peak bus will need to be added to all fixed-route schedules, to accommodate charging. If, however, current lay-over time were consolidated to happen once every round-trip (at the charging location) only 8 – 9 minutes per day per peak bus will need to be added to fixed route schedules to accommodate in-route charging.

7.3.2 Bus Maintenance

The bus maintenance program will need to evolve 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 MCTS diesel buses; only 25 – 40 percent of current maintenance activities will change. Nonetheless, the following maintenance issues will require attention:

- All maintenance employees will require high voltage training, and many propulsion system 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 regular 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 Fleet

Maintenance Facility, or MCTS 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. This will be a major expense which must be budgeted for annually, beginning 6-7 years after the first battery buses enter service. 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. MCTS 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 MCTS. 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.

7.3.3 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 32 °F and 70 °F. 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. Batteries have high thermal mass (they cool off slowly) and generate internal heat as they are discharged during driving. As such, cold winter weather is not expected to pose significant constraints on electric bus operation, if buses start the day with internal pack temperature above 50 °F. Since buses are generally stored indoors at MCTS depots, this is easily achievable. Nonetheless, MCTS operating personnel must be aware of this constraint, and put in place procedures to ensure that buses are not left outdoors at the depot overnight during the winter, and that heating systems in bus storage areas are operational.

7.3.4 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 400 miles or greater range from a full tank of fuel. As such, MCTS 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, MCTS should:

- For Depot Charging: equip each depot 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.
- For In-route Charging: 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.
- For In-route Charging: Develop procedures and systems to monitor charging status and state of charge 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 road supervisors or 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 depot) due to low charge state.
- Develop the maintenance capability to respond to all 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 9 PM and 5 AM for depot charging, or between 6 AM and 8 PM for in-route charging.

7.3.5 Charging Infrastructure Maintenance

MCTA will need to develop an entirely new maintenance capability, which does not exist today, involving servicing, diagnostics, and repair/replacement of charging infrastructure, for either depot chargers or 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; 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 many jurisdictions, anyone working on electrical components when there is a potential to contact live conductors must be licensed as an electrical contractor by the state. Employees conducting some routine maintenance tasks may not require licensing, but those performing failure maintenance may.

MCTS 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.

7.3.6 Contingency for Loss of Grid Power

For a full fleet roll-out of electric buses, MCTS should make contingency plans for maintaining some level of bus charging even if grid power is disrupted to one or more charging locations. 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[30], with each providing the ability to supply power to one in-route charger.

The number of chargers 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

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

simultaneously. MCTS should work with WeEnergies to identify historical trends and to project future needs.

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