Final Report

Ann Arbor Area Transportation Authority

Alternative Propulsion Bus Study

December 2022

Stantec

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Alternative Propulsion Bus Study – Final Report

Bus Propulsion Study

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Ann Arbor Area Transportation Authority

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ALTERNATIVE PROPULSION BUS STUDY – FINAL REPORT

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Abbreviations

AAATA	Ann Arbor Area Transportation Authority
AC	Alternating Current
AC Transit	Alameda-Contra Costa Transit District
API	Application Programming Interface
APC	Automatic Passenger Counter
AVL	Automatic Vehicle Locator
AVTA	Antelope Valley Transit Authority
BEB	Battery-electric Bus
BTC	Blake Transit Centre
CAM	Cathode Active Materials
CCS	Carbon Capture Storage
CFU	Cubic Foot per Meter
CMS	Charge Management System
CMU	Concrete Masonry Unit
CNG	Compressed Natural Gas
CTE	Center for Transportation and the Environment
DC	Direct Current
EIA	Energy Information Administration
ESS	Energy Storage Systems
EV	Electric Vehicle
FCEB	Hydrogen Fuel Cell-electric Bus
FTA	Federal Transit Administration
FY	Fiscal Year
GHG	Greenhouse Gas
GTFS	General Transit Feed Specification
HRU	Hydrogen Refueling Unit
HVAC	Heating, Ventilation, and Air Conditioning
HVDC	High-voltage Direct Current
ICE	Internal Combustion Engine
IP	Internet Protocol
LFP	Lithium Iron Phosphate
Low-No	Low and No Emissions Program
LTO	Lithium Titanate Oxide
MDOT	Michigan Department of Transportation
MPDGe	Miles per Diesel Gallon Equivalent
MPSC	Michigan Public Service Commission
MTPD	Metric Tons per Day
MVA	Megavolt Ampere

MW	Megawatt
NCA	Nickel, Cobalt and Aluminum Oxide
NFPA	National Fire Protection Association
NMC	Nickel, Manganese and Cobalt Oxide
NREL	National Renewable Energy Laboratory
NTP	Network Time Protocol
OCPP	Open Charge Point Protocol
OCTA	Orange County Transportation Authority
OEM	Original Equipment Manufacturer
PM	Particulate Matter
PPE	Personal Protective Equipment
PSI	Pounds per Square Inch
PV	Photovoltaic
RFP	Request for Proposals
SARTA	Stark Area Regional Transit Authority
SEMCOG	Southeast Michigan Council of Governments
SMART	System Maintenance Automated Repair and Test
SMR	Steam Methane Reformation
SOC	State of Charge
SOH	State of Health
SWOC	Strengths, Weaknesses, Opportunities, and Challenges
TCO	Total Cost of Ownership
TCRP	Transit Cooperative Research Program
TTC	Toronto Transit Commission
UI	User Interface
VPN	Virtual Private Network
YTC	Ypsilanti Transit Center
ZE	Zero Emission
ZEB	Zero-emission Bus
ZEV	Zero-emission Vehicle
ZEBRA	Zero Emission Bus Resource Alliance

1.0 EXECUTIVE SUMMARY

1.1 OVERVIEW OF STUDY

The Ann Arbor Area Transportation Authority (AAATA) Alternative Bus Propulsion Study was conducted to explore zero-emission bus (ZEB) propulsion technologies and assess the benefits and challenges of transitioning from a fossil fuel bus fleet to a ZEB fleet.

The move to ZEBs is primarily driven by an increasing regulatory push towards cleaner transportation, rapid advancements in bus and battery technologies, favorable fiscal incentives, new funding programs, and a maturing electric vehicle market providing lower costs and reduced technological risks. Although diesel buses have gotten cleaner, there are emerging ZEB technologies available today that will provide an even cleaner alternative.

The last several years have seen a rapid deployment of low-emission and ZEB technologies globally. As of 2021, 1,287 ZEBs have been deployed in the US, roughly 2% of the ~66,000 transit buses nationwide. In Michigan, a total of 15 BEBs and 2 FCEBs are currently in operation[1].

While Michigan has no state mandate for transit agencies to adopt ZEBs, the City of Ann Arbor has established targets to reduce climate change through the (non-binding) A^2ZERO Climate Action Plan. The A^2ZERO Plan estimated that AAATA's fleet emits ~10,700 tons of CO_2e annually, or about 0.5% of greenhouse gas (GHG) emissions throughout the region. Overall, the GHG emissions from AAATA's fleet is small and the cost to decarbonize is high.

The Alternative Bus Propulsion Study first considered a range of low emission and ZE technologies including: compressed natural gas, trolleybuses, battery-electric, and hydrogen fuel-cell electric buses. However, because natural gas buses are still carbon emitters and because trolleybuses would not be feasible due to environmental impacts related to tree-cutting required to install overhead wires, these technologies were not analyzed in depth.

The two technologies analyzed in detail in this study are hydrogen fuel cell-electric buses (FCEB) and battery-electric buses (BEB). Diesel and diesel hybrid-electric technologies were used for comparison to ZEBs and to create baseline scenarios.

BEBs and FCEBs are considered ZE technologies. Both use electricity to power their traction motors but require different fueling methods. BEBs use batteries to store electricity and typically require numerous charging stations and several hours to recharge. FCEBs use fuel cells to generate electricity by combining hydrogen and oxygen. They are fueled by filling a storage tank on the order of several minutes, and typically require only one fueling station.

[1] https://calstart.org/wp-content/uploads/2022/01/2021-ZIO-ZEB-Final-Report_1.3.21.pdf

The study comprised of six main elements to evaluate the benefits, opportunities, challenges, risks, and costs of adopting different propulsion technologies:

1. Overview of current bus propulsion technologies
2. Assessment of AAATA's current bus operations
3. Battery-electric bus (BEB) technology assessment and modeling
4. Hydrogen fuel cell-electric bus (FCEB) technology assessment modeling
5. BEB and FCEB fleet transition financial analysis
6. BEB and FCEB emission reductions analysis

1.2 AAATA CURRENT CONDITIONS

AAATA currently operates a fleet of 103 heavy-duty transit buses for fixed-route service. AAATA operates both diesel and diesel hybrid-electric buses and typically completes bus refueling overnight in preparation for the next service day.

The agency's facility houses vehicle service, fueling, interior fleet parking, exterior employee parking, maintenance, administration, and operations. The facility meets AAATA's current operations and maintenance functions. Nevertheless, space is at a premium at AAATA's facility; the fleet size is currently housed in a facility designed for a fleet of about 100 buses, so any fleet expansion—whether for service growth and/or because of propulsion-related technology limitations—will need careful planning to minimize disruptions. In essence, AAATA's current facility may limit the ability of AAATA to fully transition to ZEBs or at the very least, to expand the fleet to increase service levels.

Operationally, buses are rotated through different bus assignments—known as blocks—each day, meaning the range of the propulsion system is sized for the requirement of the largest bus assignment. An analysis of bus assignments indicates that mileages typically do not exceed 300 miles per day, and about 70% of blocks are scheduled for 200 miles or fewer per day. As a point of reference, diesel buses can comfortably achieve 400 miles on a single tank, while BEBs can achieve about 100-250 miles, and FCEBs can achieve about 200-300 miles.

1.3 BEB AND FCEB GENERAL CONSIDERATIONS

When comparing BEB and FCEB technologies, several factors should be considered. Table 1 below provides a general comparison of BEBs and FCEBs on key factors.

Table 1: BEB and FCEB General Considerations

Factor	BEBs	FCEBs
Range	Shorter range (100-250 miles) of operation compared to fossil fuel buses (400+ miles)	Range of operation comparable to fossil fuel buses (200-300 miles vs. 400+ miles)

Factor	BEBs	FCEBs
Capital Cost	Vehicles are about double the capital cost of fossil fuel fleets As fleet size increases, so do incremental costs such as additional chargers and energy demand	Vehicles are about triple the capital cost of fossil fuel fleets Requires costly hydrogen fueling infrastructure
Operating and Maintenance Costs	Fuel costs likely to be lower than diesel because electricity rates are more stable and predictable, and BEBs are more fuel efficient compared to diesel buses Fewer parts to maintain, so cost savings can be incurred from maintenance	Hydrogen fuel costs are more expensive than electricity and diesel fuel, but costs are expected to come down in the future Fewer parts to maintain, so cost savings can be incurred from maintenance
Pros	Lower vehicle costs compared to hydrogen Lower maintenance costs Battery range expected to improve Lower fuel costs	Long operating range – can deliver over 90% of AAATA service in cold weather Minimal changes to servicing cycle (fueling, etc.) Lower maintenance costs More cost effective at scale
Cons	Range limited. Can deliver 62% of AAATA service in cold weather Space requirements for chargers and related infrastructure Electrical upgrades required Electricity rates more complex than diesel contracts Less cost effective at scale	Space requirements for on-site fueling infrastructure More expensive vehicles Significant building upgrades More expensive fuel compared to electricity – costs coming down

Scalability is also a crucial factor to take into consideration. With a small fleet, a BEB implementation is less expensive and simpler. However, a larger bus fleet will require more chargers and utility upgrades, increasing the price and complexity of the implementation. Conversely, FCEBs can be a more cost-effective option for larger fleets. The larger fixed cost of hydrogen fueling infrastructure becomes cheaper on a per bus basis (Figure 1).

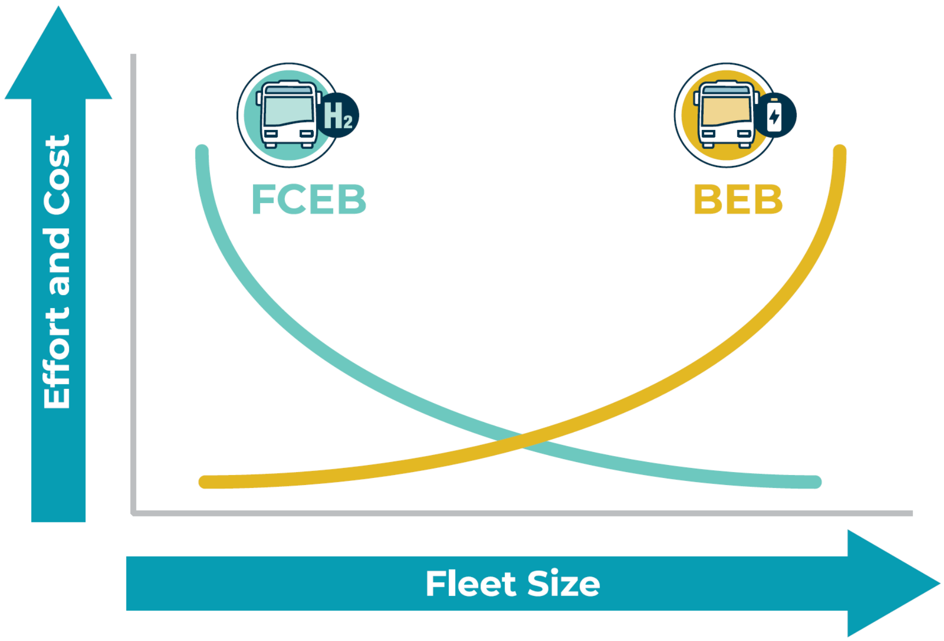


Figure 1: Scalability of FCEBs and BEBs (Source: TCRP, CTE)

In addition, energy density is a key factor to consider. The energy density of a fuel directly impacts the range of the vehicle. Different types of fuels have different relative energy densities, and some require more storage space and are heavier. Gasoline and diesel require less storage space, are relatively light weight, and have a high energy content per unit volume. Batteries and hydrogen fall lower on these scales, as illustrated in Figure 2 below.

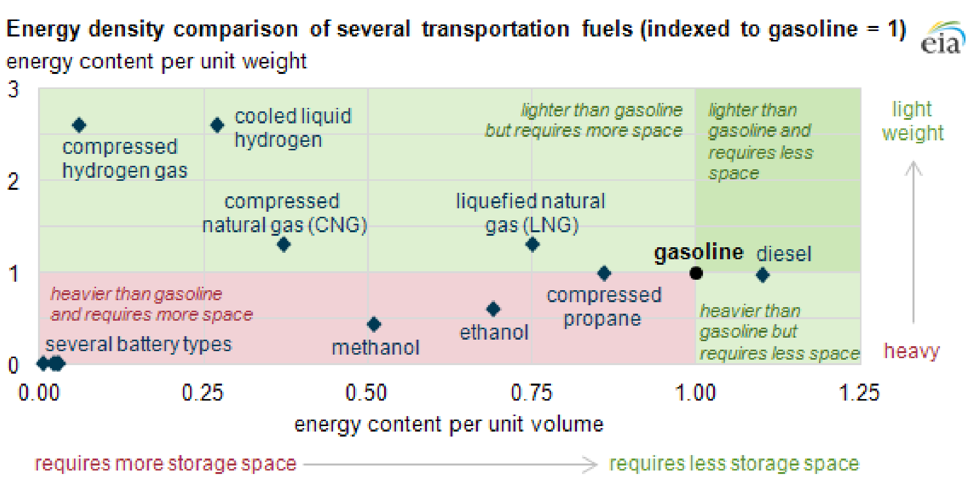


Figure 2: Energy density of transportation fuels. Source: EIA

Figure 2 illustrates how much more energy-rich fossil fuels like diesel tend are by volume. Furthermore, on the graph, diesel fuel sits to the right of batteries as a fuel, meaning that diesel fuel requires less storage space for a greater amount of energy per unit volume. Put another way, batteries need to be very large to carry the same amount of energy as diesel fuel. Heavy battery packs may in turn reduce fuel efficiency as well as limit potential route alignments based on weight restrictions for certain roadways like bridges or overpasses.

Similarly, compressed hydrogen gas is less energy dense than diesel, but slightly more than batteries. However, because compressed hydrogen gas is much lighter weight than diesel fuel, more of it can be stored onboard a bus without excessively increasing the weight compared to batteries. Overall, the notion of energy density helps explain some of the trade-offs associated with ZEBs and their operating range characteristics.

1.4 BATTERY-ELECTRIC BUS ASSESSMENT AND MODELING

AAATA and Stantec developed a preferred BEB concept based on workshops and conversations with AAATA staff, service analysis, and route modeling. The preferred concept is a BEB fleet with long-range batteries that will be charged in-depot. BEBs with 675 kWh batteries could successfully deliver 97% of service on mild days (59°F), but only 62% on cold days (10°F). Deploying on-route opportunity chargers at transit centers could elevate that cold day success rate to 87%, but may introduce other operational challenges, as well as increase capital and operating costs.

The preferred site concept uses an overhead pantograph charging arrangement while clustering charge cabinetry remotely. While pantograph chargers are more expensive than plug-in chargers, the space limitations at AAATA's facility requires an overhead approach to minimize the footprint and maximize space for vehicles. A BEB implementation will require electrical service upgrades because the existing electrical system is not adequate to serve the loads that will result from the full build out of BEB chargers.

With a BEB fleet, a portion of service will require restructuring of vehicle assignments that exceed the operating ranges of BEBs. Furthermore, AAATA can explore other options such as considering blocking range limitations for summer and winter weather, procuring BEBs with diesel-fired heaters, or deploying BEBs primarily on blocks within feasible ranges while keeping diesel buses assigned to the most challenging blocks. As battery technology improves, the operational alterations required are likely to diminish long-term. However, additional analysis is required to map out the scheduling of BEBs for AAATA's future service plans.

1.5 HYDROGEN FUEL CELL BUS ASSESSMENT

The preferred FCEB concept will replace diesel buses one-to-one. Route modeling demonstrated FCEBs can achieve 100% of AAATA blocks on mild days, and 91% of blocks on very cold days. Therefore, minor re-blocking will be required to achieve 100% service on very cold days. However, additional analysis is needed to consider the impacts of FCEB scheduling regarding AAATA's future service plans.

The preferred site concept requires site alterations to accommodate new hydrogen fueling infrastructure. If FCEBs are implemented, major HVAC system upgrades and a new gas detection system will be required. Additionally, building retrofits will be necessary to facilitate indoor hydrogen fueling.

1.6 FINANCIAL ANALYSIS

The financial analysis included a total cost of ownership (TCO) analysis and an evaluation of operating and capital budget impacts. This two-tiered approach is critical to ZEB planning for two primary reasons. First, it facilitates the ability to make final tweaks to the ZEB scenarios to ensure they are optimized for costs in addition to operational impacts, delivering maximum value for taxpayer dollars. Second, it provides valuable information for AAATA to facilitate future budgeting activities, grant applications, and more informed decision making.

Four different scenarios were financially modeled for the ZEB transitioning at AAATA. These scenarios included the following:

1. Transition to BEBs, procurement-based approach (8 buses per year, 13 years to complete)
2. Transition to BEBs, accelerated approach (14 buses per year, 7 years to complete)
3. Transition to FCEBs, procurement-based approach (8 buses per year, 13 years to complete)
4. Transition to FCEBs, accelerated approach (14 buses per year, 7 years to complete)

A “procurement-based approach”—applied to scenarios 1 and 3—involves the annual replacement of 8 diesel buses from 2024 through 2035, with 3 remaining buses replaced in 2036. This is in line with AAATA’s current procurement practices of replacing an average of 8 buses per year. Essentially, the procurement-based approach maximizes the value of AAATA’s existing fleet assets, and ZEBs are modeled to replace diesel buses only once the diesel buses have reached the end of their useful life.

The “accelerated approach” (scenarios 2 and 4), with the aim of converting AAATA’s entire fleet into ZEBs by the year 2030, was also analyzed. In the accelerated approach, 14 diesel buses are assumed to be replaced per year with ZEBs from 2024 through 2029, with the remaining 15 buses replaced in 2030.

The financial modeling, when completed over a 25-year forecast period, illustrates that scenario 1 (transition to BEBs, procurement-based approach) has the most favorable business case, with a TCO of $115M, compared to $138M, $130M, and $157M for scenarios 2, 3, and 4 respectively. This suggests that a ZEB replacement schedule that dovetails with AAATA’s current procurement schedule is ideal, and ensures that AAATA’s current diesel buses can continue to be utilized for their full 12-year lifecycle. Exploring a faster transition plan, for example full fleet conversion by 2030, or exploring different ZEB technologies such as FCEBs would make for a more complex transition, would necessitate additional costs, and would result in an underutilization of existing assets.

The major cost drivers of a transition to BEBs include the capital cost of infrastructure (approximately $22M of incremental costs) and the capital cost of the vehicles (approximately $310,000 of incremental costs per bus, compared to diesel buses). However, there could be cost saving opportunities on the operating and maintenance side, with a "best guess" estimate at $101M in savings over the 25-year forecast period through the implementation of scenario 1. However, to achieve these cost savings, AAATA will require an additional $75M in capital funding throughout the forecast period, and an initial $7.7M investment in year 1 (2023). It is important to also appreciate that capital requirements may end up being larger than $75M in the event the transition to BEBs necessitates additional vehicle purchases, or in the event that unit costs do not decrease over time to the extent envisioned.

1.7 KEY CONSIDERATIONS

1.7.1 Benefits

Greenhouse Gas (GHG) Emissions Reduction

The chief benefit of transitioning to a ZEB fleet is the reduction of the region's GHG emissions. Four scenarios were modeled over 12 years to understand how ZEB technologies will impact emissions. Based on the agency's current diesel operations, the modeling estimated that AAATA's existing fleet emits approximately 7,000 tons of CO_2 annually, slightly lower than the GHG emissions estimated by the A^2ZERO Plan (10,700 tons).

While ZEBs are zero emissions at the tailpipe, the electrical grid in Michigan isn't 100% green, and hydrogen sources vary in their carbon neutrality. Assuming that AAATA will purchase green energy from DTE and green hydrogen produced through electrolysis, a 12-year period of ZEB replacement will result in:

- 41,000 tons of GHGs for BEBs
- 43,000 tons for FCEBs using electrolysis
- 61,000 tons for FCEBs using steam methane reforming methods of hydrogen production

Comparatively, continued operation of diesel buses will emit 82,000 tons of GHGs over the same time period. Emissions never reach zero in this timeframe due to emissions created by the continued operation of diesel buses during the transition to ZEBs. However, a fleet of entirely ZEBs with green electricity or green hydrogen would virtually eliminate the carbon footprint of AAATA's fleet.

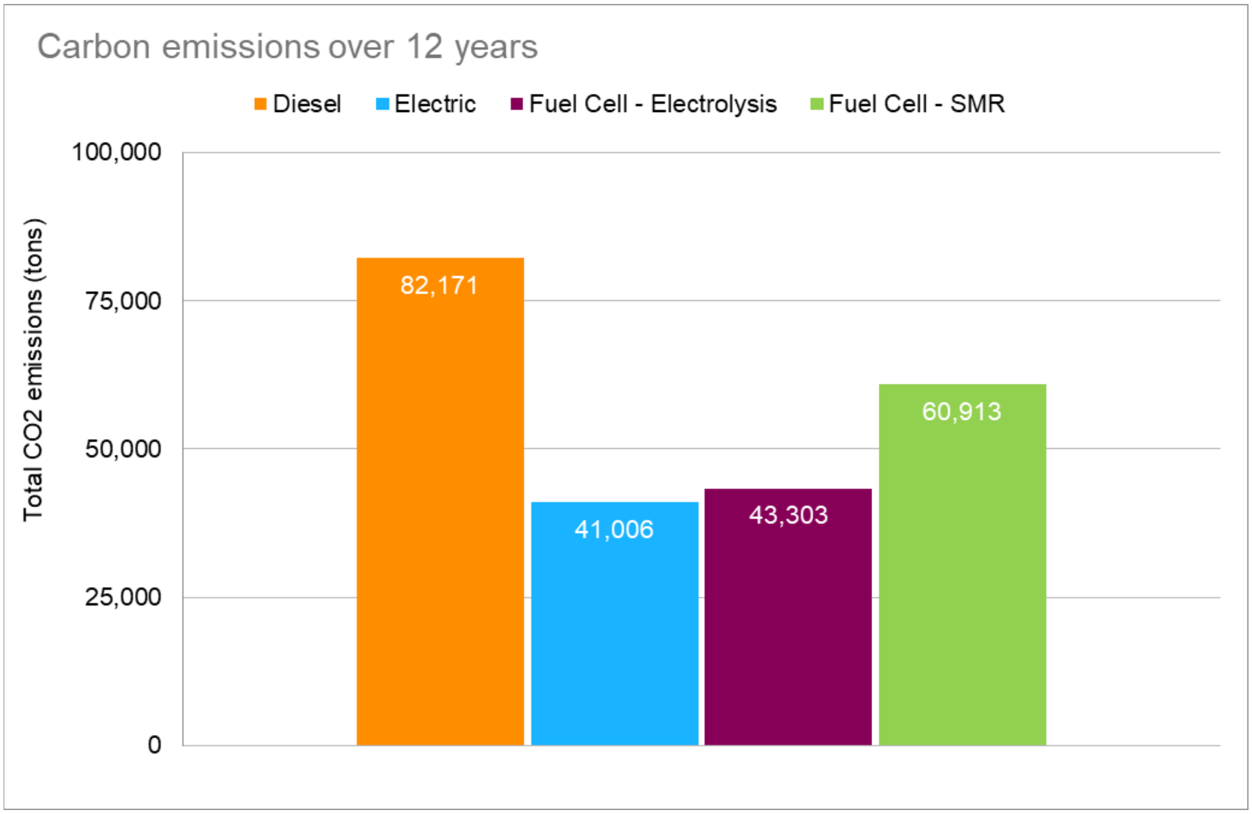


Figure 3: Total Carbon Emissions over 12 Years

Overall, adopting **ZEBs could reduce AAATA's fleet-based carbon footprint by 27-50% over a 12-year timeframe, which translates to a community-wide emissions reduction of less than 0.5%.** This aligns with the fact that the mileage AAATA's buses travel is also less than 1% of all vehicle miles traveled in the region. The Southeast Michigan Council of Governments (SEMCOG) estimates that in 2019, there were 3.95 billion total vehicle miles driven in Washtenaw County. AAATA's fixed-route buses traveled slightly more than 4 million miles that same year (0.1% of all vehicle miles traveled). Even if only half the total miles can be attributed to the Ann Arbor/Ypsilanti area, AAATA bus mileage would only be 0.2% of the total. Also in 2019, there were 173,441 vehicles registered in the cities of Ann Arbor and Ypsilanti, while AAATA had 103 buses (0.06%).

While AAATA is a small emitter, more localized benefits of ZEB conversion can help improve air quality where buses operate, particularly in communities with existing air quality issues, as well as at bus stops and at transit centers where buses generally idle while serving passengers. For example, diesel buses have been estimated to release between 2,700-3,500 grams of $CO2_e$ per mile along a corridor (depending on operating conditions like traffic, frequency, dwell times), and up to 300 grams of $CO2_e$ while at a bus stop[2]. And importantly, interior cabin air in ZEBs will also be cleaner and more healthful for

[2] Alam, A. and M. Hatzopoulou. 2014. Reducing transit bus emissions: Alternative fuels or traffic operations? Atmospheric Environment, 89: 129-139; https://www.sciencedirect.com/science/article/pii/S1352231014001393

passengers and bus operators. It is unclear whether these levels are significant and further study may be warranted.

In addition, the conversion could also eliminate 16,000 kg of nitrous oxide (NOx) and 113 kg of particulate matter (PM) per year. Further greening of the electrical grid, as well as green hydrogen sources, together with a 100% ZEB fleet will reduce the carbon footprint even further.

Cost Savings

During the COVID-19 pandemic, diesel fuel prices were about $3 per gallon. As of August 2022, diesel fuel now hovers around $5 per gallon. The volatility of diesel fuel prices, coupled with the predictability and lower costs of electricity could translate to future cost savings with a BEB fleet. While hydrogen fuel is more expensive than electricity or diesel fuel, costs are expected to decrease over time to provide a cost savings compared to diesel fuel.

Additionally, the propulsion of systems of ZEBs involve fewer moving parts than a traditional diesel engine, which could result in reduced maintenance needs and cost savings. The learning curve for the new technologies will be steep and retraining of existing staff will be required for a ZEB fleet, but is expected to level off with technology maturation and increased experience from maintenance staff.

Social

There are also social benefits to transitioning to a ZEB fleet through the reduction of negative externalities like health impacts related to GHG reduction. The US Department of Transportation estimates a monetized value of the social costs of carbon emissions at $53 per ton. Therefore, removing 7,000 tons of CO_2 annually represents a potential social benefit of approximately $371,000 per year.

Other

Other factors, such as improved cabin air quality and near-silent operations, make riding the bus safer and more pleasant for both operators and passengers. In addition, the cachet of ZEBs could be leveraged as a marketing tool to grow ridership by offering green transit.

1.7.2 Risks and Challenges

There are several risks associated with ZEB technologies related to planning/scheduling, operations maintenance, cost, safety, and human resources. The risks with the highest likelihood and impact include:

- Service changes and the impacts on fleet size and scheduling
- Uncertainties in bus and battery performance and life
- Availability of resources for unexpected maintenance/repair requirements
- ZEB life cycle is not fully proven out
- Unknown long-term commodity prices for fuel (electricity, hydrogen, etc.)

Alam, A., E, Diab, A. El-Geneidy, M. Hatzopoulou. 2014. A simulation of transit bus emissions along an urban corridor: Evaluating changes across several years and under various service improvement strategies. Transportation Research Part D, 31: 189-198. http://tram.mcgill.ca/Research/Publications/Bus_emissions.pdf

- Battery replacement costs
- Bus and battery residual value
- Hydrogen fuel cell replacement/ refurbishment costs
- Workforce training and retention
- Execution and deployment of ZEBs
- Balancing competing capital needs for AAATA

AAATA will encounter agency-specific challenges while transitioning to ZEB technologies. AAATA's current operating base and maintenance facility lack the space needed for future growth and for ZE charging and fueling infrastructure. This will require facility upgrades that are carefully planned and phased to not impact the agency's day-to-day operations.

If BEBs are implemented, substantial electrical upgrades will be required to meet power demand. Charging equipment for buses will also need to be installed inside the building. If FCEBs are implemented, major HVAC system upgrades will be required to provide sufficient exhaust and make-up air to the maintenance and bus storage areas of the building.

There are also several industry-wide challenges common to ZE fleet transitions. Short term, the global supply chain is driving up the costs of vehicles and manufacturing, while also increasing lead time for parts and vehicles. In addition, agencies will need to retrain staff, particularly maintenance technicians and operators, on ZEB technologies and sufficient lead time is required for training and workforce development. Maintenance can also be challenging once maintenance activities shift from the manufacturer to the agency. Lastly, ZEB and infrastructure procurement requires a large capital outlay. Although the Federal Transit Administration (FTA) has demonstrated its support for ZEB transition by doubling funding for bus acquisitions, future funding levels may not be sufficient to support industry-wide transition to ZEBs. Funding at the state and local level will be required for matching funds to unlock federal grants.

1.8 NEXT STEPS

With a preliminary understanding of ZEB technologies and the potential transition, necessary next steps include:

1. Determine the preferred alternative propulsion technology for AAATA. In the interim, AAATA will continue to procure the newest and cleanest diesel buses to minimize emissions.
2. Determine necessary modifications to the current facility, or if a new facility will be used
3. Conduct further analysis of future service plans to determine potential implications on the conversion to ZEBs.
4. Determine the relative priority of propulsion compared to other needs like transit center and customer-facing projects. This will affect grant applications and the timeline of the transition to a ZEB fleet.
5. Develop a phasing plan that outlines the transition to a ZEB fleet.
6. Determine if additional consulting work is needed to reach decisions about the transition.
7. Take steps towards filling grant applications such as the FTA Low-No program.

8. Assess staffing requirements to oversee and manage a successful transition and ensure adequate resources. Workforce training should also be considered.
9. Begin planning for future garage modifications that take into consideration the specific requirements of the ZEB technology.

2.0 INTRODUCTION

The Ann Arbor Area Transportation Authority AAATA, known publicly as TheRide, is the public transportation provider for the Ann Arbor and Ypsilanti area of Michigan. TheRide provides fixed-route services with 35 routes, along with paratransit, commuter (carpool and vanpool) services, and FlexRide late-night and holiday service.

AAATA provides service to a 130 square mile area with a population of 258,829. In 2019, AAATA provided over 6.9 million unlinked passenger trips across all its services, with over 6.3 million from bus operations, with 85 buses operated in maximum service for fixed route operations[3], and a total fleet size of 103 heavy-duty diesel and diesel-hybrid fixed-route buses. AAATA has one garage and two terminals.

The purpose of the Alternative Bus Propulsion Study is to conduct an impartial review of alternative bus propulsion technologies to provide AAATA an assessment of the state of maturity of zero-emission bus (ZEB) technologies and what it could take to transition AAATA's current fossil fuel bus fleet to a ZEB fleet.

This report starts with a general overview of bus propulsion technologies and short-lists the technologies considered further in this bus propulsion study. It then provides the following information:

1. A summary of current AAATA conditions related to bus operations, an assessment of the maintenance and operations facility, as well as an analysis of opportunities and challenges around potential adoption of ZEB propulsion options.
2. An analysis of battery-electric bus (BEB) technologies, including information around vehicle and charger technologies, a battery technology overview, an overview of battery performance and BEB operations and range, and an overview of the electricity market in Ann Arbor. Furthermore, route modeling and bus simulations were conducted to understand the feasibility of operating AAATA's services with BEBs as well as the development of site concept plans for BEB implementation that informs a cost assessment of a BEB fleet.
3. An analysis of hydrogen fuel cell-electric bus (FCEB) technologies, considerations for transit deployments, an overview of different fueling strategies and infrastructure alternatives, and an overview of the local hydrogen supply chain. Furthermore, route modeling and bus simulations were conducted to understand the feasibility of operating AAATA's services with FCEBs as well as the development of site concept plans for FCEB implementation that informs a cost assessment of an FCEB fleet.
4. An analysis of potential emissions eliminations from a transition to ZEBs.
5. A financial analysis of either a BEB fleet transition or an FCEB fleet transition. The financial modeling compares the capital and operating costs of a BEB or FCEB fleet with a 'business-as-usual' approach of continued use of diesel buses. Furthermore, two phasing scenarios are explored for each technology type—an aggressive transition to achieve a 100% ZEB fleet by 2030, and a replacement-focused approach to phase out diesel buses with ZEBs as diesel buses are retired.

[3] NTD 2019 agency profile.

6. A concluding discussion that examines the benefits and opportunities, risks and challenges, implications for AAATA, and next steps for a ZEB transition.

3.0 BUS PROPULSION TECHNOLOGY OVERVIEW

This section begins by defining the bus propulsion technologies that were considered and analyzed in this study. It provides a general comparison between ZEB technologies and traditional internal combustion engine (ICE) bus technologies, which are defined as technologies based on fossil fuels (i.e., diesel and natural gas-powered engines). This section then discusses transit operating practices relevant to propulsion technologies to help frame the basic challenges and trade-offs of ZEBs for transit applications. Finally, this section provides a summary of lessons learned from deployments of ZEBs in the United States and elsewhere to provide some real-life examples of ZEB operations.

3.1 ZERO EMISSION AND FOSSIL FUEL BUSES

The last several years have seen a rapid deployment of low-emission and ZEB technologies globally. As of 2021, 1,287 ZEBs have been deployed in the US, roughly 2% of the ~66,000 transit buses nationwide. In Michigan, a total of 15 BEBs and 2 FCEBs are currently in operation.

The move to ZEBs is primarily driven by an increasing regulatory push towards cleaner transportation, rapid advancements in bus and battery technologies, favorable fiscal incentives, new funding programs, and a maturing electric vehicle market providing lower costs and reduced technological risks. Although diesel buses have gotten cleaner, there are emerging ZEB technologies available today that will provide an even cleaner alternative.

The AAATA Alternative Bus Propulsion Study initially considered several technologies:

- **Diesel and diesel hybrid** – these propulsion technologies are currently employed by AAATA. These buses use fossil fuel-burning technologies and are not carbon neutral. In this study, these vehicles are only considered for comparison purposes and to create baseline scenarios.
- **Battery-electric bus (BEB)** – BEBs use onboard electric storage systems (ESS), also known as batteries or battery packs, to store electricity. Recharging methods vary by bus type and local requirements. There are typically numerous charging stations in a bus depot to charge individual BEBs. These vehicles are zero emission at the tailpipe—i.e., no GHGs or any other emissions are produced by the BEB itself. However, the production and transmission of the electricity can create upstream emissions that are taken into account. BEBs are considered in this propulsion study.
- **Hydrogen fuel cell-electric bus (FCEB)** – hydrogen FCEBs use fuel cells to generate electricity for propulsion by combining hydrogen and oxygen to generate electricity—a process called hydrolysis. FCEBs are fueled by filling an onboard hydrogen storage tank, similar to refueling a regular gas tank. FCEB also require a small onboard battery. Typically, there is only one hydrogen fueling station and FCEBs are fueled sequentially. FCEBs only produce water as a tailpipe by-product and are zero emission at the tailpipe. But as with BEB, there may be carbon

created upstream when the hydrogen is produced. FCEBs are considered in this propulsion study.

- **Compressed natural gas (CNG)** – many agencies throughout North America use CNG buses rather than diesel buses since they emit lower levels of GHGs. Nonetheless, CNG buses are not carbon neutral. AAATA's CEO and Stantec did discuss the potential for CNG to be a bridging technology, a way to reduce emissions until ZEB technology is fully ready. However, this idea was abandoned because it calls for two propulsion transitions instead of one, would lead to massive complexity with possibly three types of propulsion systems at the same time, and CNG is still a source of carbon emissions. For these reasons, CNG is not considered further in this project.
- **Trolleybuses** – Electric trolleybuses are ZEBs that use overhead wires and connection poles on the bus to generate electricity to power the traction motor. Very few transit agencies in North America currently operate trolleybuses. One clear drawback of this technology is the infrastructure associated with overhead power wires. In Ann Arbor and Ypsilanti many trees may need to be trimmed or cut down. Furthermore, the fixed infrastructure placement means that bus routes must use streets with wires, though there are models that can run 'off wire' for a short duration. This requirement makes bus service less flexible. The CEO feels that the high investment needed, lack of flexibility, and impact to trees make trolleybuses untenable. As such, trolleybuses are not considered further in this project.

A summary of key attributes of the technologies discussed above is provided in Table 2.

Table 2: Bus Technology Summary.

	Diesel	CNG	BEB	FCEB	Trolleybus (overhead wire)
Capacity (40-ft bus)	35 to 40-seated; 60-70 typical with standees				
Range	300+ miles	300+ miles	100-250 miles	200-300 miles	5-20 miles off wire
Battery	Not Applicable	Not applicable	250-400 kWh typical Up to 650 kWh	50-120 kWh	20-100 kWh
Top speed	60 mph	60 mph	Typically 60 mph	60 mph	<40 mph typical 45 mph maximum
Vehicle capital costs	Baseline	Slightly more than diesel	Much higher	Much higher	Much higher
Operational and maintenance costs	Baseline	Lower fuel costs; On par or slightly higher maintenance costs	Much lower fuel costs; Lower maintenance costs	Currently high cost but expected to fall in future; Lower maintenance costs	Much lower fuel costs; Higher maintenance costs
Considered in this Study?	Yes, as a baseline	No, not carbon neutral	Yes	Yes	No, not feasible for Ann Arbor/Ypsilanti

Moving forward in this project, we consider only FCEBs and BEBs as ZEB technologies, and diesel and hybrid-electric diesel buses as ICE or fossil fuel buses for comparative purposes. Table 3 lists the characteristics of the technologies considered in this study—BEBs and FCEBs, compared to traditional ICE buses powered by diesel fuel. The comparisons presented Table 3 are high level and only applicable to the broader technology types; subsequent sections of this report go into greater detail.

Table 3: Comparison of ZEB Technology and Internal Combustion Technologies for Standard 40-ft Buses.

	Diesel Bus	BEB	FCEB
Estimated Operating Range	Approximately 300-500 miles (depending on tank size and operating conditions)	Approximately 100-250 mi (depending on battery pack size, charging, and operating conditions)	Approximately 200-300 mi (depending on hydrogen tank size and operating conditions)
Fueling/ Charging Method	Fueled by a diesel dispenser (at a depot)	Can be charged on-route and/or at a depot using one of the following methods: • Plug-in charging • Overhead conductive charging • Wireless inductive charging	Fueled at a hydrogen storage and fueling station; one of the following is required: • Gaseous or liquid hydrogen delivery • On-site production through natural gas reformation or electrolysis
Main Capital Costs	\$500,000-700,000 per vehicle	• \$700,000-1,200,000 per vehicle (depending on battery size, which impacts range) • \$100,000-850,000 per charger for charging infrastructure (cost depends on power output of the charger, which impacts the speed of charging; typical in-depot charges have two dispensers and can charge two buses simultaneously, while on-route chargers vary in capacity based on service design, but assumptions are typically five to six buses per charger per hour)	• \$1.0-1.5 million per vehicle (depending on battery size, fuel cell size, and tank capacity) • For 55 or fewer buses, approximately \$4 million for fueling infrastructure (liquid hydrogen storage) • For 56-110 buses, approximately \$5.1 million for fueling infrastructure (liquid hydrogen storage) • For 111-165 buses, \$6 million for fueling infrastructure (liquid hydrogen storage) • For larger deployments, on-site production of hydrogen may be more cost effective and ranges On-site SMR: \$3.4-4.8 million, as well as vaporizer, cryopump, storage, and dispensers: \$4.1-6.9 million
Considerat ions compared to ICE	N/A	• BEBs are better suited for smaller deployments as they are less costly and less complex than FCEBs • Shorter range that will require operational changes, on-route charging, additional vehicles, or a combination of these three approaches • Electricity rates and tariff / regulatory structures require close collaboration with local utilities and regulators • Not easily scalable compared to ICE buses or FCEBs; increasing costs and space requirements for growing fleet	• FCEBs are initially more costly to deploy; however, they become more attainable with economies of scale as hydrogen demand and usage increases • The fueling infrastructure is more easily scalable as more buses may not require more fueling infrastructure • Refueling time comparable to CNG buses, but slower than diesel • Availability of low cost and low GHG footprint electricity and water requirements may be an issue if producing on-site hydrogen

Transit agencies across the globe have started to deploy BEBs and FCEBs, with some agencies adopting both, either to respond the varied nature of their services or as pilots to test the best fit for their agency. In the United States, large scale deployments (>100 vehicles) of BEBs or FCEBs at a single agency has yet to be achieved.

A key distinction between diesel, BEB and FCEB is the energy density of the fuel as this directly impacts the range of the vehicle. The graph below[4] illustrates the relative energy densities of several types of fuel.

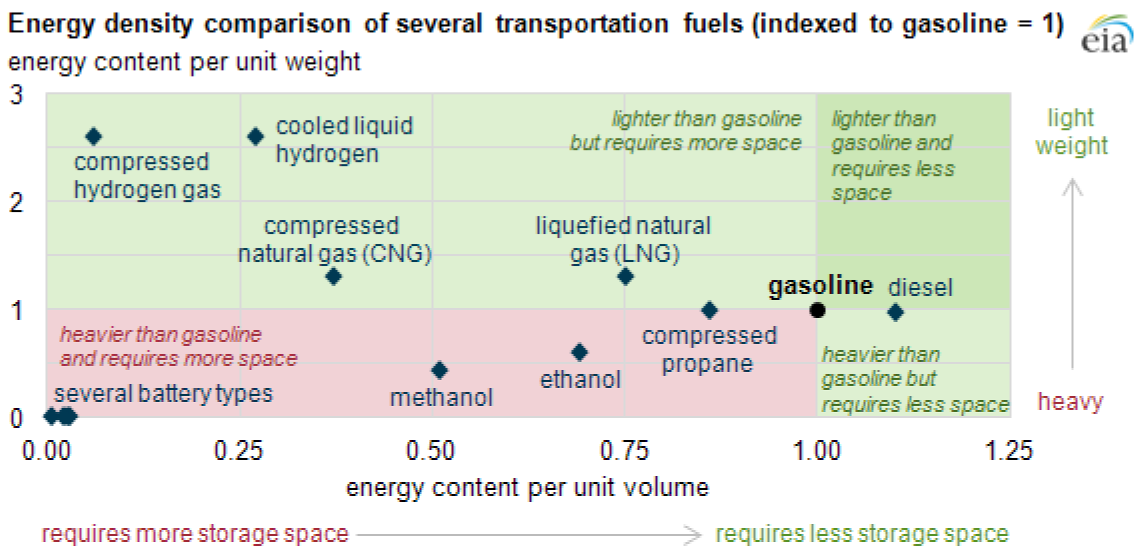


Figure 4: Energy density of transportation fuels. Source: EIA

Figure 4 illustrates how much more energy-rich fossil fuels like diesel tend to be by volume. Furthermore, on the graph, diesel fuel sits to the right of batteries as a fuel, meaning that diesel fuel requires less storage space for a greater amount of energy per unit volume. Put another way, batteries need to be very large to carry the same amount of energy as diesel fuel. The implication of this for a transit bus is that battery packs carry significant weight, which may in turn reduce fuel efficiency as well as limit potential route alignments based on weight restrictions for certain roadways like bridges or overpasses. Similarly, compressed hydrogen gas is less energy dense than diesel, but slightly more than batteries. However, because compressed hydrogen gas is much lighter weight than diesel fuel, more of it can be stored onboard a bus without excessively increasing the weight compared to batteries. Overall, the notion of energy density helps explain some of the trade-offs associated with ZEBs and their operating range characteristics.

3.2 TRANSIT OPERATING PRACTICES RELEVANT TO PROPULSION

Mass transit agencies try to use economies of scale and standardization of bus fleets to achieve efficiencies and cost savings, and reduce the likelihood of errors in service delivery. Much of this is

[4] https://www.eia.gov/todayinenergy/detail.php?id=9991

premised on the inter-operability of a bus fleet—that any bus could operate on any daily assignment or route. Laypersons are sometimes surprised to learn that individual buses are not assigned to specific routes or drivers, but instead are rotated daily, sometimes in service and sometimes out of service for maintenance. While a driver may drive the same assignment for months, they will likely have a different bus every day. It is important to remember that transit buses are heavy-duty vehicles that can be in continuous operation for 20 hours each day.

For the agency to manage its fleet efficiently, buses must be standardized and have near identical attributes. This is particularly relevant to the propulsion system. Changes to the distance a bus can travel can have impacts to many aspects of agency operations, costs, and personnel.

Each day's transit service is divided into numerous vehicle assignments called "blocks". Every morning a bus is assigned to a new block for that day. The blocking process ensures that there are enough buses to cover all routes and bus trips, that the bus fleet is utilized efficiently, and that the total size of the fleet is minimized. Fleet size is important to minimize costs for buses and garage space. An optimized fleet is just big enough to provide the service required at peak hours without costing more than necessary.

This relationship between routes, blocks, and vehicle assignments is shown in Figure 5. In the example below, Bus 1 pulls out of the garage to complete Block A (which is made up of Route 1, deadhead, and Route 14), pulls back into the garage, and completes Block B later in the day. On this example day, Bus 1 completed two blocks that included service on four routes. Block design typically remains the same during a service period (i.e., Block A always includes service on routes 1 and 14 on a weekday), but the assignment of blocks to vehicles can change day-to-day. In addition, while some vehicles may be assigned multiple blocks on a given day, other vehicles may only be assigned a single block.

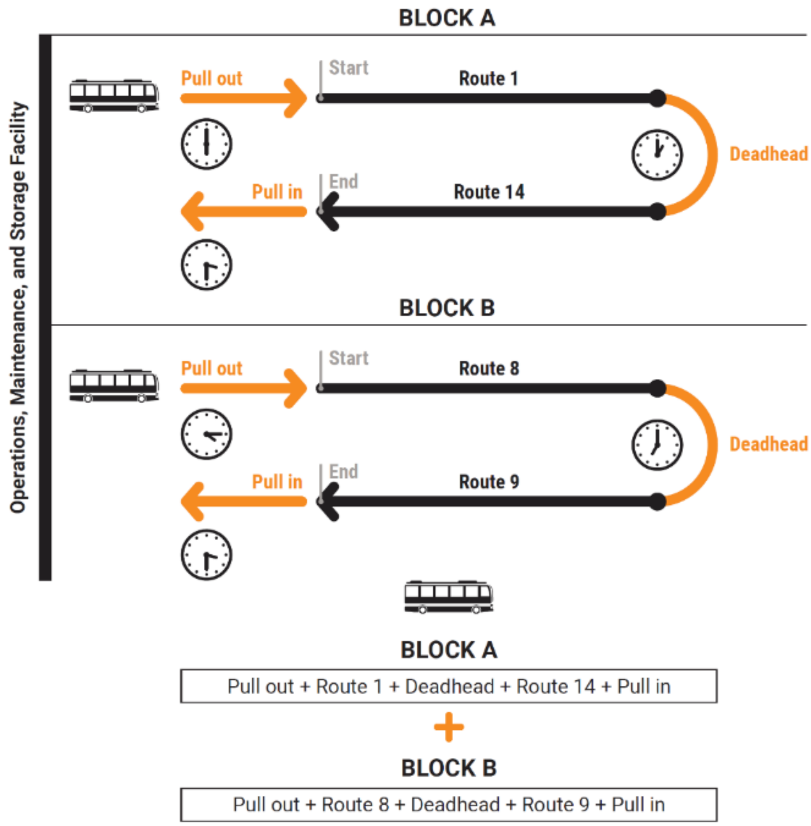


Figure 5: Relationship between routes, blocks, and vehicle assignments

The blocking process works best when all buses are essentially identical and interchangeable, thereby allowing maximum inter-operability. There is some latitude to assign specific buses to specific blocks or trips/runs for a particular reason—such as when a larger articulated bus is required at a specific moment, say rush hour, to handle heavy passenger loads. Generally, such exceptions have been about the size or type of the bus, for example a 40-foot urban transit bus or a 60-ft articulated bus. However, such exceptions introduce inefficiencies and erode economies of scale, and create complexity that increases costs and the risk of error into the fleet management process.

With fossil fuels, the distance the bus could travel (i.e., operating range) was never a concern for blocking or daily assignments. As long as all buses were refueled overnight, the entire fleet could be used the next morning. However, **ZEBs often have a shorter range than diesel buses, introducing a critical constraint into the blocking process. Most agencies can handle a small number of exceptions without significant costs, but if a large proportion of the fleet have varying or low ranges, it can create significant internal complications that will eventually cause increased operating costs (and potentially capital costs) to provide the same amount of service.**

For example, consider a hypothetical route that completes a round trip in one hour. A bus assigned to that route might need to operate from 6 am until midnight—18 hours and 250 miles. Two drivers may use the bus during the day, and a diesel bus would have no trouble completing that assigned duration or distance of operation. A BEB, however, might run out of charge halfway through. To avoid disruptions to customers an agency might be compelled to buy two electric buses and swap the buses out midday, requiring another staff person to drive the second bus. This would double the number of buses (for this route), garage space, maintenance requirements, and staffing costs while providing no additional service. Alternatively, the block could be restructured so that one bus would complete 12 hours of service (approaching the limit of a BEB), and then the remaining 6 hours could be added to another vehicle assignment that was initially shorter, say 4 hours, resulting in a slightly longer block. In this manner, the total number of vehicles or revenue hours aren't changed, just how the hours are assigned to different vehicles. While these are simplified examples, they illustrate the behind-the-scenes logistical challenges that can occur because of propulsion systems.

In addition to range, there are other factors that affect vehicle performance. Factors like topography, passenger load (number of passengers onboard the vehicle), heating and cooling, and even individual driver habits can impact fuel economy for any type of bus. Such previously unnoticed variables can become more prevalent with lower-range ZEBs.

Later, this report will reference opportunities to change blocking to accommodate lower-range ZEBs. As well as mitigation strategies like on-route charging that can extend range, simply accepting a larger fleet size and/or higher operating costs may be needed depending on the propulsion technology.

3.3 LESSONS LEARNED FROM ZEB DEPLOYMENTS

This section provides an overview of ZEB deployments around the world, deployments in the United States, and two experiences of transit agencies operating ZEBs and fossil fuel buses 'head-to-head'.

3.3.1 Global Best Practices

Across the world, cities on every continent have deployed some form of ZEB or low-emission vehicle in a transit context (Figure 6).

Figure 6: Global Electric Bus Adoption Snapshot[5].

China accounts for nearly 99% of the global fleet of electric buses. In the past few years, there has been increasing ZEB adoption in Europe, North America, Latin America, and India. China's success in the large scale adoption of electric buses can be attributed to some key factors: strong national leadership and centralized planning, clear policy vision towards mainstreaming electric mobility, national and local subsidies for electric buses, long-term focus on building domestic electric bus and battery supply chains, and robust partnerships among public and private stakeholders including national and local governments, financial organizations, utilities, bus manufacturers, operators and charging service providers[6].

A sample of global ZEB deployments and adoption models is provided in Table 4.

Table 4: Sample of Global ZEB Deployments and Adoption Models.

City	Number of ZEBs	% of fleet	Type of technology	Best practices
Shenzhen, China[7]	16,359	100%	BEB	Public private partnership; Using a vehicle and battery leasing model, financial leasing companies own the buses and batteries with life cycle warranty for key parts offered by the bus OEMs
Santiago, Chile[8]	410	6%	BEB	Innovative financing models and participation of new stakeholders (utilities) in electric bus deployments

[5] https://files.wri.org/d8/s3fs-public/barriers-to-adopting-electric-buses.pdf
[6] https://openknowledge.worldbank.org/bitstream/handle/10986/35935/Electrification-of-Public-Transport-A-Case-Study-of-the-Shenzhen-Bus-Group.pdf?sequence=1&isAllowed=y
[7] https://openknowledge.worldbank.org/bitstream/handle/10986/35935/Electrification-of-Public-Transport-A-Case-Study-of-the-Shenzhen-Bus-Group.pdf?sequence=1&isAllowed=y
[8] https://www.c40knowledgehub.org/s/article/From-Pilots-to-Scale-Lessons-from-Electric-Bus-Deployments-in-Santiago-de-Chile?language=en_US

City	Number of ZEBs	% of fleet	Type of technology	Best practices
Bogota, Colombia[9] [10]	483	6%	BEB	Innovative financing models and participation of new stakeholders (utilities, banks) in electric bus deployments
London, UK[11]	485	5%	BEB, Hydrogen (2)	Strong local leadership; Forward thinking public transit authority; National and local government support
Toronto, Canada[12]	59	2.5%	BEB	Strong sustainability and green technology strategy and targets; Partnerships with multiple stakeholders; Peer-to-peer learning. Largest ZEB deployment in North America currently.

Strong government policy through mandates and funding has been crucial for the widespread adoption of ZE vehicles across the transportation space, namely because of the high costs associated with the technology and the subsidies and incentives large governments are able to sustain. Some examples of countries taking the lead to provide incentives for the greater adoption of ZEBs are summarized in Table 5.

Table 5: Best Practices in Government Support for ZEBs.

	Germany	US	China	India
Program	Guidelines for the Promotion of the Purchase of Electric Buses in Public Transport	Low or No-emission (Low-no) vehicle grant/loan program	National and local support programs	Faster Adoption and Manufacturing of Electric Vehicles (FAME-II)
Type of support	Capital grant	Capital grant	Capital and operating subsidies	Capital subsidies for buses and charging stations
Budget	$312 million (2018-2022)	$85 million (2019)	Operating subsidies of around $90,000 equivalent; Capital subsidies	US $1.4 billion (equivalent)
Funding agency	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety	Federal Transit Administration	Central government ministries, Local government	Department of Heavy Industries and Public Enterprises, Government of India

[9] https://energy-base.org/news/paving-the-way-for-e-mobility-in-latin-america/
[10] https://www.sustainable-bus.com/infrastructure/enel-x-public-transport-latin-america/
[11] https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/cleaner-buses
[12] https://www.c40knowledgehub.org/s/article/Vancouver-and-Toronto-Our-e-bus-transition-advice?language=en_US

3.3.2 U.S. Case Studies

In the United States, ZEB implementation has occurred over the last ~15 years largely in the forms of small-scale pilots, including pilots in collaboration with the National Renewable Energy Laboratory (NREL) to test various ZE technologies. The maps in Figure 7 show the number of ZEBs by state, 1,287[13] as of 2021, roughly 2% of the ~66,000 transit buses nationwide[14].

Most North American agencies that operate ZEBs have deployed BEBs, with fewer testing FCEBs. Furthermore, lessons from many of these pilots emanate from prototypes and vehicles that are no longer produced, and should be treated with caution as technology continues to evolve. Nonetheless, as the technologies continue to mature, more deployments are going beyond the pilot phases.

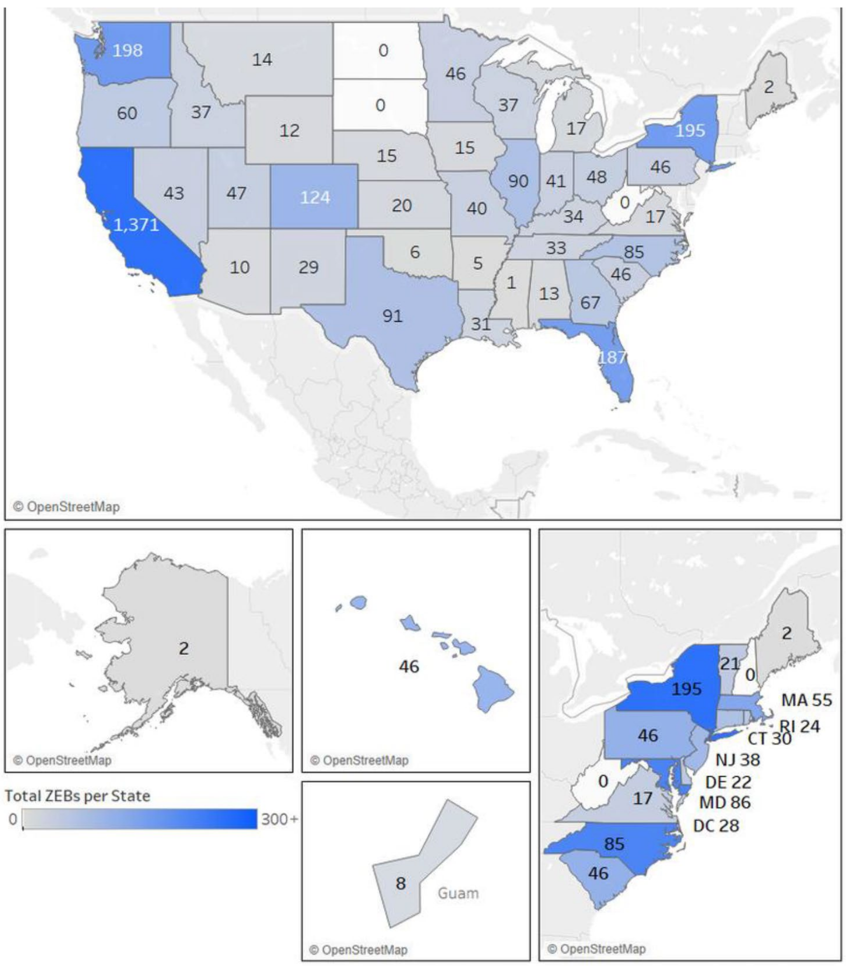


Figure 7: Full-Size ZEBs Funded, Ordered, and Delivered in the United States[15].

[13] https://calstart.org/wp-content/uploads/2022/01/2021-ZIO-ZEB-Final-Report_1.3.21.pdf
[14] https://www.apta.com/wp-content/uploads/APTA_Fact-Book-2019_FINAL.pdf
[15] https://calstart.org/wp-content/uploads/2022/01/2021-ZIO-ZEB-Final-Report_1.3.21.pdf

In Michigan, 17 ZEBs have been deployed—2 FCEBs and 15 BEBs. In Ann Arbor, in November 2021, the University of Michigan announced an order of 3 40-ft BEBs and 1 60-ft BEB from New Flyer. And in 2020, MDOT received more than $6 million from the Federal Transit Administration (FTA) through the Low-No program and distributed funding to 6 agencies across the state. While an important advancement, more funding and commitment will be required to increase the rate of sustainable ZEB adoption both in Michigan and throughout the country. One challenge is that most grant programs to date have been limited to funding *replacement* buses only, requiring the retirement of a diesel bus. It can jeopardize service to lose a reliable, long-range diesel bus if the replacement has a shorter range and may not be as reliable.

Table 6 provides a summary of a sample of ZEB deployments throughout the county, with a focus on Michigan and nearby agencies, to highlight some of the variety in technologies and some key attributes of these deployments.

Table 6: Sample of ZEB Deployments in the United States.

Agency City, State	Fixed-Route Fleet Size[16]	Fossil Fuel Fleet (Fixed-Route)	ZEB Fleet	Fueling/Charging Strategy	Notes and Comments
Mass Transportation Authority (MTA)[17] Flint, MI	123	Diesel and CNG	Hydrogen FCEB	FCEBs fueled off-site at a hydrogen fueling station	• Launched in 2012 with FCEB from Van Hool[18] (retired) • Additional FCEB in 2016 with Proterra FCEB (retired) • ElDorado National FCEB purchased in 2015 • Range of 280 miles • Hydrogen electrolyzer plant built nearby in Grand Blanc (Air Products) by Air Products; MTA also sells hydrogen as a retailer[19]
Blue Water Area Transit[20] Port Huron, MI	34	CNG	BEB	Depot and on-route charging	• Acquired 2 Proterra ZX5+ (450 kWh) BEBs • Used a $1.5M FTA Low-No grant, and a local match of $232,555 from MDOT.21 • Partnered with DTE Energy • Charging can occur overnight at the main facility, as well as on-route at the downtown transit center[22]
SMART and DDOT[23] Detroit, MI (*on order*)	SMART – 278 DDOT – 308	Diesel	BEB	Depot and on-route charging	• DDOT – 2 Proterra Catalyst E2 Max 40-ft buses, 2 125 kW and 1 500 kW chargers • SMART – 4 Proterra Catalyst E2 40-ft buses, 4 125 kW and 1 500 kW chargers • Funded through $2.6 from Low-No

16 NTD, 2019.
17 https://www.mtaflint.org/wp-content/media/strategic-plan-2016-2026.pdf; https://mptaonline.org/content/flint-mta-unveils-proterra-hydrogen-fuel-cell; https://www.metro-magazine.com/10022553/mich-mta-unveils-hydrogen-bus-alt-fuel-facility
18 https://www.sciencedirect.com/science/article/pii/S1464285912701554
19 https://afdc.energy.gov/stations/#/station/73480
20 http://bwbus.com/wp-content/uploads/BWATC-Electric-Bus-Media-Release-1.pdf
21 https://www.secondwavemedia.com/the-keel/features/BWAT-goes-electric.aspx
22 https://wgrt.com/blue-water-transit-adding-electric-buses/
23 https://www.smartbus.org/How-to-Ride/FAQs/ADA/smart-ddot-become-proterras-100th-customer-with-purchase-of-proterra174-battery-electric-buses-and-charging-systems

Agency City, State	Fixed-Route Fleet Size[16]	Fossil Fuel Fleet (Fixed-Route)	ZEB Fleet	Fueling/Charging Strategy	Notes and Comments
Champaign–Urbana Mass Transit District Champaign-Urbana, IL	121	Diesel	FCEB	Onsite electrolysis powered by solar PV panels, with capacity for up to 16 vehicles	• Initial demonstration of two 60-ft FCEBs under heavily subsidized program to use an electrolyzer powered solely by solar energy. Low-No covered 20% of the cost, and state funds covered 65%. • Implementing FCEs will allow the agency to continue operations as normal without modifications to their service, as the Managing Director put it ***"…we want to plan our routes and schedules for the needs of the community, not the needs of the vehicles."***
SunLine Transit Thousand Palms, CA	88	CNG	BEB, FCEB	FCEB: Onsite SMR and electrolysis, augmented with trucked-in liquid hydrogen BEB: plug-in depot charging	• Initial demonstration of FCEBs under heavily subsidized programs to test feasibility of technology followed by additional deployment of vehicles at larger scale • Difficult for onsite production to meet 100% of needs; onsite production does improve resiliency. • Early adopters can benefit from higher funding opportunities, but take greater risks • Using a variety of ZEB technologies to meet the needs of a range of services and routes.
Alameda Contra Costa (AC) Transit Oakland, CA	618	Diesel, Diesel Hybrid	BEB, FCEB	FCEB: Onsite electrolysis powered with solar PV panels, augmented with trucked-in hydrogen BEB: plug-in depot charging	• Difficult for onsite production to meet 100% of needs • First to implement a hydrogen station open to the public. • Early adopters can benefit from higher funding opportunities, but take greater risks
Foothill Transit Pomona, CA	317	CNG	BEB, FCEB (planned)	BEB: Depot charging with overhead plug-in dispensers in addition to on-route charging FCEB: Trucked-in liquid hydrogen	• Initial deployment of BEBs with on-route charging • Foothill Transit has decided to procure FCEBs for longer routes • Foothill Transit was an early adopter of on-route charging in California but has since decided to adopt depot-only charging due to reliability issues with overhead chargers

Some key takeaways from the lessons include:

- The adoption of ZEBs in Michigan is mainly BEB technologies, although Flint MTA has had three generations of FCEBs over the last 10 years. More recent acquisitions are BEBs and have leveraged federal and state funding.
- Some agencies adopt a mix of ZEB technologies to better match their varied service needs.
- Most agencies currently deploying FCEBs used trucked-in hydrogen deliveries, although Champaign-Urbana has onsite green hydrogen production.
- Early adopters tended to benefit from substantial funding opportunities, but with assumed risks around prototype technologies.

3.3.3 Learnings from Side-by-Side Technology Comparisons

Two transit agencies leading the charge on publishing comparative experiences with fossil fuel buses and ZEBs are AC Transit in Oakland, California and the TTC in Toronto, Ontario, Canada.

3.3.3.1 AC Transit 5x5 Transit Bus Technology Analysis

AC Transit is one of the first adopters of ZEBs in the nation. Moreover, AC Transit is deploying both FCEBs and BEBs in their fleet to ensure that technology fits the purpose of their service design. Given that they are deploying two types of ZEBs, AC Transit has a rather unique opportunity to not only study the similarities and differences between the two technologies, but by comparing operations and other elements with a 'control' fleet of fossil fuel buses (diesel and diesel hybrid), AC Transit can uncover how ZEBs stack up to non-ZEBs[24].

The following chart in Figure 8 directly compares the results of the study over the time frame of January to June 2021.

[24] https://www.actransit.org/zeb; https://www.actransit.org/sites/default/files/2021-12/ZETBTA%20Volume%202.pdf; https://www.actransit.org/sites/default/files/2021-07/EDT-060420_Report-ZETBTA.pdf

FLEET	DIESEL (BASELINE)	DIESEL HYBRID	FUEL CELL ELECTRIC (FCEB)	BATTERY ELECTRIC (BEB)	LEGACY FUEL CELL
Series Grouping	1600	1550	7000	8000	FC
Technology Type	Diesel	Hybrid	Fuel Cell	Battery	Fuel Cell
Bus Qty	5	5	5	5	5
Manufacturer	Gillig	Gillig	New Flyer	New Flyer	Van Hool
Year	2018	2016	2019	2019	2010
Length	40′	40′	40′	40′	40′
Data Summary (January - June 2021)					
Fleet Mileage	120,749	98,189	88,389	54,275	70,859
Cost/Mile	$1.41	$1.80	$1.97	$2.02	$4.07
Cost/Mile (w/ credits)	$1.37	$1.78	$0.58	$0.69	$4.07
Emissions (CO_2 Metric Tons)	298	182	0	0	0
Fleet Availability	96%	75%	69%	47%	68%
Reliability (MBCRC)	12,075	4,091	6,314	3,618	2,531

Figure 8: Overview of Fleet and Summary Results of AC Transit 5x5 Study[25].

AC Transit compared a total of 5 groups of buses, with 5 buses in each group. Moreover, AC Transit also tested two types of FCEBs—an older legacy bus from Van Hool, and a newer New Flyer FCEB (Figure 8). Apart from the legacy FCEB, the other 4 groupings were similar in age and other baseline characteristics.

Key findings include:

- ZEBs cost more to operate per mile. Unless coupled with credits related to low-carbon emissions and warranties, the cost per mile for ZEBs was greater than for fossil fuel buses, mainly due to higher fuel costs for hydrogen for the FCEBs. Total maintenance costs for the FCEBs and BEBs were lower than for the diesel and diesel hybrid fleet, but the ZEBs operated a lower total mileage, resulting in a greater maintenance costs per mile for ZEBs compared to fossil fuel buses.

- Fleet availability (readiness for pull-out) and reliability (the mean mileage between failures) is worse for the ZEB fleet compared to the diesel fleet. Key factors include the BEB fleet experiencing long out-of-service periods waiting for batteries and other parts, while the FCEB fleet experienced defects throughout the period of testing.

Key emerging lessons include:

[25] https://www.actransit.org/sites/default/files/2021-12/ZETBTA%20Volume%202.pdf

- Operating costs for ZEBs are strongly dependent on fuel/energy costs. While maintenance costs seem to be lower than fossil fuel buses, how much an agency pays for electricity and/or hydrogen will largely dictate operating costs per mile. While diesel costs had been lower, current inflation is driving the costs higher, while expanding hydrogen supply could lower the costs of hydrogen fuel.

- Reliability of ZEBs is below that of fossil fuel buses, but it is improving. The availability of parts, mechanics with expertise in high-voltage systems and other technology on BEBs and FCEBs strongly impact maintenance and the availability of ZEBs for service. As such, AC Transit has developed a robust training program for mechanics by working with manufacturers as well as developing internal training programs, including a combination of hands-on training and classroom lessons.

- Other interesting information relates to facility costs related to ZEB infrastructure. For 6 stationary chargers and 1 mobile charger for BEBs, together with other electrical infrastructure upgrades, cost around $900,000 in 2020. AC Transit upgraded two garage divisions for FCEBs at a cost of $5-6 million each. The infrastructure included liquid hydrogen storage tanks, vaporizers, compressors, and gaseous storage and can fuel ~13 buses in a 12-hour window. AC Transit recently upgraded one division to fuel up to 65 FCEBs (larger storage tank etc.) for $4.4 million. Both divisions have 2 hydrogen dispensers on the fueling island along with diesel dispensers for seamless fueling. Monthly maintenance for the hydrogen fueling infrastructure is $16,000-20,000.

- Lastly, the chart in Figure 9 summarizes the specifications of the buses studied in the 5x5 project. Costs of ZEBs were seen to be ~2 to 2.5 times more expensive compared to a diesel bus, and 35% to 76% more expensive compared to a diesel hybrid bus. Also important is the reduced operating ranges of the ZEBs compared to fossil fuel buses.

FLEET	DIESEL (BASELINE)	DIESEL HYBRID	FUEL CELL ELECTRIC (FCEB)	BATTERY ELECTRIC (BEB)	LEGACY FUEL CELL
Series Grouping	1600	1550	7000	8000	FC
Manufacturer	Gillig	Gillig	New Flyer	New Flyer	Van Hool
Bus Purchase Cost	$488,247	$699,060	$1,156,044	$938,184	$1,232,095
Energy/Fuel Capacity	120 gal	120 gal	38 kg	466 kw	40 kg
OEM Range Specification	480 miles	600 miles	300 miles	200 miles	220 miles
Propulsion Design	Conventional Diesel	Diesel/ Battery	Battery Dominant	Battery	Fuel Cell Dominant
Battery Design	N/A	Lithium-Ion	Lithium-Ion	Lithium-Ion	Lithium-Ion
Engine/Powerplant	Cummins	Cummins	Ballard/A123	Xalt Energy	UTC/EnerDel
Transmission/Propulsion	Voith	BAE	Siemens	Siemens	Siemens
In Service Date	Jan 2018	Aug 2016	Jan 2020	May 2020	Aug 2011

Figure 9: Bus Specifications from AC Transit 5x5 Study[26].

3.3.3.2 TTC (Toronto) Green Bus Program

In Toronto, the focus was on comparing BEB technology to legacy fossil fuel/hybrid buses, as well as comparing BEB manufacturers[27]. Unlike AC Transit, the TTC is only deploying BEBs and not FCEBs. Importantly, Toronto has a climate and annual temperatures comparable with the Ann Arbor/Ypsilanti area.

The TTC currently operates BEBs from 3 different manufacturers—Proterra, New Flyer, and BYD—and the head-to-head study examined factors like system compatibility, maintainability, cost, vendor performance, and customer experience. The chart in Figure 10 from the Board report summarizes the results of the study (as of April 2022).

[26] https://www.actransit.org/sites/default/files/2021-12/ZETBTA%20Volume%202.pdf
[27] Green Bus Program Update Board Presentation (azureedge.net); TTC's Green Bus Program: Preliminary Results of TTC's Head-to-Head eBus Evaluation (azureedge.net)

Evaluation Domain	BYD	New Flyer	Proterra	Nova HEV
System Compatibility	!	✓	!	✓
Accessibility	✓	✓	✓	✓
Reliability - MDBF	!	✓	!	✓
Distance Between Repairs - DPR	!	!	!	✓
Fleet Availability	!	✓	!	✓
Energy Consumption	!	✓	!	Not Evaluated
Fall Regen Rate	✓	⊖	⊖	Not Evaluated
Winter Regen Rate	⊖	⊖	✓	Not Evaluated
Winter Regen Rate - Wheel Slip Condition	!	⊖	!	Not Evaluated
Range - Summer	✓	✓	✓	Not Evaluated
Range - Winter	✓	✓	!	Not Evaluated
Vehicle Delivery Schedule	!	⊖	⊖	✓
Quality Review - Site 1	✓	✓	⊖	✓
Quality Review - Site 2	!	✓	⊖	✓
Quality Defects	⊖	⊖	⊖	✓
Duration to FAC	!	⊖	!	✓
30-Day Reliability	!	⊖	!	✓
Contract Deliverables	⊖	✓	✓	Not Evaluated
Canadian Content	✓	✓	✓	Not Evaluated
Training	✓	✓	✓	Not Evaluated
Average Days to Repair	!	⊖	!	✓
Customer Experience	✓	✓	✓	Not Evaluated
Operator Experience	✓	✓	✓	Not Evaluated
Energy Costs	✓	⊖	⊖	!

Figure 10: Overall Performance Study from the TTC Head-to-Head Evaluation[28].

Prominent findings and lessons include:

- Overall, the New Flyer vehicles performed better than BYD and Proterra vehicles. Proterra vehicles performed slightly better than the BYD vehicles of evaluation domains.
- Similar to AC Transit's experience, BEBs had generally lower availability and reliability than diesel hybrids, mainly due to part shortages and long lead-times. The experience of both the TTC and AC Transit demonstrate that procurement contracts should include reliability and availability targets with failure triggering liquidated damages.
- While both BYD and Proterra vehicles had better fall (mild weather) energy consumption and ranges than New Flyer vehicles, in the winter, BYD and Proterra vehicles worsened by 40-50%

[28] https://ttc-cdn.azureedge.net/-/media/Project/TTC/DevProto/Documents/Home/Public-Meetings/Board/2021/April_14/6_TTCs_Green_Bus_Program_Preliminary_Results_of_TTCs_Head_to_Head_eBus_Evaluation.pdf?rev=5c348c81e8504ef0b83735556437f7ec&hash=E6789DA35DB0E6CA426A2D391FD426AB

compared to a drop of 3% for New Flyer vehicles. A consistent and predictable energy usage throughout seasons is preferable for planning and scheduling and operations than a vehicle with the “lowest” energy consumption at a particular temperature.

- The operating costs per mile of the BEBs were lower than for the diesel buses mainly because electricity costs at the TTC are more favorable than diesel costs. Therefore, the actual cost savings touted by manufacturers related to ‘fuel savings’ will largely depend on local electricity (and/or hydrogen) costs. Moreover, since all BEBs are under a two-year warranty, the TTC was unable to report maintenance costs.
- The capital cost difference between BEBs and diesel hybrid was approximately $160,000 ($200,000 CAD), about $40,000 ($50,000 CAD) less than initially estimated by the TTC. The TTC expects that the gap will diminish as adoption increases throughout the industry.

T A K E A W A Y S

- There are several kinds of propulsion technologies including diesel, diesel hybrid, battery electric buses (BEB), hydrogen fuel cell electric buses (FCEB), compressed natural gas (CNG), and electric trolleybuses. This study considered BEBs and FCEBs because they are zero-emissions (ZE) technologies.
- ZE technologies are being adopted around the world. Best practices for successful deployments include public/private partnerships, utilization of innovative financing models, participation of utilities, national and local government support, and strong sustainability targets, and peer-to-peer learning.
- Most ZEB deployments in North America have been BEBs. Michigan reflects this trend, with primarily BEB fleet deployments.
- Side-by-side comparison of technologies show that operating and maintenance costs for ZEBs are generally higher than diesel buses, but this largely depends on how much the agency pays for electricity and/or hydrogen.
- Fleet availability and reliability are lower for ZEB fleets compared to diesel fleets due to part shortages and long lead times.

4.0 AAATA CURRENT CONDITIONS AND CONTEXT

This section provides information on AAATA's fleet, operations, and facility, as well as context on the internal and external relevant policies that are helping to influence and guide AAATA's investigation of the feasibility of different ZE technologies.

4.1 RELEVANT AGENCY AND CITY POLICIES

4.1.1 AAATA Board of Directors Policy 1.2.2

The Board of Directors adopted the AAATA Policy Manual V 2.19 in July 2021, with the following vision for public transportation: *"A robust public transportation system that adapts to the area's evolving needs, environment, and quality of life."* The policies outlined in the manual define the purpose of AAATA, what results are to be achieved, for whom, and at what cost. The manual serves as a guiding document for provision of service and future investments to improve service.

The policy from the Policy Manual that guides and is the foundation for this study is Policy 1.2.2, ***"Public transportation options minimize energy use and pollution, and conserve natural resources."*** This bus propulsion study addresses this policy area by proactively looking at ways that AAATA can transition its fleet to ZE propulsion types, thus minimizing energy use, reducing pollution, and positively impacting the environment. AAATA also has a history of interest in green technologies through its adoption of diesel/hybrid buses beginning in 2007, and now diesel/hybrid buses make up 44% of its current service fleet.

4.1.2 City of Ann Arbor - A^{2}ZERO Carbon Neutrality Plan

In 2020, the Ann Arbor City Council adopted the A^{2}ZERO Carbon Neutrality Plan which includes the following passage:

> *"The global climate is changing and nowhere are the effects felt more acutely than at the local level….*
>
> *… on November 4, 2019, Ann Arbor City Council unanimously adopted a Climate Emergency Declaration, …. In passing the resolution, the Council also committed to charting a path for how the entire Ann Arbor community could achieve carbon neutrality by the year 2030…*
>
> *This document outlines the path needed to achieve a just transition to carbon neutrality, community-wide, by the year 2030."*

Strategy 2 of the Plan calls for the switch from fossil fuel-powered vehicles and appliances to electric-powered vehicles and appliances[29]. The A^{2}ZERO Plan focuses on tailpipe emissions and recommends that the electric grid be transitioned to renewable sources. The A^{2}ZERO Plan states a goal for AAATA and the University of Michigan to operate fleets of electric buses by 2030, hoping to eliminate a total of 13,800 annual metric tons of GHGs, or about 0.5% of regionwide carbon emissions; 10,700 tons of GHGs

[29] https://www.a2cp.org/sites/default/files/A2Zero%20Carbon%20Neutrality%20Strategy.pdf

are estimated to be released annually by AAATA's fleet (0.5% of regionwide carbon emissions), according to the A^{2}ZERO Plan. The GHG estimates of the existing diesel fleet produced through the modeling in this Alternative Propulsion Bus Study are slightly lower than the GHG emissions from the A^{2}ZERO Plan. This aligns with the fact that the mileage AAATA's buses travel is also less than 1% of all vehicle miles traveled in the region. The Southeast Michigan Council of Governments (SEMCOG) estimates that in 2019, there were 3.95 billion total vehicle miles driven in Washtenaw County. AAATA's fixed-route buses traveled slightly more than 4 million miles that same year (0.1% of all vehicle miles traveled). Even if only half the total miles can be attributed to the Ann Arbor/Ypsilanti area, AAATA bus mileage would only be 0.2% of the total. Also in 2019, there were 173,441 vehicles registered in the cities of Ann Arbor and Ypsilanti, while AAATA had 103 buses (0.06%).

Of significance to AAATA, the A^{2}ZERO Carbon Neutrality Plan identifies the need to electrify buses and also help reduce automobile use by 50%. This plan is a clear example of how the region has similar goals of reducing pollution output and how local community values inform AAATA Board policies. It also identifies the competing need for funding to change propulsion technologies while making transit service more attractive.

4.2 INTERNAL STAKEHOLDER WORKSHOP

During a site visit[30], Stantec met with several staff from AAATA and conducted discussions with them to capture their thoughts and opinions about the transition to alternate propulsion technologies. Highlights of this discussion include:

- AAATA already deploys several strategies to minimize its GHG emissions. Newer "clean" diesel buses use filters, advanced engines, and other technologies to reduce emissions and smoke. Furthermore, AAATA uses biodiesel as a renewable fuel source.
- AAATA Staff noted that the current facility (Dawn Gabay Operations Center, 2700 S. Industrial Hwy) was built in 1984 and likely has fulfilled its original lifespan according to FTA standards. From their perspectives, it will be costly to upgrade to current standards and building codes to accommodate a ZEB transition. There may also be warranty impacts. However, the current garage is ideally located to minimize deadheading costs and operationally efficient with a fleet of about 80-100 buses.
- Staff pondered whether a new facility or a satellite facility is ultimately required to support the transition to ZEB or alternate propulsion types. While a new facility would likely make the transition to alternate propulsion types most straightforward, it is important to consider that any change to garage location could drive up operational costs from deadheading.
- Staff asked whether CNG would be a better interim step than jumping directly to ZEBs. Stantec advised that the answer is likely no because there is a heavy upfront cost, and it is unlikely the AAATA will get the full life cycle out of the interim equipment as bus OEMs transition out of fossil

[30] October 25, 2021.

fuel technology. Instead, Stantec suggested that AAATA would likely benefit more from going to BEB or FCEB directly since the equipment and costing is similar.

- AAATA Staff felt that electric trolleybuses were an untenable solution for Ann Arbor because of the environmental impacts of such a decision—to accommodate the power lines required to install electric trolleybuses, irreplaceable mature trees would likely need to be taken down. They also stated that heavy icing during the winter cause power lines to break regularly; this could impact transit services during winter months.
- AAATA Staff believe there is still much uncertainty and unknowns with ZEBs since the technology is still in its infancy and quickly evolving. AAATA's previous experience with hybrid buses was not a positive one as those vehicles have been some of the most unreliable in the fleet.
- Numerous AAATA Staff expressed considerable curiosity about FCEBs and their applicability for AAATA given the cold climates.
- AAATA Staff expressed concern for the reliability of electric grid in Michigan, as well as natural gas being a source of fuel in the state for power generation. Uncertainty about future control of the local grid in Ann Arbor is also a concern.
- AAATA suggested that Stantec consider fire issues related with the transition to ZEBs. The Ann Arbor fire department may not be equipped to combat a large garage fire generated by an electric or lithium-ion battery fire. There are concerns that a fire could risk the loss of the entire fleet or render the garage unusable for a time. The perception within AAATA is that the risk of fire increases with a transition from diesel to ZEB, and that this risk needs to be adequately managed.

Overall, AAATA Staff feel that multiple paths exist as the agency explores alternate propulsion types which moves the agency away from its legacy diesel/diesel-hybrid fleet.

4.3 AAATA BUS FLEET

AAATA's current bus fleet is summarized in Table 7. AAATA currently operates a fleet of 103 heavy-duty buses for fixed-route service, including 13 buses kept for contingency purposes. All are low-floor transit buses and most are 40-feet long. The average age of the fleet is 5.7 years, and all vehicles are within their useful life benchmarks with the exception of the 2007 Gillig diesel-electric hybrids which are in the process of being phased out.

Table 7: AAATA Bus Fleet.

Year	Model	Quantity	Age	Fuel Type	Size	Seated Capacity
2007	Gillig	2	13	Diesel-electric hybrid	40’	36
2008	Gillig	5	12	Diesel-electric hybrid	40’	36
2009	Gillig	7	11	Diesel-electric hybrid	40’	36
2010	Gillig	4	10	Diesel-electric hybrid	35’	32
2011	Gillig	10	9	Diesel	40'	36

Year	Model	Quantity	Age	Fuel Type	Size	Seated Capacity
2013	Gillig	5	7	Diesel	40'	38
2013	Gillig	11	7	Diesel-electric hybrid	40'	36
2015	Gillig	3	5	Diesel-electric hybrid	40'	36
2015	Gillig	4	5	Diesel	35'	29
2015	Gillig	7	5	Diesel	40'	36
2015	Gillig	4	5	Diesel	35'	29
2016	Gillig	9	4	Diesel	40'	36
2017	Gillig	3	3	Diesel/electric hybrid	40'	36
2017	Gillig	7	3	Diesel	40'	36
2018	Gillig	4	2	Diesel	40'	36
2018	Gillig	2	2	Diesel	40'	36
2019	Gillig	8	1	Diesel	40'	36
2021	Nova	8	0	Diesel	40'	31

There are 45 hybrid diesel/electric buses currently in the fleet[31]. AAATA is phasing out the hybrids because capital and operating costs were high, federal subsidies were discontinued, and emissions reductions were relatively low.

Each diesel bus has a fuel tank that can hold about 100-125 gallons of diesel fuel and have a one-tank range of up to ~400 miles. Vehicles are fueled onsite from diesel storage tanks that were installed in 1997.

4.4 BUS ASSIGNMENTS AND RANGE NEEDS

Like other transit agencies, the AAATA strives to maximize efficiency with a standardized, interchangeable bus fleet, and selects propulsions systems that can achieve the range required by daily bus assignments.

Daily assignments vary in distance traveled and hours in operation; some buses are in continuous operations for 18 hours a day, while others are only on the road for a short time during rush hour. But since buses are rotated through different assignments each day, they all need to be able to cover the distance of the longest designed assignment**. The fleet is standardized and kept inter-operable to allow buses to easily swap between different assignments. This means the range of the propulsion system is sized for the requirement of the largest assignment. The longer range of diesel buses allows the AAATA to maximize bus utilization while minimizing the total size of the fleet.**

The chart in Figure 11 shows the distances required by the AAATA's weekday bus assignments.

[31] Not counting the 13 hybrid buses kept for contingency purposes.

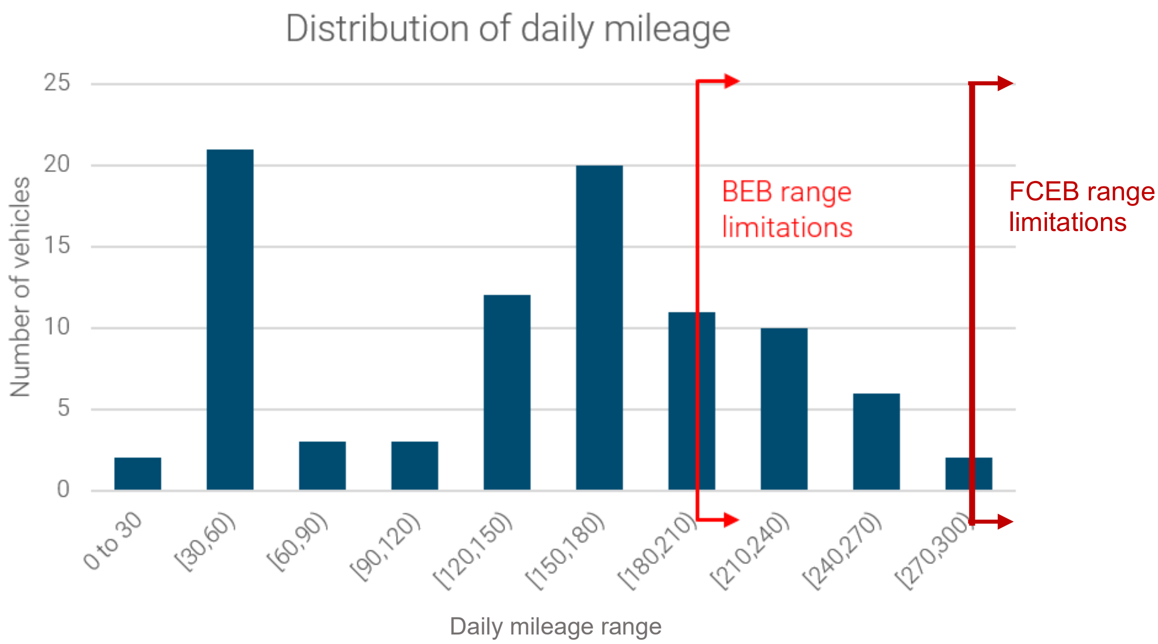


Figure 11: Distribution of Daily Vehicle Mileage.

Approximately 70% of vehicles travel 200 miles or less per day which is within most BEB manufacturer's stated range (Figure 11), although vehicle simulations are described in later sections to assess how AAATA's actual operating conditions influence energy usage and thus expected operating range. Generally, all the vehicles travel below the operating range limitations of FCEBs (~300 miles; Figure 11); again, as with BEBs, vehicle simulations are described in later sections to consider the impacts of passenger loads, driving cycles, heating, and other factors on actual FCEB ranges.

At the time of this report's preparation, TheRide had just approved a new Long-Range Plan for future services. The plan envisions more frequent services and later hours of service. It is not yet clear whether the distribution of bus assignments will remain the same as in Figure 11 above. However, the growth envisioned in the Long-Range Plan suggests new services, a larger fleet, increasingly complex operations, the continued need for scalability and interoperability, new facilities that can have ZEB elements planned from the beginning, and competition for limited capital funding resources. Pursuing both a service expansion and a propulsion transition at the same time will need careful planning.

4.5 DIESEL BUSES AT AAATA

Diesel-powered buses have been used by transit agencies for more than 50 years; the technology is mature and reliable. Advancements in diesel technology aimed at reducing emissions include:

- Clean diesel technology that leverages ultra-low sulfur diesel fuel, advanced engines, filters, and other elements to reduce smoke and GHG emissions, while reducing the cost of operations[32]. Operating mileage, depending on bus length and tank size, can range from 300-400+ miles.
- Diesel hybrid-electric technology that combines ICE and battery technologies; electric power is generated by the ICE and regenerative breaking and is used for acceleration. This technology reduces GHG emissions as well as cost of operations, as well as enables longer operating ranges than diesel only buses, ranging from 300-600 miles, depending on tank size and bus length[33].
- AAATA has extensive experience operating both diesel and diesel hybrid-electric buses, though the agency's experience with diesel hybrid-electric has not always been positive due to equipment unreliability, an issue felt by other transit agencies that deployed earlier generations of hybrid buses.

Diesel and diesel hybrid buses are produced by all major US bus manufacturers. Table 8 provides an overview of available models.

Table 8: Sample of Diesel Bus OEMs.

OEM	Propulsion Type	Length(s) (ft)	Notes
New Flyer	Clean Diesel and Diesel Hybrid-Electric	35, 40, 60	Clean diesel reduces emissions like NOx by 95% and particulates by 80%[34] Hybrid buses recoup about 40% of energy from braking for acceleration[35]
Nova	Clean Diesel and Diesel Hybrid-Electric	40, 60	Hybrid buses lowers emissions by up to 40%, while reducing fuel consumption by up to 30%[36]
Gillig	Diesel and Diesel Hybrid-Electric	29, 35, 40	

Diesel and diesel-hybrid buses vary in cost depending on length and other features, but generally range from $500,000-700,000. Operating costs for diesel buses depend mainly on the price of diesel fuel, which fluctuates from time to time depending on a range of factors such as weather, political issues, events like the COVID-19 pandemic, and other demand-related factors. Maintenance costs for diesel buses depend to a large extent on labor cost that depends on cost of living, unionization, and availability of skilled labor which varies throughout the country[37].

Diesel and diesel-hybrid buses are refueled by connecting a diesel dispenser and diesel fuel is stored in large tanks. Bus refueling takes several minutes per bus—as such, AAATA, like peer agencies, typically

32 https://www.newflyer.com/site-content/uploads/2021/12/Xcelsior-Clean-Diesel-Brochure.pdf
33 https://www.actransit.org/zeb; https://www.actransit.org/sites/default/files/2021-12/ZETBTA%20Volume%202.pdf; https://www.actransit.org/sites/default/files/2021-07/EDT-060420_Report-ZETBTA.pdf
34 https://www.newflyer.com/bus/xcelsior-diesel/
35 https://www.newflyer.com/bus/xcelsior-hybrid/
36 https://novabus.com/blog/bus/lfs_hev/
37 https://afdc.energy.gov/files/u/publication/financial_analysis_be_transit_buses.pdf

completes bus refueling overnight in conjunction with cleaning and other maintenance activities over the course of several hours so buses are ready to go in the morning for the next service day.

4.5.1 Diesel Supply

For the Michigan market, diesel fuel is refined in nearby states including Indiana, Illinois, and Ohio. A limited number of pipelines import diesel into the state with most fuel transported by trucks. In the August 2002 blackout in Michigan, the supply of diesel fuel was minimally impacted in the Ann Arbor area.

AAATA's current diesel supply is provided by several local companies, predominately Atlas Oil, Corrigan Oil, and RKA Petroleum. AAATA releases a request for proposals (RFP) every two weeks for the procurement of diesel fuel and generally selects the bidder with the lowest bid. This established method helps ensure competitive fuel costs, and the maturity of the diesel supply chain locally provides redundancy and resilience.

4.5.2 Externalities: Emission Reduction Opportunities

A key push factor to adopting ZEBs is to eliminate the GHGs and other emissions coming from not only the burning of diesel fuel from the ICE fleet, but also the production and transportation of diesel fuel itself. Nationally, the transportation industry contributes about 29% of GHG emissions—the single largest source [38]. Nonetheless, it is important to remember that buses carry many more people than a single personal vehicle, so per person, the GHGs emissions are lower per person-trip. It is estimated that transit use reduced gasoline consumption by about 4.1 billion gallons nationwide in 2019[39].

Diesel engines have seen improvements in efficiency through developments in engine technology. Engine downsizing, down speeding, waste heat recovery, engine stop/start technology to prevent idling, variable valve actuation, closed loop combustion control[40], and advanced diesel wastegate turbocharger technologies[41,42] have been used to improve diesel engine efficiency and emissions reduction. Advanced diesel wastegate turbocharger and waste heat recovery (along with engine optimization) will play a significant role in the improvements to the diesel engine efficiency in the future too. By using waste heat recovery technology along with optimization of the engine and complicated interactions among the engine subsystems, the highest brake thermal efficiency in a heavy-duty diesel engine achieved is up to 55%. This is accomplished by the Cummins SuperTruck II team. Although the SuperTruck II team has achieved an efficiency of 55%, the engines still burn diesel fuel which emits CO_2 and almost half of the energy is still wasted through thermal losses even with technology advancements.

Further, diesel is a carcinogen and the fumes emitted by diesel burning, even with the newest filters and 'clean' diesel technologies on newer buses, still causes air and noise pollution, while reducing the air quality in the bus passenger cabin. As such, the transition to ZEB alternatives is a worthwhile goal for transit agencies and will help the cities and regions in which they operate achieve climate goals—the

[38] https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions
[39] https://www.apta.com/wp-content/uploads/APTA_Fact-Book-2019_FINAL.pdf
[40] https://www.forconstructionpros.com/equipment/fleet-maintenance/diesel-engines/article/12076140/four-technologies-that-will-impact-diesel-engine-efficiency
[41] https://www.garrettmotion.com/news/newsroom/article/worlds-first-commercial-diesel-engine-with-brake-thermal-efficiency-above-50-launched-by-weichai-boosted-by-garrett/
[42] https://www.garrettmotion.com/event/modern-hd-diesel-wastegate-turbocharger-technology/

main challenges, as discussed throughout this report, is the maturity, viability, and complexity associated with ZE technologies.

To consider the emission reduction opportunities for AAATA, we estimated current AAATA diesel operations emissions. Our analysis, discussed in greater detail in Section 7.0, revealed that on an annual basis, AAATA's fleet emits 7,000 tons of CO_2e; this level of emissions is equivalent to ~17.4 million miles driven by an average gas-powered car, or 1,500 cars being driven for one year[43].

4.6 AAATA OPERATING BASE AND MAINTENANCE FACILITY

This section provides a high-level overview of the existing conditions of the infrastructure and facilities at AAATA's yard, and also provides general guidance on what potential constraints with the current facilities and infrastructure may need to be considered as part of the alternative fuel analysis.

4.6.1 General Site Information

AAATA's Dawn Gabay Operations Center is located at 2700 South Industrial Hwy, Ann Arbor, MI 48104. The facility occupies a site of approximately 9.38 acres (408,000 sq. ft.), which houses vehicle service, fueling, interior fleet parking, exterior employee parking, maintenance, administration, and operations. Significant area within the property frontage is dedicated to a storm water swale and landscaping (Figure 12 and Figure 13). The property currently houses 91 40-ft buses, 12 30-ft buses, 2 25-ft cutaways, 20 non-revenue vehicles, and 150 parking spaces for employees, visitors, and accessible parking.

[43] https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

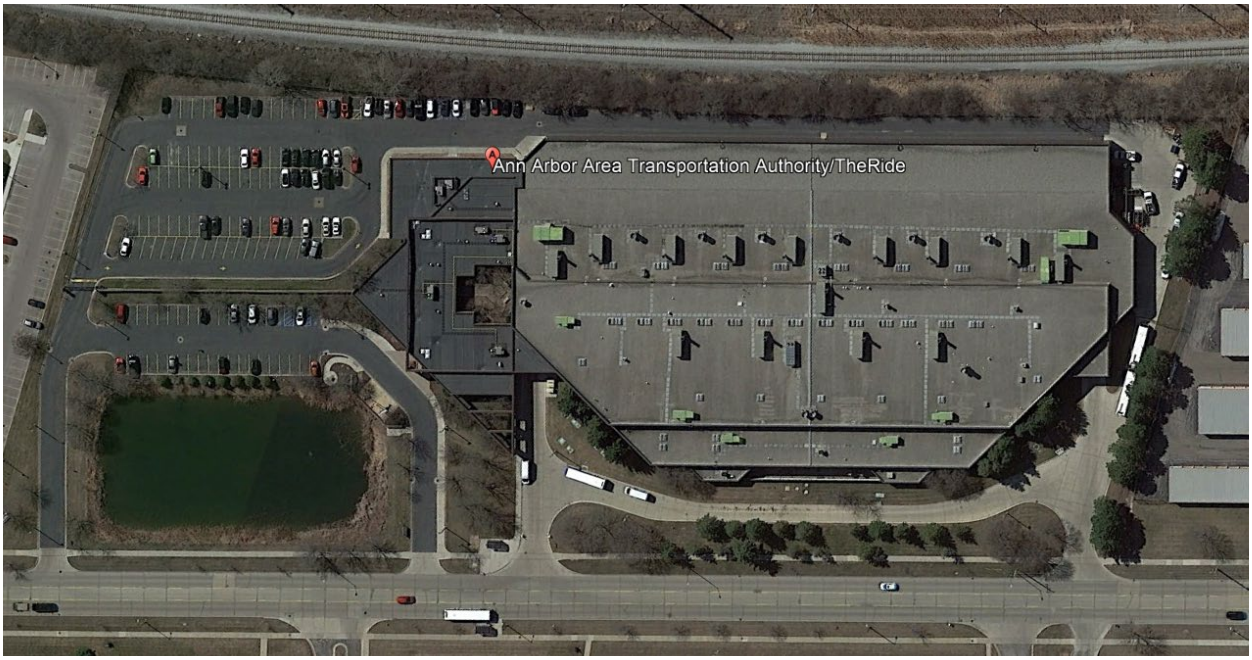


Figure 12: Aerial Image of Facility (Source: Google Maps).

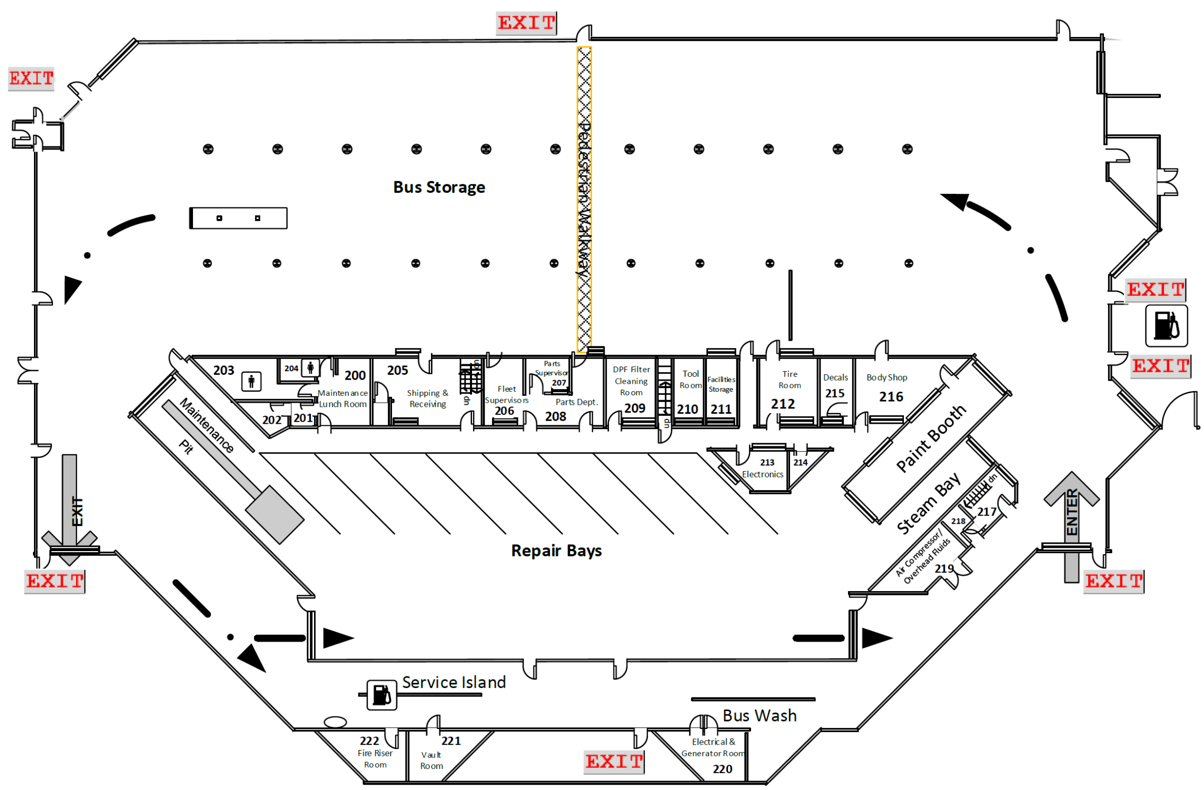


Figure 13: Facility Indoor Layout.

The facility consists of a singular, approximately 160,000 sq. ft., building housing almost all of the agency's functions. The building is divided into two primary components—the 18,000 sq. ft. administration and operations area on the south end of the building and the much larger maintenance, service, and vehicle storage area. The original 1984 facility has undergone two significant modifications—a 21,000 sq. ft. vehicle storage expansion in 2012 and 4,400 sq. ft. of office area in 2000. The facility is currently built out to the maximum site coverage allowed by the Ann Arbor zoning code.

4.6.2 Maintenance Areas

4.6.2.1 Summary

A detailed building and facility assessment was not performed as part of this report, but general commentary is provided below based on an onsite review and walk through of the facility with AAATA staff, review of the provided record drawings and other documents provided by the agency.

The maintenance building has nine maintenance bays plus a paint booth bay and a service and inspection pit. The current shop space is well organized, and all of the major building spaces are currently being used as originally designed. The maintenance bays are angled and have a central circulation aisle with overhead doors on the entry and exit drive aisles, effectively creating a maintenance 'building' within the larger building. The shop is configured with back-in, pull-out maintenance bays, with only the service and inspection, and pay and paint booth as drive-through. In-ground vehicle lifts and other typical vehicle maintenance equipment was generally observed at the facility but was not assessed as a part of this study. However, it is noted that each maintenance bay has been equipped with fall protection systems (Figure 14). Mobile ladders are used for gaining access to the rooftop of the buses. These systems are important as ZEBs have additional components on the roof.

Figure 14: Interior Maintenance Bays with Fall Protection.

4.6.2.2 Conditions

The maintenance area of the facility is generally in fair physical and working condition and is mostly original to the facility completion in 1984. Considering the useful life of similar vehicle maintenance and operations facilities, the AAATA facility appears in acceptable condition. However, it is immediately apparent from the size of the facility relative to the size of the fleet **that the agency has outgrown the functional design of the facility but still manages to operate and service vehicles in the same manner as originally designed.** The quantity of vehicles surpasses the original intended capacity for vehicle storage and maintenance functions. Due to the way the facility was originally designed, with the maintenance component being locked into the center of the larger facility, **there is little opportunity for significant expansion to provide for future growth. Outside of the building itself there is also essentially no room for expansion due to the current facility's configuration. Also given the age of the facility, major renovations or replacement of building systems should be expected.**

4.6.2.3 Preliminary Considerations

Since the facility is currently only just capable of meeting the agency's current operational and maintenance functions, any impact to the physical facility could be a major disruption to operations at the facility. In other words, upgrades or improvements to the building would need to be very carefully planned and phased so as to not impact the agency's day-to-day operations. **With any facility upgrades, regardless of vehicle fueling type, careful planning will be necessary. Dependent on the type of alternative fuel, major building upgrades will be required.**

With the implementation of FCEBs, major HVAC system upgrades will be required to provide sufficient exhaust and make-up air to the maintenance and bus storage areas of the building. With the implementation of lighter-than-air fuels such as natural gas or hydrogen, classified areas of the building, particularly the upper 12-inches to 18-inches of the underside of the building structure will need careful attention to provide exhaust within this area at an appropriate amount of air exchanges to limit to the classified areas of the building and avoiding the need to provide explosion-proof fixtures and fittings throughout. Since this is an existing facility, the amount of required exhaust would be even greater in order to reduce these classified areas in the structure because it would not be feasible to replace or upgrade all aspects of the electrical systems in the building. Also, a new gas detection system would also be required throughout all vehicle storage and maintenance areas since such a system does not currently exist in the facility.

If BEBs are to be implemented, major upgrades will be required for the facility. The current electrical service for the facility is likely only sufficient for the building as it currently exists. Charging equipment for the buses would need to be installed inside the building since all of the vehicles are stored inside, as well as within some, if not all of the maintenance bays. However, with the implementation of electric vehicles, upgrades to the HVAC systems are likely not required due to the presence of EVs inside the facility (HVAC upgrades are likely required as a baseline for continued use of the facility). The upgrades to the existing fire protection systems are also not likely to be required for the maintenance bays.

4.6.3 Vehicle Servicing Cycle[44]

4.6.3.1 Summary

The property has four driveways for ingress and egress of vehicles, two ingress/egress for employees and visitors, and dedicated ingress and egress drives for transit vehicles. Buses enter through the northern driveway and enter into the building through a single overhead door. Buses exit the building in a similar manner through a singular overhead door on the south end of the maintenance/storage portion of the building. Deliveries also access the facility from the north driveway. All four curb-cuts access South Industrial Hwy via non-signalized driveways.

When returning to the facility, operators pull into the facility from the north entry, circulate in a counterclockwise movement, and park in the parking aisles facing south and then return to dispatch in the office portion of the building. Service workers will then take a bus from this position, circulate around the maintenance ‘building’ portion of the facility to one of two service lanes (Figure 15).

[44] “Service cycle” refers to the daily routine a bus completes after finishing revenue service to prepare for the next day’s revenue service, including refueling, interior cleaning, exterior washing, fare collection, and some minor maintenance checks.

Figure 15: Interior Service Lanes.

Fueling, fluid check, and fare retrieval are all done with the bus in the same position. Buses are then pulled forward through the one wash bay or bypass to go back to the parking aisles. The main electrical room is adjacent to the wash bays, bringing electrician and water into proximity. Detailed interior cleaning is performed in the parking aisles.

The interior storage/parking area is well designed but is crowded (Figure 16). As originally designed, the parking aisles would each hold ten 40-foot standard buses. There are currently eight parking aisles, including the eastern most lane which appears to have originally been intended as a bypass lane. Buses are also stored in the maintenance area and within drive aisles. The size of the fleet has grown beyond the originally designed capacity of the building and the facility is at ‘crush capacity.’ In addition, a lack of sufficient outdoor staff parking has resulted in staff parking in the bus garage, although they must leave by 5 pm when buses start returning. While adaptive, this approach illustrates how crowded the facility has become.

Bus maintenance facilities are typically designed with some fleet growth and a modest understanding that some vehicles will always be in service or in maintenance. However, it is not best practice to utilize functional spaces such as by-pass lanes, maintenance bays, servicing lanes, etc. for vehicle storage because it compromises the functionality and safety of the facility.

In summary, AAATA’s facility cannot accommodate any additional vehicles for fleet expansion and the facility, as currently utilized, is already at a reduced functionality from its original designed intent.

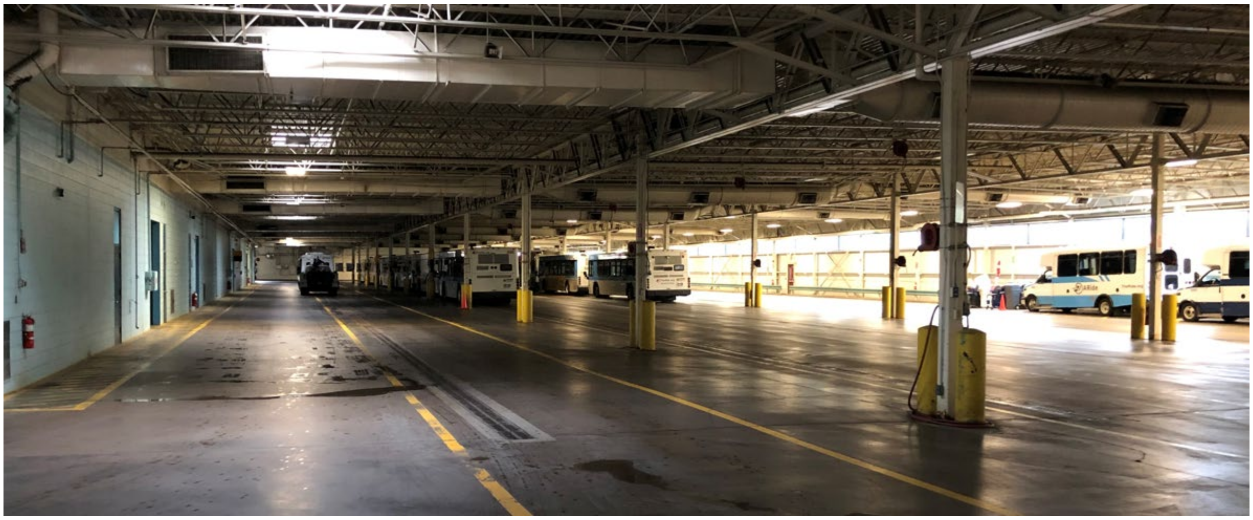


Figure 16: Interior Parking Aisles.

4.6.3.2 Conditions

The current service cycle functions are in fair condition like the rest of the facility. The two service lane positions are very congested with equipment. A detailed assessment of the existing equipment and facilities was not provided but can be assumed to be in need of replacement during the normal life cycle of such equipment. The area around the wash bay is also in fair condition. The access to the main electrical room through the wash bay creates a suboptimal configuration for future expansion of future electrical needs. Further consideration for optimization of the service cycle once an alternative fuel fleet has been implemented is likely not required because the current site and building constraints don't allow for significant changes.

4.6.3.3 Preliminary Considerations

With an implementation of FCEBs, only minor changes to the servicing cycle (associated with potentially slightly longer at-the-pump times of 8-10 minutes per bus) would be required if the fueling dispensers were to be located at the existing fuel lanes. The primary impact to the facility will be the installation of a new hydrogen-fueling plant nearby the fueling lanes and the associated space and power that it would require.

For BEBs, weather-sensitive chargers and dispensers would need to be planned throughout the parking aisles, but since the parking area is already covered and enclosed it is unlikely that significant modifications to the current parking layout would be required. Implementation of electric vehicles would also unlikely change the current servicing cycle except that the fueling function would happen in the parking aisles and no longer happen at the service lanes. However, locating the charging cabinets may be challenging given the already tight constraints within the facility. Chargers would need to be efficiently grouped in clusters inside the building with remote charging dispensers either mounted to existing columns or suspended via retractable reels between the rows of bus parking (see example in Figure 17). Charging dispenser locations would need to be carefully planned to efficiently access the charging ports on the buses.

Figure 17: Clustered Vehicle Chargers (left; dotted red area) with Overhead Retractable Dispensers (Foothill Transit, California).

Alternatively, overhead pantograph charging could also be deployed for charging purposes, minimizing space requirements on the ground (Figure 18).

Figure 18: Overhead Pantograph Equipment for BEB Charging (Edmonton Transit, Alberta).[45]

Any significant upgrades to the electrical service should also consider strategies to mitigate moisture transmission from the wash bays into and around the electrical room as well as the precarious path of travel to access the electrical room. The addition of a new main electrical room would be an appropriate phasing strategy to install new electrical service gear as well mitigate issues with current configuration.

4.6.4 Electrical

Electrical power is supplied to the AAATA facility from a pad mounted transformer located near the east end of the maintenance building in a partially walled enclosure area. Utility electrical service is from the on-premises underground utility lines along South Industrial Hwy. The medium voltage services are overhead to the property line. The access to the main electrical room through the wash bay creates a suboptimal configuration for future expansion of future electrical needs.

DTE Energy is the electrical utility serving AAATA offices and bus facility. A 105-kW standby diesel generator onsite to provide backup power to operate the facility. This generator appears to be sized to run essential services and a select number a fueling system. The generator can only power 156 A at 480 V at 0.8 power factor. This generator, while sufficient for basic building functions, would be insufficient to power bus chargers to any meaningful extent.

[45] https://transforming.edmonton.ca/electric-buses-set-to-roll-out-on-streets-of-edmonton/

4.6.4.1 Conditions

The existing electrical distribution system appears to be in operational condition and maintained. Age of the equipment is approximately 38 years old and has exceeded its service life. Note, the original manufacturer of this equipment is FPE and this series of equipment has been out of production for over 35 years. Reconditioned parts are becoming very difficult to secure and significant failure in this equipment runs a risk to the facility. The existing electrical service is rate for 480 V, 2,000 A and has estimated capacity of 1.7 MVA.

4.6.4.2 Preliminary Considerations

The existing electrical system was designed to support the office building, bus service building maintenance operations, and traditional (diesel) fueling operations. Primary electrical demands in the office building are lighting, HVAC, typical office support loads and bus service operations. The maintenance area of the building has air compressors, bus lifts, a bus wash station, lighting, and HVAC loads.

The existing electrical system is not adequate to serve the loads that would result from the full build out of BEB chargers. BEB charger demands vary depending on the model but demands often exceed 120 kW per charger and peak fleet charging demands greater than 3 and 4 MVA are common even with charger management systems.

The chargers would each require a new 480-V electrical feed and upgraded service from DTE Energy. DTE Energy has 5-kV and 15-kV distribution services in the South Industrial Hwy area that could potentially feed a new service(s) to provide electricity for the chargers.

The existing electrical room would *not* be adequate to support an electrical service of this capacity. A new room approximately 25-ft. wide by 50-ft. long would be required. We would recommend a double-ended substation and two (2) utility transformer an interlock tied breaker and secondary emergency Automatic Transfer Operation to back-up generators. The transformers would still be owned by AAATA and could be located outside the proposed room. Two (2) utility feeds would be requested from DTE Energy. One of them could be the existing service but upgraded to support the new loads.

Back-up power recommendations could include two (2) 1,000 kW generators with either diesel or natural gas as a fuel source. If diesel is selected for the fuel source, the tank would be sized for approximately 12 hours of continuous fuel load operations or 24 hours or typical load operations. These generators are approximately 25-ft. long by 8-ft. wide and would need to be placed a minimum of 20-ft. from the building envelope.

4.6.5 General Maintenance Facility Considerations

4.6.5.1 Gas Detection and Ventilation Considerations

For a facility considering the implementation of FCEBs, a compliant gas-detection system must be installed in the maintenance, service, and vehicle storage portions of the building (i.e., anywhere a bus can travel) that would operate and maintain buses. These systems are very common to facilities with

CNG buses and require similar ventilation requirements. Given the relatively new implementation of hydrogen fueling across the country, there is less familiarity with the systems required for hydrogen detection but fortunately this is not a significant challenge to implement the detection systems. However, these systems would need to be entirely new at the AAATA facility since the equipment and systems do not exist. The current conditions of the mechanical exhaust systems have not been specifically assessed as a part of this study, but it is safe to assume that extensive modifications would be required to the existing duct systems, rooftop equipment, etc. in order to implement gaseous fueling.

4.6.5.2 Fire Protection Considerations

Fire hazards are not unique to ZEBs, but there are elements that make them more challenging. For example, hydrogen fires are invisible, while battery fires require unique suppression strategies.

Due to the relatively new advent of BEBs, building and fire protection codes have not specifically addressed many of the concerns with large scale battery storage and charging infrastructure. The National Fire Protection Association (NFPA) 855 ‘Standard for the Installation of Stationary Energy Storage Systems’ is a standard that can potentially be applied to BEB storage, but this particular standard is overkill relative to the nature of the batteries onboard buses being physically separated from other buses. This standard was created to try to address thermal runaway events (i.e., fires) with battery energy storage systems but does not address the specific concerns with electric vehicles. The need for enhanced fire protection systems has not been determined as a baseline requirement for BEB implementation and would be left up to the discretion of the local fire marshal and the building officials. Early coordination with the local building authorities and first responders is highly recommended to understand their requirements and concerns.

Peer agencies have noted that for addressing fires, they equip BEBs with the Amerex system model V25ABC that includes a dry chemical compound based on ammonium phosphate that is effective in suppressing and extinguishing class A, B, and C fires. These fires can be involved in ordinary combustible materials, flammable liquids, and fires involving energized electric equipment. Another alternative is Purple K which is potassium bicarbonate-based dry chemical that is effective in suppressing and extinguishing class B and C fires involving flammable liquids and is safe on fires involving energized equipment.

Small hydrogen fires can be extinguished with dry powder retardant, carbon dioxide, a halon extinguisher, or a fire blanket. Large hydrogen fires can only be extinguished by shutting off the fuel supply of the fire.

Overall, as more ZEBs are adopted throughout the industry, practices around safety generally and fire suppression specifically will continue to evolve.

4.6.5.3 Fall Protection and Safety Infrastructure Considerations

Safety is of paramount importance at all bus maintenance facilities and should be assessed at a very detailed level for any future facility modifications. A detailed safety assessment is outside the scope of this report, but assumptions can be made that the existing fall protection systems in the interior maintenance bays are currently adequate for safely accessing rooftop equipment. This requirement will not be going away with the implementation of any of the ZE technologies discussed in this report and may even increase due to battery packs and fuel tanks being located on the rooftops of vehicles. Regardless, equipment will continue to be located on the roofs of vehicles, whether it be batteries, fuel tanks, or air conditioners, and therefore the need for additional accommodations for rooftop access may be required in the future such as dedicated rooftop access bay with elevated platforms with fixed stairs and guardrails.

5.0 BATTERY-ELECTRIC BUSES

This section discusses battery-electric bus (BEB) technologies and their implications in a public transit system. BEBs are buses that use electricity stored in batteries as their onboard energy source. BEBs require recharging that can occur at the bus depot as well as on-route, typically at layover locations throughout an agency's network. Compared to fossil fuel powered buses, BEBs have shorter operating ranges, even with the newest battery capacities and technologies. Battery degradation is also a concern for a reduced range. Nonetheless, key advantages of a BEB fleet can include cost savings from electricity vs. fossil fuels as well as potential savings in maintenance costs, as BEBs have fewer moving parts than fossil fuel buses.

This section presents:

- An overview of current BEB technologies including discussions of key factors for consideration,
- Charging infrastructure and electricity pricing programs,
- Computer modeling of how BEB technologies could work in the Ann Arbor/Ypsilanti environment,
- Review and discussion of the changes needed for garage and terminal facilities to use BEBs,
- Implications for transit operations,
- Preliminary workforce implications and training requirements,
- A preferred scenario for how BEBs could be adopted by the AAATA.

5.1 VEHICLE TECHNOLOGY OVERVIEW

BEBs function by using electricity stored in an onboard battery to propel the vehicle. The major internal component that dictates the vehicle's range is the battery size and capacity—the larger the battery, the longer the bus can operate on a single charge.

Larger batteries increase a bus's range, but also weigh more. Together with passenger loads, the bus may become so heavy that the size and weight of the battery required to move the vehicle reduces its fuel economy and operating range, suggesting a fundamental limitation and point of diminishing returns to the current technology. To create buses that meet vehicle operating parameters, OEMs and agencies are trying to balance the trade-offs associated with vehicles that have larger, heavier batteries.

The ultimate solution to heavy batteries is the anticipated invention of better batteries capable of storing more energy in smaller batteries. One promising technology in development is solid state batteries. However, these technologies are not yet proven.

Figure 19: A BEB plugged into a charger in Charleston, SC.

Figure 20: A BEB recharging during a layover in Los Angeles, CA.

One work-around for limited batteries that bus manufacturers have developed is to recharge a bus while on route via overhead chargers. With this infrastructure, buses can recharge during operating periods to extend their range (Figure 20). However, allowing sufficient time to recharge buses during operation (5-10 minutes for every trip) may have impacts on fleet size, service frequency, operator labor, and operating and capital costs. On-route charging can also restrict flexibility since BEBs need to be assigned specifically to blocks that operate on routes equipped with charging equipment.

BEBs can be classified by range and battery size:

- **Short-Range BEBs:** they can be equipped with smaller batteries (<300 kWh) that enable operating ranges of approximately 130 miles. The vehicles usually required supporting infrastructure along the routes to extend service.
- **Standard BEBs:** vehicles equipped with batteries between 440 kWh and 525 kWh for ranges of 180–210 mi. These vehicles can be operated with a single overnight charge (depending on range needs) and/or paired with on-route charging infrastructure.
- **Long-Range BEBs:** vehicles with larger batteries (i.e., 660 kWh) for ranges up to 260 mi. These vehicles can be operated with a single overnight charge (depending on range needs) and/or can be paired with on-route charging infrastructure.

Regardless of the battery size, the charging methodology can also be a way to classify BEBs:

- **Depot-charging only**: These buses are charged in-depot at the end of their service day, or midday when they return to the depot in between blocks. The charging rate for this equipment is usually between 60 kW up to 150 kW. The charger configuration for these buses can be either plug-in or overhead pantograph connections.
- **On-Route fast charging**: They are ideally recharged on-route as the battery depletes during operation using fast-charging equipment that has power outputs higher than 300 kW and up to 600 kW. These buses also require in-depot recharging so that they are ready for service the following day; on-route charging is used to extend operating range. The charger configuration for these buses can only be an overhead pantograph connection for the fast on-route charging but they could also have a plug-in connection for the depot-charging (low-power) equipment. OEMs are starting to offer BEBs with the capability to accept both plug-in charging and overhead conductive charging.

Table 9 lists transit BEB manufacturers and models currently available for US transit agencies. Transit agencies in US have a broader selection of BEBs than FCEBs as the industry has historically favored BEBs. Reasons for this include the relatively lower capital costs for BEBs versus FCEBs (especially for smaller scale deployments) and the lack of readily available, reliable, and affordable hydrogen as a fuel source in most parts of the country.

Table 9: Non-exhaustive List of Available Transit BEBs, Battery Capacities, Range and Fuel Economy.

Manufacturer	Propulsion Type	Length(s) (ft)	Battery Capacity (kWh)	OEM Stated Range (mi)	Fuel economy (kWh/mi)[46]	Estimated Vehicle Cost
BYD	BEB – Long Range (with optional on-route charging)	30, 35, 40, 60	215-578	150-220	1.45-2.65	30 ft - $610,000 35 ft - $710,000 40 ft – $761,000 60 ft – $1,229,700

[46] The fuel economy ranges quoted here are from OEMs. However, expected operational fuel economies will differ between agencies and communities based on topography, ridership, climate, and other factors.

Manufacturer	Propulsion Type	Length(s) (ft)	Battery Capacity (kWh)	OEM Stated Range (mi)	Fuel economy (kWh/mi)[46]	Estimated Vehicle Cost
New Flyer	BEB (with optional on-route charging)	35, 40, 60	388-466	135-220	2.08-2.11	35 ft – $795,000 40 ft – $805,000 60 ft – $1,225,000
Nova	BEB	40	594	210-290	2.03-2.82	$826,000
Proterra	BEB	35, 40	260-800	95-330[47]	1.59-2.80[48]	35 ft – $884,000 40 ft – $894,000
Gillig	BEB	35, 40	450	180-200	1.80-2.20	35 ft – $809,000 40 ft – $813,000

Actual operating conditions will impact BEB fuel economy and ranges. Furthermore, the last column provides an estimate of costs for different base models. Costs for longer buses are more expensive that smaller buses, while larger battery packs will also incur greater costs. Currently, BEBs are nearly double the cost of a diesel equivalent bus, but only about 35-40% more expensive compared to diesel-hybrid buses. Final costs will depend on agency-developed specifications, as well as the potential for bulk discounts and other factors. The greatest contributor to this cost premium of BEBs is the batteries.

5.2 BATTERY TECHNOLOGY OVERVIEW

Both BEBs and FCEBs rely on on-board batteries to convert electricity to power a traction motor. Batteries are significant components of the overall cost of the vehicles. This report section provides an assessment of:

- Battery chemistry and energy density
- Costs
- Performance
- Range
- Factors impacting battery health

A discussion on battery second life and recycling is provided in Appendix A Battery Second Life and Recycling.

[47] With Duopower drivetrain; https://www.proterra.com/vehicles/catalyst-electric-bus/range/
[48] Ibid.

5.2.1 Battery Chemistry and Energy Density

While Lithium-ion batteries are the battery of choice for most BEBs, there are different lithium-ion chemistries in use. Additionally, heavy-duty buses typically have demanding duty cycles, carry heavier weights, and have longer expected lifetimes. Thus, energy and lifetime requirements of batteries become important considerations. Typically, within the lifetime of a BEB or a FCEB, batteries need to be replaced at least once, usually around year 7 of operation, or when the battery loses 20-30% of its capacity.

Lithium-ion batteries are typically classified based on the types of battery chemistries used—the types of materials used in the anode and cathode. The three main types include the following:

- NMC/NCA: Cathode material is made up of either a composition of lithium, nickel, manganese and cobalt oxide (NMC) or lithium, nickel, cobalt and aluminum oxide (NCA). The anode is made of graphite.
- LFP: Cathode material is made of lithium iron phosphate ($LiFePO_4$) while the anode is made of graphite.
- LTO: Unlike the battery chemistries mentioned above which are named after the cathode materials, LTO batteries are named after their anode material, which is lithium titanate oxide (LTO), with lithium iron phosphate used as the cathode material.

Each of these battery chemistries come with different properties when it comes to energy density, cost, battery life, and battery performance. **Energy density**, the amount of energy stored in a volume of space such as a battery or fuel tank, differs between battery types and propulsion types, and is an important factor in determining vehicle range. Figure 21 compares the energy density for the different battery chemistries[49].

[49] https://www.sustainable-bus.com/news/bmz-poland-lithium-ion-battery-technology-electric-buses/

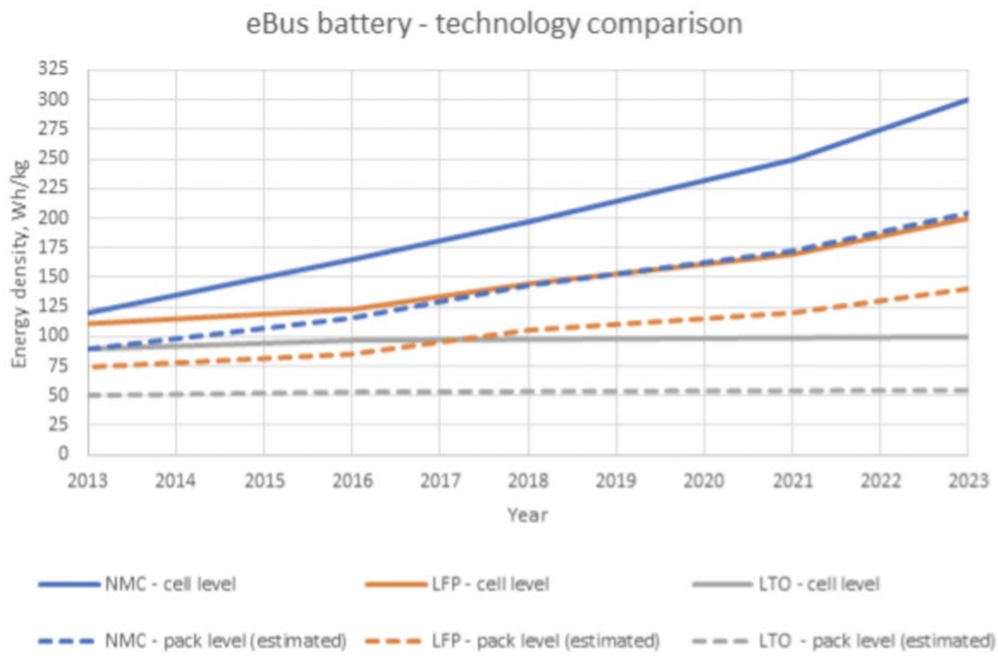


Figure 21: Evolution of Energy Density Comparison for Different Battery Chemistries.

NMC batteries have the highest energy density as seen from the graph above, and are therefore finding widespread adoption in applications requiring higher performance and range. While NMC batteries are more popular in the US, LFP batteries are the predominant battery chemistry used in electric buses in China, due to their lower costs, and also shorter-range requirements in dense urban environments.

Recent improvements in battery technology continue to increase the driving range of BEBs. For example, in early 2022, Proterra announced a BEB with a 738-kWh battery[50], which is a 10% improvement on the existing ZX5 MAX model. According to Proterra, this model can deliver more than 300 miles of driving range on a single charge, depending on route characteristics and driving conditions.

Energy density is correlated with range because higher battery capacities can be achieved without a weight penalty. There is a vast amount of research and development happening in alternate battery chemistries. While it is difficult to predict which ones will commercialize, there are many options emerging with the trend in energy densities potentially tripling in the next five years. The energy density of a Proterra bus battery is currently 160 Wh/kg. Chemistries like lithium metal anode-NCM cathode are achieving up to 460 Wh/kg and are close to commercialization.

In the near term, battery manufacturers will continue to optimize existing battery chemistries and introduce new materials, as well as optimize battery assembly and pack design to incrementally improve energy density and performance. Furthermore, battery management systems play a key role in battery health, so advances in the software used to manage battery dynamics can further improve range. In the future, new concepts around different battery chemistries and solid state technology can result in greater

[50] https://www.proterra.com/press-release/zx5-electric-bus-738kwh/

improvements to vehicle range[51]. Taken together, it is likely that as battery technology continues to mature, energy density will improve, and driving ranges will be extended to match fossil fuel-powered vehicles.

It is also important to consider the effect of battery degradation over time and how this will impact operations, however, state of health modeling was not in scope for this study. Once operational, electric buses should also be rotated on different routes to make sure that degradation is happening at similar rates across individual buses, and that newer buses with less battery degradation be assigned to longer blocks. This additional complication does not apply to diesel or hydrogen buses.

Compared to the other fuel sources used for transit buses, as shown in Figure 22, battery energy densities are very low compared to liquid hydrogen and diesel fuel. For this reason, on-board batteries are very large (and heavy) in order to store enough energy to provide operating ranges still short of traditional fossil fuel-powered buses.

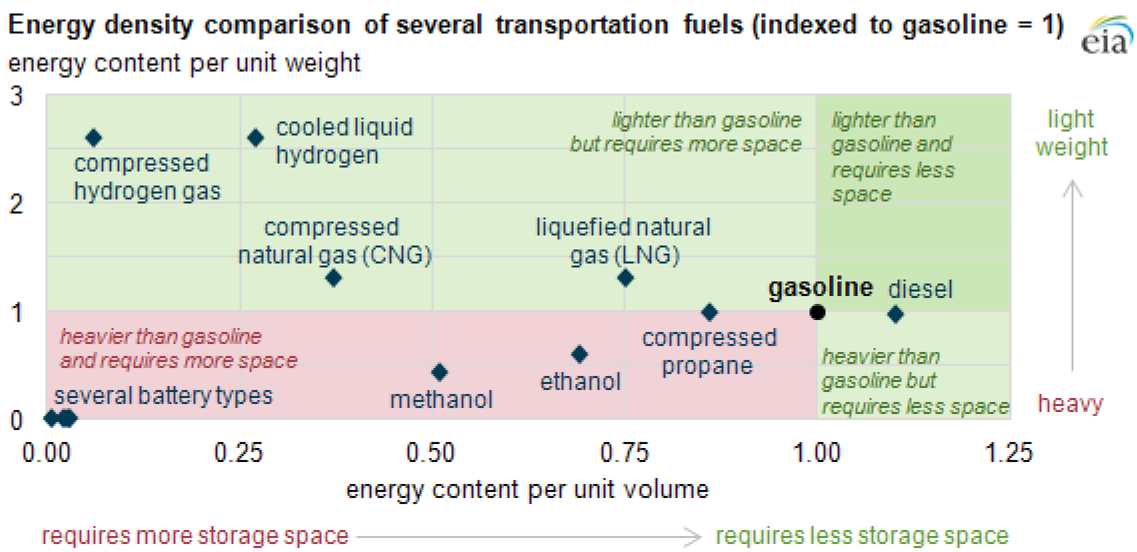


Figure 22: Energy density of transportation fuels. Source: EIA

5.2.2 Battery Prices

Battery prices account for a substantial share of the overall cost of an electric bus. With improvements in battery technologies and greater competition in the global marketplace, battery costs have been steadily decreasing over time and are projected to further reduce in the future.

It is widely noted in industry and research that battery price per kWh for lithium-ion batteries has been rapidly decreasing from around $1,000/kWh in 2010, to less than one quarter of that in 2018/2019. Forecasts vary, but most experts agree that the downward price trend is expected to continue, with an

[51] Deloitte. *New market. New entrants. New challenges. Battery Electric Vehicles.* 2019; International Energy Agency. *Global EV Outlook 2020: Entering the decade of electric drive.* 2020; The Faraday Institution. *High-energy battery technologies*. 2020.

average price per kWh continuing to decrease the rest of the decade down to around $65/kWh in 2030 (Figure 23).

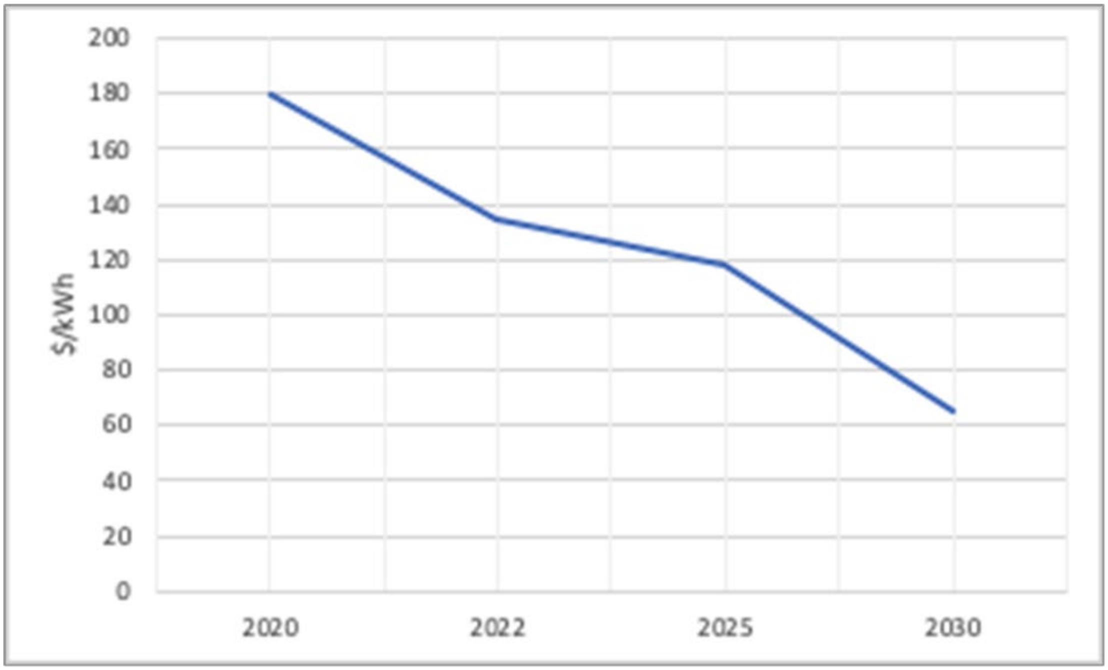


Figure 23: Cost of High-Volume Light Vehicle Batteries per kWh Over Time[52].

The chief factors which impact battery costs include:

- Raw materials
- Manufacturing process
- Battery manufacturing plant
- Cell chemistry

The economics behind these factors are volatile, making future projections challenging, and could strongly impact the overall cost of a BEB.

5.2.2.1 Raw Materials and Manufacturing

Raw materials account for a significant portion of the total cost of the battery. As shown in Figure 24 and Figure 25, depending on their chemistry, the cathode active materials (CAM) could account for more than 50% of the total cell cost. The impact of cobalt and nickel on costs of CAM manufacturing is shown via a sensitivity analysis in Figure 25. Cobalt-based cells show a large variation in prices with some increasing by as much as 63%.

[52] https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf

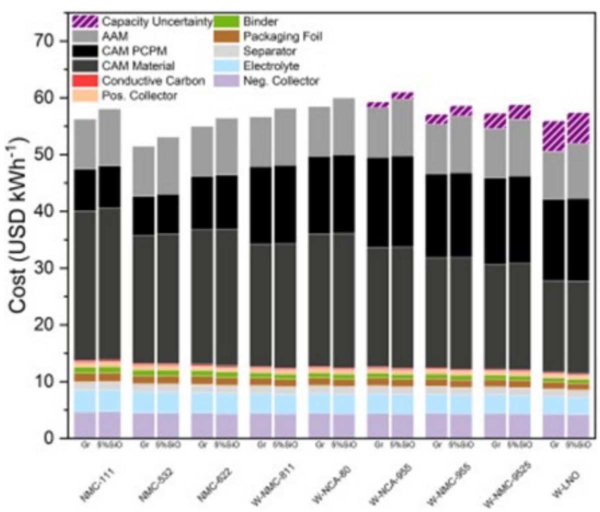


Figure 24: Raw Material Cost[53].

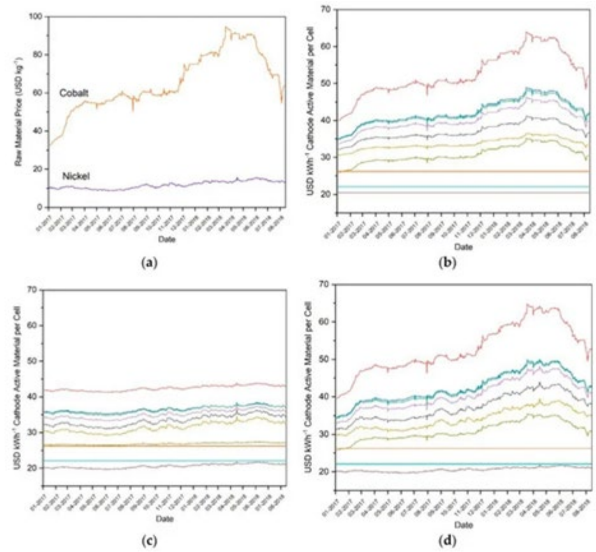


Figure 25: Sensitivity of CAM Costs to Market Prices[54,55].

According to BloombergNEF, the most respected publication on future battery pricing, along with chemistry and raw materials, manufacturing process improvements may reduce costs by nearly 30%, for an expected cost of $56.60 per kWh (Figure 26). It is notable that mining for the raw materials needed for batteries is an environmentally damaging process, and as more industries begin to adopt ZEVs, demand for batteries will continue to drive mining and possibly create supply chain issues into the future. The long-term risks are nonetheless difficult to foresee.

[53] https://www.sciencedirect.com/science/article/pii/S266624852100010X#bib39
[54] https://www.mdpi.com/1996-1073/12/3/504/htm
[55] (**a**) Real-world market prices of raw cobalt and nickel metal from 01-2017 to 03-2018, along with sensitivity of total CAM manufacturing costs to real-world market price of (**b**) cobalt, (**c**) nickel, and (**d**) cobalt and nickel during this same time window as determined by CellEst for NMC-111 (red), NMC-442 (blue), NMC-532 (green), NMC-622 (purple), NMC-811 (yellow), NCA (black), LMO (turquoise), LNMO (brown), LR-NMC (olive), and LFP (orange)

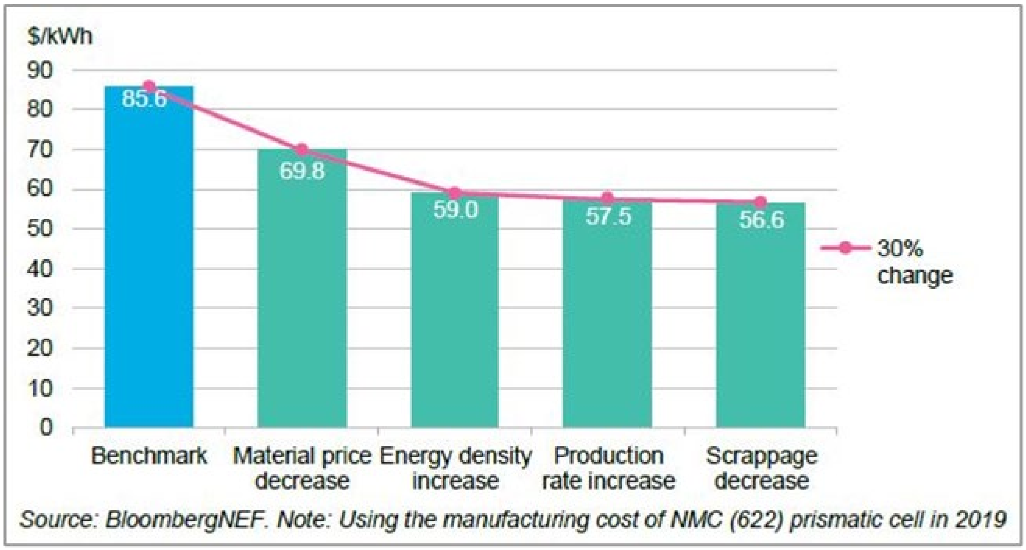


Figure 26: Manufacturing Cost[56].

5.2.2.2 Processing and Cell Chemistry

Economies of scale can further bring down costs of processing and pack assembly. As production capacity increases, the cost of a battery pack is expected to decrease. The decrease in cost depends on the share of pack and processing cost to the total manufacturing cost (Figure 27).

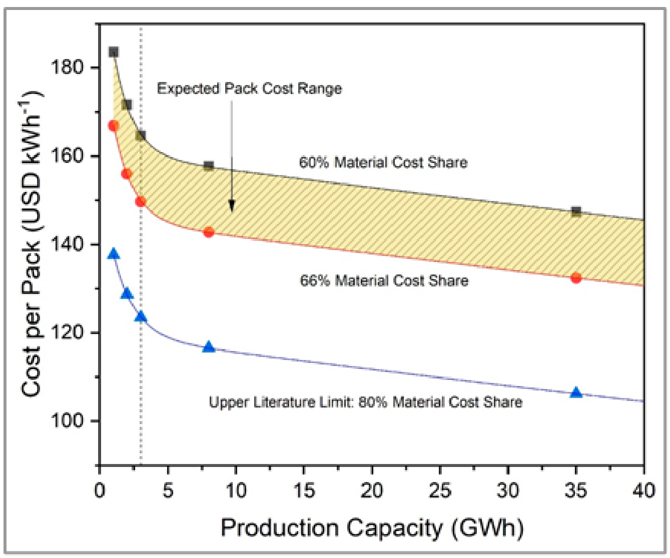


Figure 27: Cost Per Battery Pack for Batteries Based On NCA//Graphite Cell Chemistry[57].

56 https://www.transportenvironment.org/sites/te/files/publications/2021_05_05_Electric_vehicle_price_parity_and_adoption_in_Europe_Final.pdf

57 https://www.mdpi.com/1996-1073/12/3/504/htm

Cell chemistry affects the energy density and the raw materials used. For instance, moving from the commonly used NMC (622) cathode material to NMC (9.5.5) would increase energy density by 23%, while decreasing raw material costs by 21% (Figure 28).

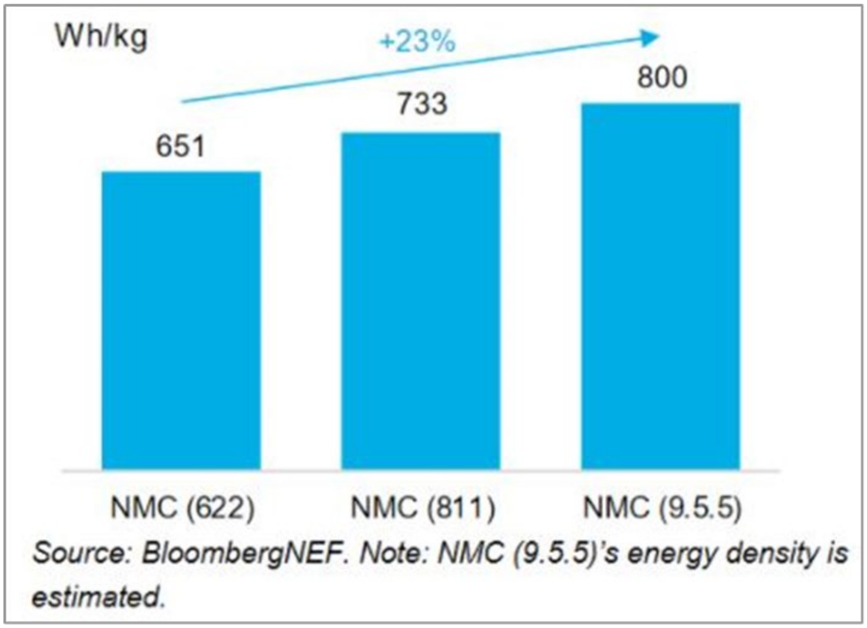


Figure 28: Cell Chemistry with Respect to Energy Density[58].

5.2.3 Battery Performance

Battery performance is another important aspect in electric bus operations, as it impacts the fuel consumption, range, charging times, as well as life cycle economics. This section illustrates the key parameters impacting battery performance which are as follows[59]:

- **Energy**: One of the core functions of a battery is to supply energy to a particular application within a certain duration. Energy is the most important factor to compare the performance of various batteries. In the context of electric buses, energy is considered as a measure of battery size and driving range.
- **Capacity**: Another important characteristic affecting the battery performance is its capacity. Typically, capacity is measured through a C-rate; a C-rate of 1.0 indicates delivering the full charge in 1 hour. When selecting a battery, the charge and discharge rates need to be evaluated against use cases for fitness.
- **Power and internal resistance**: Power and internal resistance play a key role in battery performance. In typical bus operations, the bus loads the battery with high current spikes. The internal resistance determines the rate at which the battery is able to deliver the demanded

[58] https://www.transportenvironment.org/sites/te/files/publications/2021_05_05_Electric_vehicle_price_parity_and_adoption_in_Europe_Final.pdf

[59] Standards for the performance and durability assessment of electric vehicle batteries.pdf

power. The internal resistance and pulse power requirements thus play an important role in battery selection. Power and internal resistance also influence battery ageing.

- **Storage or charge retention**: Self-discharge, which occurs when the battery system is not used for longer periods of time, is measured as storage or charge retention. Storage and charge retention can degrade with age, primarily driven by factors such as temperature, end of charge voltage, and state of charge (SOC) levels.
- **Energy efficiency**: It is the ratio of the total energy provided by a battery to the total energy necessary to restore the initial SOC by a standard charge. The overall efficiency is influenced by the round-trip efficiency of a battery system. Based on the system and chemistry, the typical value range for energy efficiency is 75 to 90%.
- **Cycle life**: A greater number of charge and discharge cycles (as well as the depths of discharge) will greatly affect the operation as well as life of the battery. The conduction loss in a battery increases with the increase in discharge rate[60].

5.2.4 Battery State of Health

The battery state of health (SOH) is a measure of the ability of an older battery to store and continue to deliver electricity as compared to a brand-new battery[61]. Generally, older batteries have worse performance than new batteries, and eventually are no longer useful for transportation purposes.

There are different ways to measure the SOH of a battery from remaining capacity to discharge cycles. For example, in a new BYD K9 all electric bus with a battery capacity of 324 kWh, if its capacity after 12 years of operation decreases to 260 kWh, the SOH is then assumed as 80%.

There are four main factors that impact lithium-ion battery SOH[62]:

- High temperatures
- Operating at high and low state of charge
- High electric current
- Usage (energy cycles)

SOH thresholds may vary across countries and organizations. For example, for vehicle-driving, the global range of SOH tends to be no less than 70-80%. Whereas for other uses, organizations in the UK have considered that battery modules with a SOH of at least 65% are sufficient for use in energy storage applications[63] and batteries with modules with the lower SOH are to be recycled.

BEB batteries tend to experience degradation from their higher usage or cycles with more frequent—typically daily—charge/discharge cycles, which can affect the long-term SOH of the battery. Real-world

[60] https://iopscience.iop.org/article/10.1088/1757-899X/688/3/033001/pdf
[61] ww.element-energy.co.uk/wordpress/wp-content/uploads/2020/01/UKESL-Non-technical-Public-Report_2020.pdf
[62] https://viriciti.com/blog/top-4-factors-that-influence-battery-degradation-in-electric-buses-how-to-avoid-them/
[63] https://www.sciencedirect.com/science/article/pii/S0301479718313124

long-term data degradation is not widely available yet since BEBs are less mature than lighter EVs such as cars. Simulations differ from specific use cases[64]. For example, a high-intensity daily use urban BEB with 200 kWh battery capacity was estimated to last up to 2,777 charging cycles corresponding to 7.60 years before the battery degraded to 70% of its initial capacity[65].

Figure 29 shows the relationship between battery SOC and level of degradation, considering three cases - i) no battery degradation ii) 11% degradation and iii) 24% degradation. The graph demonstrates that as a battery degrades, its SOC decreases together with its length of use. Overall degradation is considered to have a similar timeline across vehicle types, as it is use-case specific[66]. As a proxy, warranties for BEBs tend to range between 6–12 years with a 20-30% capacity degradation depending on the vehicle provider[67]. For a transit agency, this means that as BEBs age, their ranges will diminish and that older BEBs will need to be assigned shorter blocks or assignments.

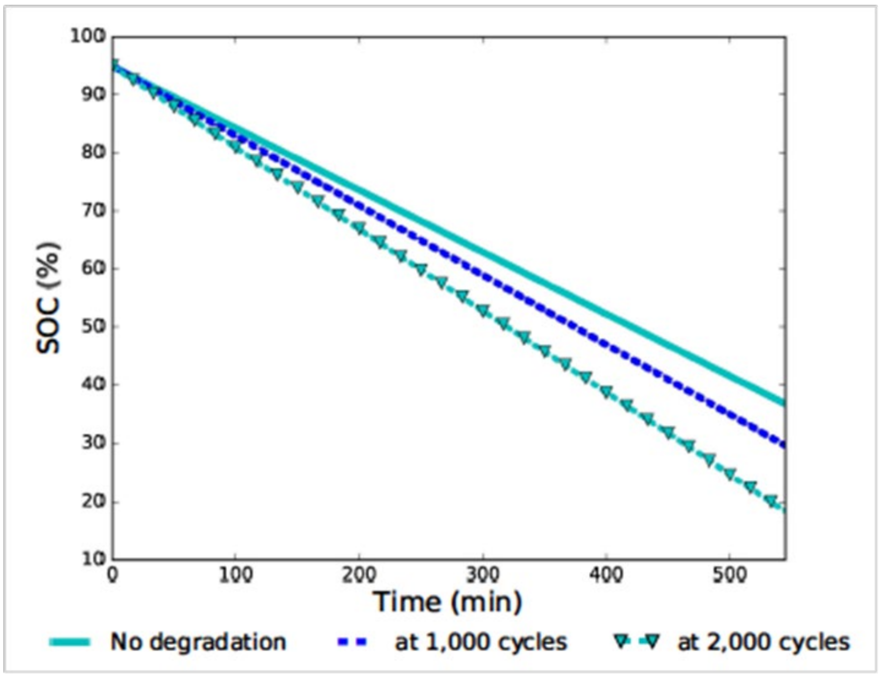


Figure 29: SOC of a BEB Across 9 hours of Operation, with No Degradation, and After Completing 1,000 and 2,000 Recharge Cycles

5.3 CHARGER TECHNOLOGY OVERVIEW

BEB charging equipment has two main components: the power cabinet and the dispenser. The power cabinet can have different power rates, depending on the number of modules that are combined. The charger module is the inner power module for DC charging stations (piles) and convert AC energy into

[64] https://www.sciencedirect.com/science/article/pii/S0301479718313124
[65] https://ieeexplore.ieee.org/document/7993351
[66] https://www.sciencedirect.com/science/article/pii/S0301479718313124
[67] Company EBUSCO = 10 years https://www.ebusco.com/battery/.
BYD 12 years: https://www.masstransitmag.com/home/press-release/12058920/byd-motors-llc-byd-announces-12-year-battery-warranty

DC in order to charge a vehicle. For example, a power cabinet can have one module of 60 kW or two modules for a total of 120 kW power rate; in this way, charging equipment is modular and scalable.

Charging equipment can be categorized based on power output as follows:

- **Standard charging:** between 60- to 150-kW power rates. Can be provided by any type of dispenser.
- **Fast charging:** for power rates above 300 kW and a maximum of 600 kW. Only pantographs can provide these high-power capacities.
- **Centralized:** new centralized solutions are grouping the charging modules in a single unit capable of distributing up to 3 MW among several modular dispensers. The dispensers connected to a centralized unit can be either plug-ins or pantographs.

There are three types of dispensers, which are the actual connections between the vehicle and the power cabinet, and those are 1) plug-in, 2) pantographs, and 3) wireless dispensers. Different installation configurations of dispensers are also possible, creating the classification shown in Figure 30.

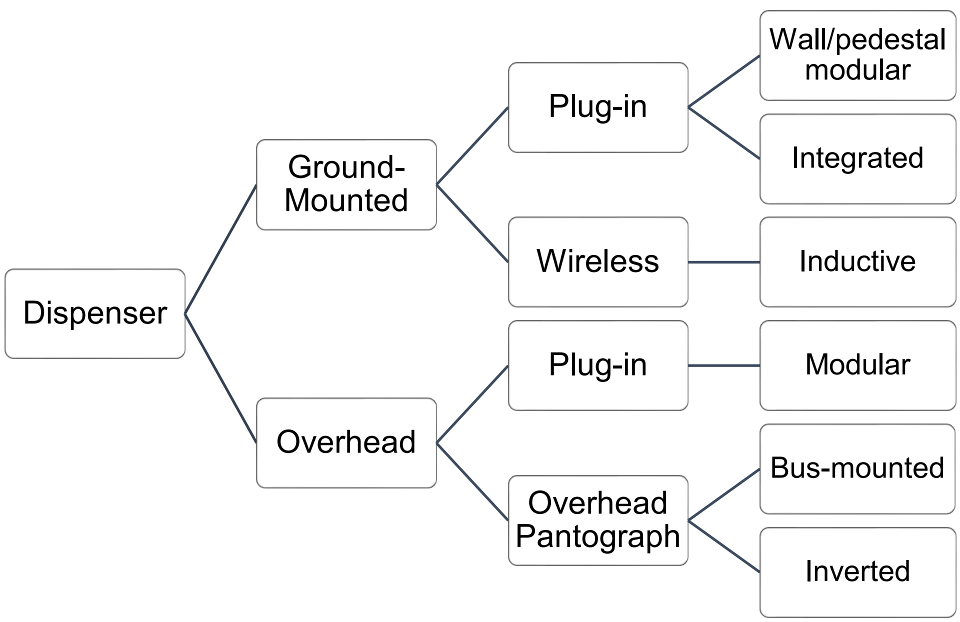


Figure 30: Dispenser Installation Configurations.

Table 10 presents images and examples of the different dispenser installations and configurations.

Table 10: Example of Dispenser Installation Configurations.

<table>
<tr><th colspan="2">Ground-Mounted Dispensers</th></tr>
<tr><td>Modular Plug-in Dispenser

</td><td>Integrated Plug-in Dispenser

</td></tr>
<tr><td colspan="2">Wireless Inductive Charger

</td></tr>
<tr><th colspan="2">Overhead Dispensers</th></tr>
<tr><td>Overhead Plug-In
</td><td>Inverted Pantograph

</td></tr>
</table>

On a modular dispenser, one or more power cabinets can supply one or more dispensers. A modular dispenser can also be referred as the “dispenser pedestal”. In contrast, an integrated dispenser has the power module and dispenser within in the same cabinet, making it a single unit.

Wireless (or inductive) chargers occupy a small footprint and can be used on-route. While aesthetically more pleasing because no large external space is needed like for overhead chargers (they are built into the roadway), charging efficiency varies greatly with bus alignment. Also, not all manufacturers offer inductive charging and there is no interoperability among wireless charger providers.

For the overhead (or conductive) inverted pantograph configuration, a charging head is lowered onto a set of DC charge rails on the top of the BEB. All BEB manufacturers have aligned with universal high-power opportunity chargers from companies such as Siemens and ABB. Additionally, interoperability is currently being tested. Pantograph chargers can be installed on-route for fast-charging or in the depot for overnight charging at lower power rates, depending on power cabinet configurations and agency needs.

Because they require fewer alterations to a facility, plug-in chargers tend to cost less than overhead and wireless chargers in terms of purchase costs and installation. Nevertheless, plug-in chargers require more space compared to overhead chargers and are subjected to increased wear and tear, relative to other charger types in a transit setting. Moreover, because rapid charging is desired for on-route applications to minimize non-productive time, fast charging configurations are required, i.e., plug-in chargers are too slow to be useful for on-route applications. A comparative analysis between depot-only charging and on-route charging technologies is shown in Table 11.

Table 11: Charging Technology Comparison.

	Depot plug-in charging (AC or DC)	**Fast Charging (DC only)**
Charging location	Plug-in charging at depots	Pantograph charging at stops on-route or at depots
Battery capacity	Larger	Smaller and/or larger
Charge rate	<150 kW	300-600 kW
Range	Typically, around 180 mi per day.	Addresses range issues but requires regular in-service charging.
Charge time	Slow - 6-10 hours Fast - 3-6 hours	3 - 10 minutes per vehicle (top up)
Impact on battery health	Low	High (fast charging is found to have a negative impact on battery health)
Typical Equipment costs	$65,000 - $130,000	$350,000 - $620,000
Maintenance	Medium	High

	Depot plug-in charging (AC or DC)	Fast Charging (DC only)
Standards	AC: SAE J3068 DC: SAE J1772	Overhead conductive: SAE J310 Wireless inductive: SAE J2954/2

Due to the power output specifications and construction/installation needs, on-route charging capital costs are generally greater than in-depot charging capital costs. Therefore, when the fleet size is smaller, the depot-only strategy is economically more feasible while opportunity charging makes sense for larger fleets, especially if operational modifications cannot be made to suit the shorter operating ranges of depot-only charging BEBs.

Table 12 shows a sample of US charger manufacturers classified as plug-ins, pantographs, and wireless chargers.

Table 12: Sample of US charger OEMs.

	Depot-charging; Plug-ins (AC or DC)	Fast-charging; Pantographs (DC only)	Wireless Inductive (DC only)
Suppliers	ABB Siemens Fimer Hitachi ABB Kempower PRIMOVE Tritium Proterra Heliox ChargePoint	ABB Hitachi ABB Siemens Kempower PRIMOVE Proterra	WAVE

5.4 BEB PERFORMANCE

Range is a crucial performance criterion for bus operations. Being able to accurately predict battery range and ensure the right charging strategies to deliver the daily mileage is a key consideration for transit service providers to avoid service disruptions. Range and charging strategies are interlinked through the battery SOC. SOC is a moment-in-time measurement of the battery's capacity and can be combined with driving efficiency to determine range.

Bus driving efficiency is impacted by vehicle specifications (weight, aerodynamics), route profiles (traffic conditions, distance, dwell times, sustained top speeds, etc.), topography (inclination), climate (air conditioning load and heating), opportunities for regenerative braking, and operational parameters (passenger loads). These values can thus vary by route, by time of day, by geography, etc.

5.4.1 Real-World Data on BEB Range

Since energy consumption directly correlates to range, large variations in energy consumption pose a significant challenge with respect to the planning of service and dispatching of buses. Inclement weather conditions in the winter months significantly impact vehicle performance. Cold temperatures, snow and ice conditions require the vehicles to expend more energy by way of heat and traction power. To mitigate this negative impact to operating range, some agencies operating in colder climates have equipped their vehicles with auxiliary diesel heaters to minimize battery consumption.

Nonetheless, some real-world experiences demonstrate that while cold temperatures do impact range and energy consumption, the expected impact can vary by manufacturer. For instance, in 2020 the Toronto Transit Commission's (TTC) eBus program uses diesel heaters[68], providing direct experience of the impacts of cold weather on BEB performance[69]. As shown in Figure 31, colder temperatures generally result in greater energy consumption, but not equally across different bus models. New Flyer buses had the most stable energy consumption across seasons compared to Proterra and BYD buses.

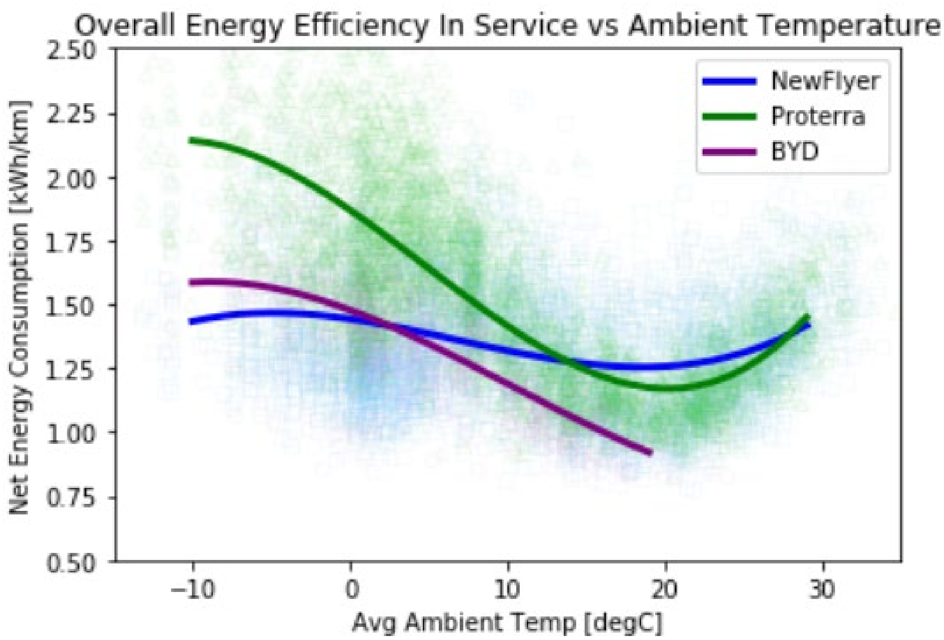


Figure 31: Energy Consumption vs. Ambient Temperature[14].

Interestingly, this disparity is largely driven by design-related features such as using an electric heater for the front windshield defroster, as well as a lack of heating the operator area resulting in operators using the front defroster as a source of heat.

Weather conditions are only one of the many variables that affect energy efficiency and range, other variables important to consider are: passenger load, operating speed, driver behavior, and route topography.

Table 13 reports the 2020 monthly average fuel efficiency of the BEB fleet measured from real-world conditions by the TTC.

[68] The TTC will continue to specify BEBs with diesel-fired heaters until heat pump technology is viable.
[69] https://ttc-cdn.azureedge.net/-/media/Project/TTC/DevProto/Documents/Home/Public-Meetings/Board/2021/April_14/6_TTCs_Green_Bus_Program_Preliminary_Results_of_TTCs_Head_to_Head_eBus_Evaluation.pdf?rev=5c348c81e8504ef0b83735556437f7ec&hash=E6789DA35DB0E6CA426A2D391FD426AB

Table 13: Daily Average Energy Efficiency and Expected Range of a Real-World BEB Fleet[70].

	Fuel Efficiency (kWh/mi)												Average Efficiency kWh/mi
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
New Flyer	2.16	2.25	2.16	2.16	2.03	1.95	2.09	2.11	2.09	2.25	2.25	2.28	2.14
BYD	-	-	-	-	-	-	-	-	1.59	1.90	1.98	2.30	1.95
Proterra	3.27	3.36	2.77	2.28	2.00	1.93	2.09	1.95	1.87	2.19	2.48	2.65	2.40

Moreover, Table 14 shows the differences between the advertised range from the three manufacturers tested by the TTC and the average range that was observed during the 12-month data collection.

Table 14: Advertised Range versus Average Actual Range from Real-World Operations of BEBs.

	Battery Size (kWh)	Advertised Range (mi)	Average Range from TTC (mi)	Difference (mi)
New Flyer	400	200	187	- 13
BYD	360	180	185	+ 5
Proterra	440	154-232	130-235	- 24 + 3

Overall, New Flyer BEBs experienced consistent energy consumption and a difference of about 6% of stated range. These BEBs with a 400-kWh battery also had longer ranges than Proterra BEBs equipped with larger (440 kWh) batteries. BYD BEBs also experienced a small 3% difference in actual vs. stated operating range.

Taken together, real-world data demonstrates that expected range could be within the margin of error of advertised range. Of course, this is dictated by a host of factors as discussed throughout this report that really varies from agency to agency, as well as by bus manufacturer. Bus simulation and route modeling are important steps in the strategic deployment of ZEBs for an agency to understand how a ZEB could perform on a given route in an agency's specific context.

5.4.2 Range Extension Strategies

One key strategy to extend the range of BEBs is rapid on-route recharging to top-up a BEB. Another strategy involves midday recharging at the bus depot that could be accommodated if a bus is assigned two shifts—one in the morning, and one later in the day. Figure 32 illustrates the link between driving efficiency, SOC (red line), range from generic bus modeling (not AAATA), and the impacts of midday in-depot recharging. The gray area is the elevation profile of the roads and the bus travels 107 miles to complete a full day of multiple routes. During the day, it stops over at the depot which presents an opportunity to charge, and the bus increases its charge from about 60% to 100%. At the end of the day, it

[70] Original data from TTC converted from kWh/km to kWh/mi

returns to the depot and its battery has about 60% charge remaining. With one charge during the day, the bus can complete its daily mileage.

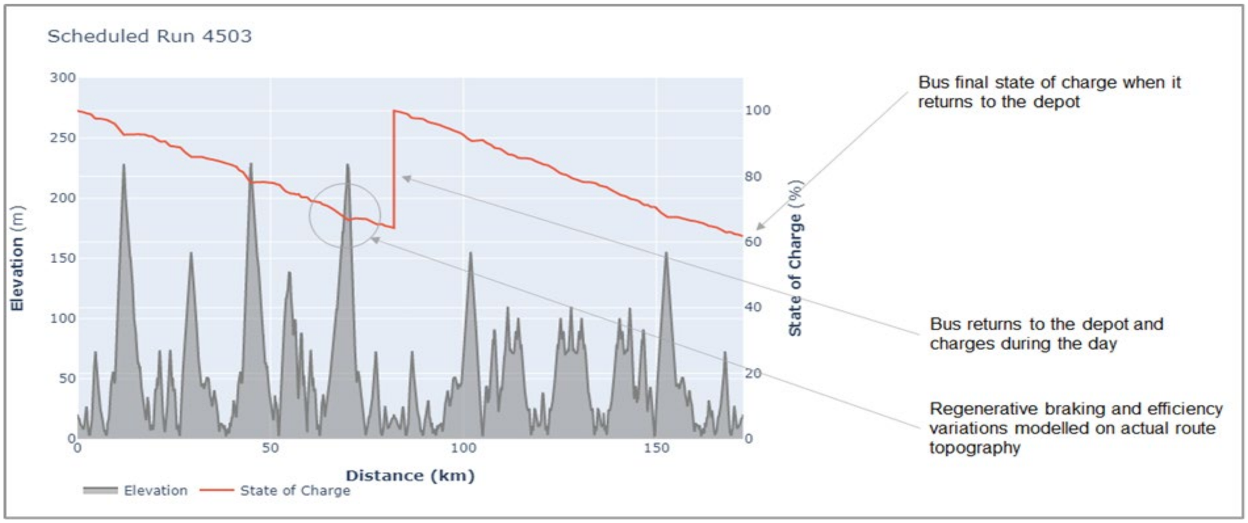


Figure 32: Relationship Between Driving Efficiency, SOC, and Range

However, even with midday charging, a block may still exceed the current range capabilities of BEBs. For example, in Figure 33, a generic bus block requires the vehicle to travel for a total distance of 304 miles and it includes a layover at the depot during which time its charge increases by about 50%. Despite this, the bus is unable to complete its full assigned mileage. Importantly, in real-world operations, SOC should be kept above 20% to avoid detrimental impacts on SOH as well as to remain within manufacturer warranty.

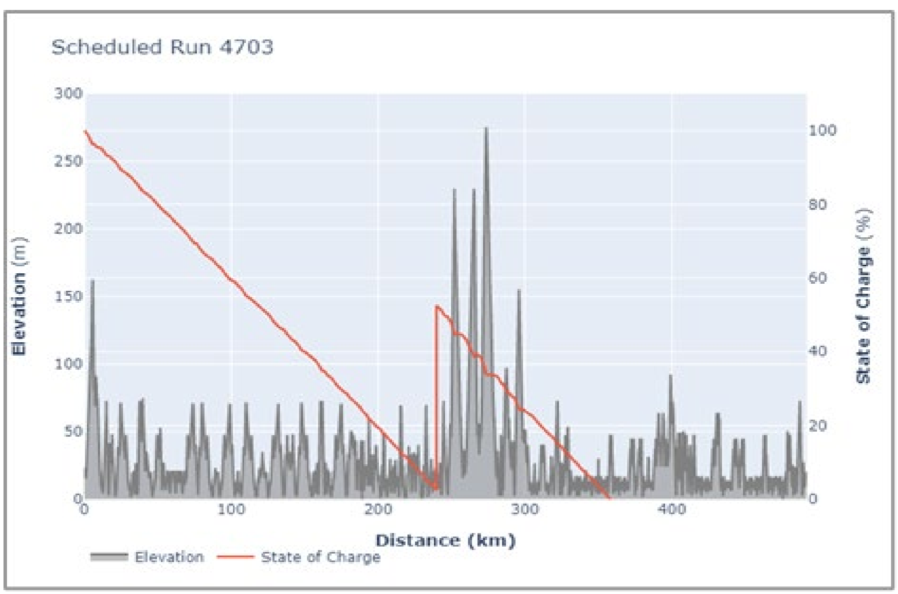


Figure 33: Unsuccessful Block

5.5 ELECTRICITY SUPPLY FOR BEBS

Agencies implementing BEBs are required to establish close working relationships with electrical utility companies since they become the main “fuel” suppliers for a BEB fleet. The conversion of a large (50+) fossil fuel bus fleet to a BEB fleet is a challenging undertaking that requires substantial electrical grid and utility upgrades to accommodate massive increases in electrical demand stemming from BEB recharging. *Without coordination with local utilities, it is unlikely that an agency can properly acquire and operate BEBs.*

The graphic in Figure 34 demonstrates the potential peak power loads of simultaneously charging 50 BEBs—exceeding the power loads of a large office building and posing challenges to agencies in terms of electricity costs and infrastructure needs.

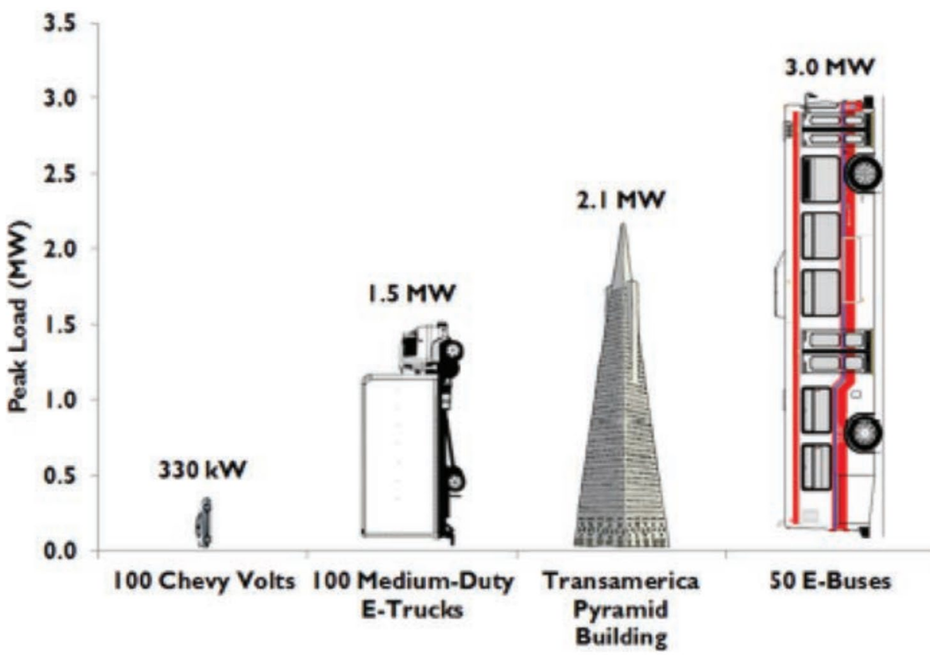


Figure 34: Peak Power Loads for BEB Charging Compared to Other Uses (TCRP Synthesis 130)[71].

5.5.1 Michigan Electricity Distribution Network

The Michigan Public Service Commission (MPSC) requires electrical energy distribution to be broken into multiple carrier systems. One carrier system is power supply, the other is delivery/distribution. This allows customers on the electrical systems to have different power supply and delivery/distribution carriers. In the general Ann Arbor area, DTE Energy predominately supplies both power supply and delivery/distribution services; AAATA uses DTE Energy for both services.

[71] https://www.trb.org/Publications/Blurbs/177400.aspx

5.5.2 Energy Sources in Michigan

In 2021, DTE Energy had a goal of 15% of energy for Michigan coming from renewable sources. Today, the majority of electricity is generated by burning coal. However, DTE has found that renewable energy is cost-competitive with natural gas and is currently investing in a mix of these two energy sources. Furthermore, DTE is also in the process of re-evaluating its future energy mix through an Integrated Resource Plan it will file with the public utility commission that will identify least-cost energy procurement strategies. These strategies will help keep costs low for customers while also helping DTE's and the state's climate goals.

Finally, DTE's MIGreenPower offers eligible electric customers simple and affordable renewable energy programs supporting DTE Energy's wind and solar projects. With the MIGreenPower program, customers can purchase renewable energy for an additional 1.9¢ per kWh for wind and/or 2.7¢ per kWh for wind and solar. As of August 2022, DTE is redeveloping its rate structure for the MIGreenPower program. Taken together, while Ann Arbor's energy mix is still predominately fossil fuel-based, it is nevertheless on the path to becoming cleaner.

5.5.3 Electricity Retail Market and Rate Structures

The Michigan Electrical Retail Market allows for competition for electrical services for the power supply component of electrical services. The delivery/distribution will be handled by local utility owner which is DTE Energy. Presently AAATA use DTE Energy for power supply rates. Rates can be based on Large General Service (D4) to Primary Supply Rates (D11). These rates are based on who owns what equipment (transformer/primary switches) and the size of the electrical services. Also, DTE Energy is starting to offer "Green Rates" (R17) that promote renewable energy. Presently, AAATA electric utility bills are based on Primary Supply Rate of D11.

All rate contracts in the State of Michigan must be reviewed and approved by the MPSC. Presently, DTE Energy only has Electrical Vehicle Rate (D1.9) under Standard Rates, this rate is intended as secondary pricing which is intended for small business applications. This rate is significantly *higher* than Primary Supply Rate (D11) which is what is AAATA is on.

Prices for electricity vary depending on the time of day when charging occurs. For the D11 rate, peak rates are applied for electricity consumed during the months of June through October and during the hours of 11 am – 7 pm. These time-of-use rates are generally intended to encourage electricity consumption during off-peak times and discourage peak-time charging via higher prices.

DTE Energy also has a ratcheting demand charge for electric services. Effectively, AAATA pays a demand penalty for the previous 11 months based on peak usage between 11 am and 7 pm and between the months of June and October. Many transit agencies in the US that have adopted BEBs have been shocked by the significant prices they have had to pay for bus charging. Accordingly, AAATA should focus on using electrical energy during off-peak hours to reduce this significant cost.

Based on past peak demands and the latest utility rates, AAATA could expect to pay, on average, between $0.09 and $0.11 per kWh in 2022 dollars for BEB charging. See Table 15 for a detailed summary of the various charges from 2021.

Table 15: Summary of DTE Energy Rate schedules for D11 Primary[72].

	DTE Energy D-11 Primary Rates		**AAATA Statement** Example from 2021	
	Rate ($)	**Unit**	**Units**	**Total**
Power Supply Charges				
Demand Charge Capacity	13.82	kW	360	$4,975.20
Demand Charge Non-Capacity	3.30	kW	360	$1,188.00
Power Supply Energy Charges				
On-Peak Non-Capacity Charge	0.04261	kWh	41,339	$1,761.46
Off-Peak Non-Capacity Charge	0.03261	kWh	117,981	$3,847.36
Power Supply Charges	0.00322	kWh	159,320	$513.01
			Power Supply Charges – Subtotal	**$12,285.03**
Delivery Charges				
Distribution Demand	4.21	kW	438	$1,843.98
Surcharges – Nuclear	0.000842	kWh	159,320	$134.15
Surcharge – LIEAF[73] Factor	0.87	Unitless	1	$0.87
Surcharge – Transitional Recovery	0.001794	kWh	159,320	$285.82
Other	Various	Unitless		$1,161.26
			Delivery Charges – Subtotal	**$3,496.08**
			Grand Total	**$15,781.10**
			Utility Rate ($ per kWh)	**$0.099053**

Taken together, time-of-use rates, demand charges, and other fees, as well as the deployment of charging will all impact the actual rates for BEB charging. The financial modeling presented later in this study used current DTE rates based on hypothetical charging of a fleet of BEBs focused at minimizing peak-hour charging to reduce overall costs. In addition, if AAATA moves ahead with BEB adoption, it will need to work with DTE to understand grid requirements. Finally, one key benefit of a BEB fleet compared to a fossil fuel fleet is the general stability and predictability of electricity rates—diesel fuel fluctuates based on market conditions, and is generally volatile. In comparison, electricity rates generally fluctuate less and can be more predictable based on historical changes from a utility. The result is 'fuel' cost savings for a transit agency operating BEBs.

5.6 FINANCIAL CONSIDERATIONS

To provide some illustrative cost comparisons of BEBs with traditional diesel buses, Table 16 provides an overview of capital costs associated with BEBs and diesel buses, while Table 17 provides an overview of operating and fueling costs associated with BEBs and diesel buses. These tables are meant to provide **examples of the costs reported by transit agencies operating these technologies and are based on historical data**. The figures here may differ from what could be expected by AAATA and into the future.

[72] https://www.michigan.gov/-/media/Project/Websites/mpsc/consumer/rate-books/electric/dte/dtee1cur.pdf?rev=cf55d05b027a43fc9d4f762672e9aa9e

[73] Low-Income Energy Assistance Fund. Funds collected through the LIEAF surcharge, a state-mandated charge, are remitted directly to the state and help provide heating assistance to low income customers across Michigan.

Inputs and assumptions used in the financial modeling are presented in Section 8.0 and Appendix B Financial and Emissions Modeling Inputs.

Table 16: Illustrative capital cost comparisons between diesel buses and BEBs, current values

Item	Diesel	BEB	Comments
Vehicle	$500,000-700,000	$700,000-1,200,000 per bus[74]	Depends on bus length Depends on configuration and add-ons Depends on battery pack capacity Depends on charging configuration (plug-in, overhead, or both)
Extended warranty	NA	$40,000-120,000 per bus	Depends on OEM Depends on battery pack capacity Depends on duration of warranty
Low Power Charger – Capital	NA	$60,000-100,000 per charger	Depends on power output Chargers can have multiple dispensers (typically 2 for one charging pedestal)
High Power Charger – Capital	NA	$300,000-500,000 per charger	Depends on power output Each charger can charge two BEBs in-depot For on-route chargers, a ratio of five to six buses to one charger has been assumed by Stantec on ZEB projects[75]
Plug-In Charger – Installation and Electrical Upgrades	NA	$50,000-180,000 per bus	Depends on complexity of project Depends on power output
On-Route Charger – Installation and Electrical Upgrades	NA	$400,000-600,000 per charger	Depends on complexity of project Depends on charger type (inductive is on the lower end of the range compared to overhead pantographs) Depends on power output
Facility Modifications	NA	Varies.	Depends on fleet size Depends on the state of repair of the bus facility, the space available to accommodate buses and charger infrastructure Depends also on grid capacity and state of electrical equipment A detailed architectural and engineering study is needed to understand true costs

[74] BloombergNEF predicts that the purchase price of a transit BEB will reach parity with diesel buses by 2030 [Electric Buses in Cities: Driving Towards Cleaner Air and Lower CO2 | BloombergNEF (bnef.com)].
[75] Assumes that each bus requires approximately 10 minutes to recharge (including proper positioning, deploying the charger, etc.), and therefore approximately five to six buses can be charged in one hour.

Table 17: Maintenance and fuel cost comparisons between diesel buses and BEBs

Item	Diesel	BEB	Comments
Charger	NA	$6,000-7,000 per charger (per year)	Outside of warranty
Bus Maintenance Cost	$0.19-0.45 per mi	$0.20-0.50 per mi	Range represents reported values from pilots and feasibility studies Depends on operating conditions, learning curves for maintenance staff, and bus type Also depends on operating profile and local labor costs
Battery Pack Replacement	NA	$200-600 per kWh	Range represents different OEMs and battery pack sizes Cost range is for a battery replacement not under an extended warranty
Midlife Overhaul (body and other related work unrelated to drivetrain)	$50,000-100,000	$50,000-100,000	Depends on the condition of the bus at midlife Depends on intended useful life Depends on whether an agency uses internal resources or external garage
Fuel cost per mi ($)	$3-7 per gallon $0.70+ per mile	$0.40-0.60 per mi	Range represents for diesel bus is fuel costs from different regions in early 2022 Range for BEB from NREL data Volatility of diesel and carbon prices will likely rise more significantly that the prices of electricity Costs will rise and fall depending on fuel prices, taxes, and hedging Actual cost per mile will vary with time-of-use, demand charging, and other local factors

5.7 SUMMARY AND TAKEAWAYS

BEBs are a potential solution for the electrification of bus fleets. The technology has had a consistent improvement to operating ranges and steady reductions to purchase prices, making the adoption of such vehicles more accessible for transit agencies. Additionally, large transit agencies have announced their intentions to electrify entire fleets ranging from small agencies (less than 20 vehicles) to large systems like King County Metro in Seattle with over 900 vehicles. The variety of charging solutions (plug-ins, pantographs, on-route charging, wireless equipment, etc.) provides flexibility in adoption plans to transition to 100% BEB.

However, the vehicle range and fuel efficiency of BEBs vary depending on climates, terrains, and even passenger loads. Limited range can have a negative impact on numerous internal operations. Therefore, the applicability of a BEB solution needs to be investigated closely with respect to the specific operational conditions and needs of each transit agency. Furthermore, the design of the charging solution(s) will be informed by the fleet operational needs (e.g., if on-route charging is required to complete service) and by the facility constraints, such as limited footprint yards that can only accommodate pantograph chargers.

Lastly, agencies implementing BEBs must establish close working relationships with electrical utility companies since they become the primary “fuel” suppliers for a BEB fleet.

5.8 BEB CONCEPT FOR AAATA

Based on the information described above for BEB technology, the subsequent step in the propulsion study was to develop a potentially viable BEB deployment concept for AAATA. This step required site planning, bus modeling, and considerations for AAATA’s operations.

5.8.1 Preferred Site Concept for BEBs

To develop the preferred site concept for BEBs, two different site concepts were developed for discussion: one with *consolidated* charging equipment and one with *distributed* charging equipment. The clear limitations of space at the existing garage required an approach where the footprints of the chargers and their related equipment were minimized. As such, the main approach for charging dispensers was an overhead method of charging, either with plug-in dispensers or inverted pantographs.

Stantec and AAATA staff held a workshop session to discuss different site concepts and considerations to help refine the concepts and developed a ‘preferred’ concept for each fleet technology.

First, by considering the trade-offs of plug-in chargers (requires physical interaction of an operator or servicer with the equipment) and overhead pantographs (automated deployment triggered with a control in the BEB), AAATA staff indicated the preference for pantograph dispensers.

Next, Stantec walked through two related, but different concepts for the major infrastructure considerations for BEB charging include the grid, transformer, switchgears, chargers, dispensers, and the buses themselves.

Each BEB concept is presented below with a summary of considerations specific to each concept.

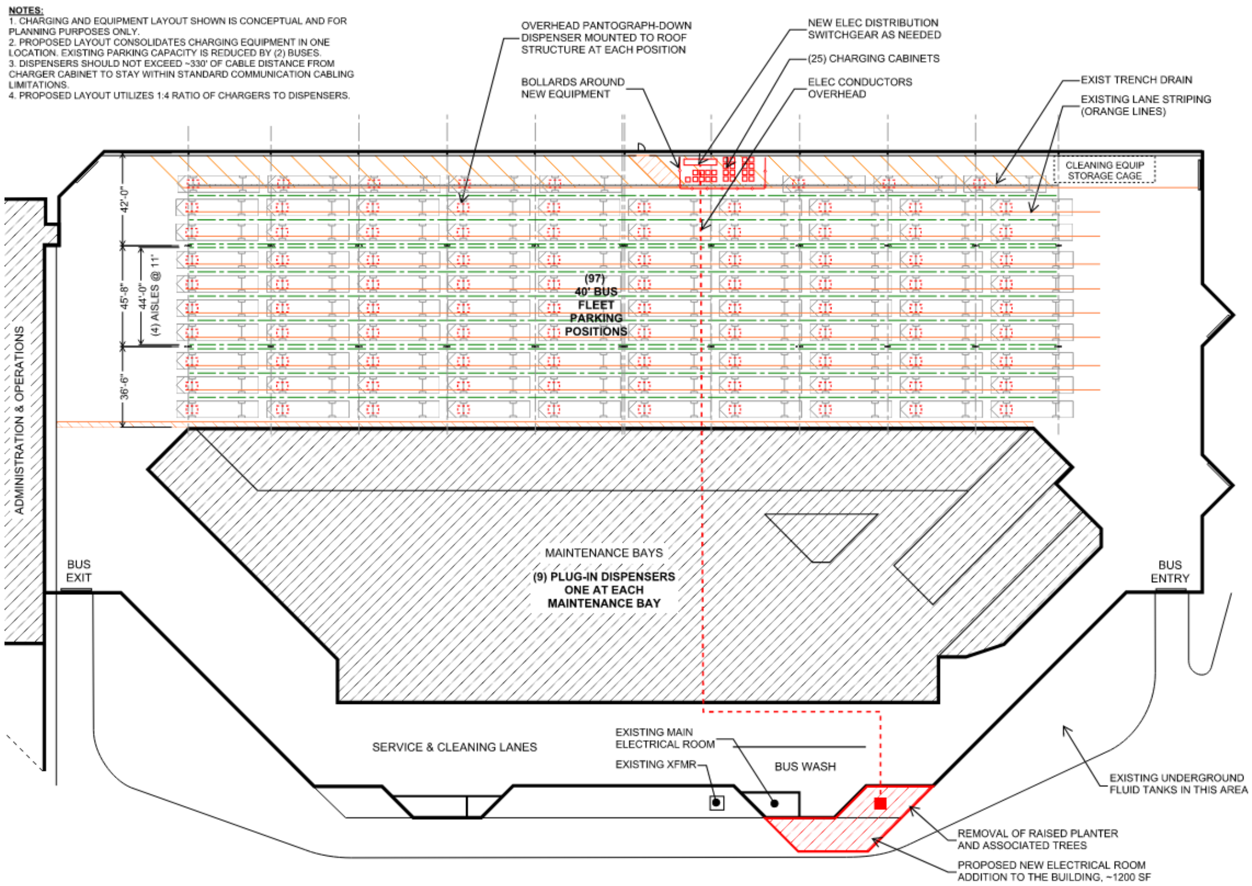


Figure 35: BEB Concept 1 - Consolidated Charging Equipment

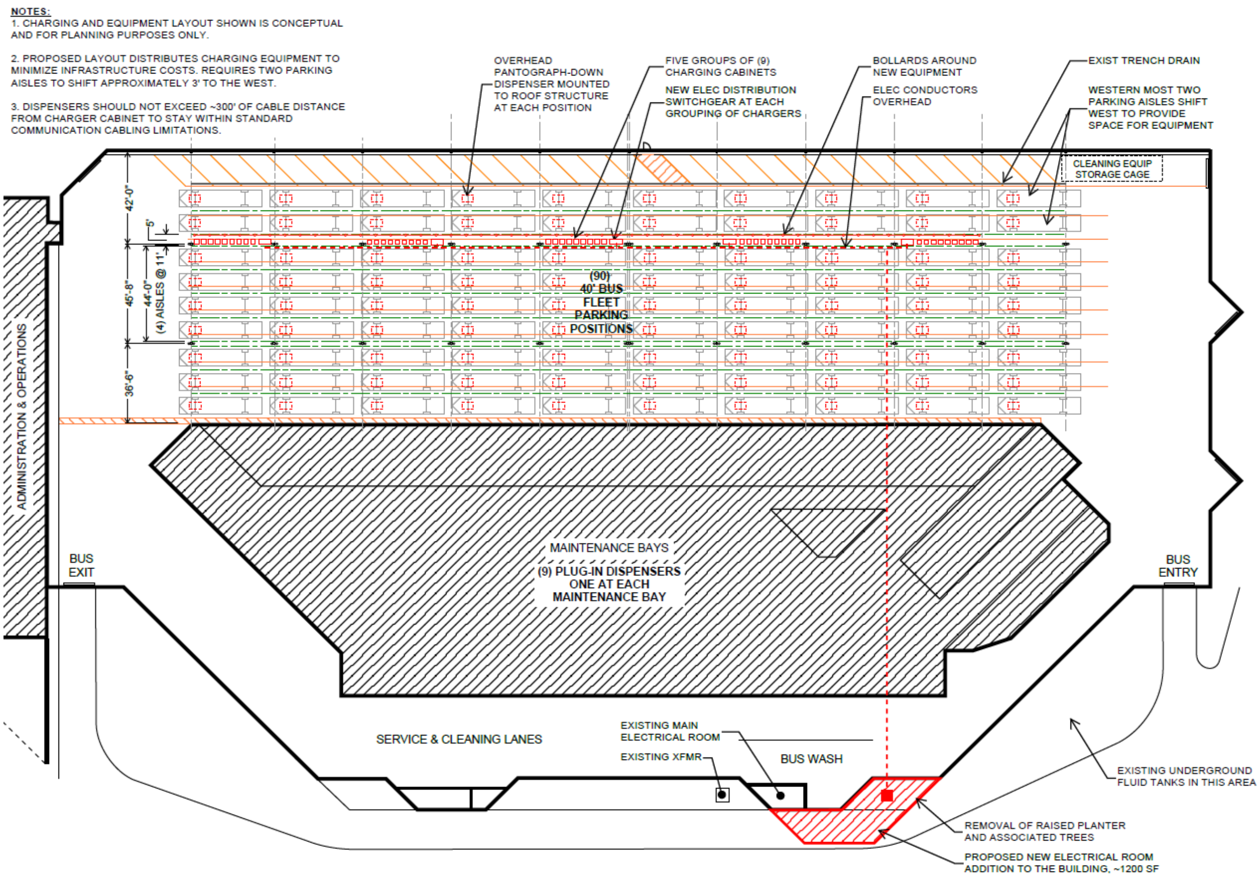


Figure 36: BEB Concept 2 - Distributed Charging Equipment

Table 18: BEB site concept considerations

Considerations	
BEB Concept 1 – Consolidated Charging Equipment	**BEB Concept 2 – Distributed Charging Equipment**
Eliminates a portion of the layover parking to accommodate charger cabinets	Maintains all layover parking
Keeps the charger cabinets out of the drive aisles	Charger cabinets in-between drive aisles
Pantograph or overhead pull-down plug-in dispensers	Pantograph or overhead pull-down plug-in dispensers
No room for expansion beyond 99 charging positions	No room for expansion beyond 99 charging positions
Locks-in parking configuration (stacked parking)	Locks-in parking configuration (stacked parking)
Charging software management is critical to monitor SOC and bus readiness	Charging software management is critical to monitor SOC and bus readiness
New electrical room as an addition to the building	New electrical room as an addition to the building

Many of the considerations are the same for each concept, with the chief differences including that Concept 1 eliminates a portion of the small vehicle layover parking along the west wall to accommodate charging equipment whereas Concept 2 does not, and Concept 1 keeps charger cabinets out of bus drive aisles where Concept 2 places charger cabinets in-between drive aisles. Nonetheless, the key assumption of the fleet size in the above concepts needed to be modified—that is—the current 99 parking positions need to be maintained in the main parking area.

After workshopping the two site concepts with AAATA staff, a third refined site concept was developed that considers space needs for the infrastructure and fleet and presents the best flow of vehicles while minimizing the risk of navigating around electrical equipment. Furthermore, this concept accommodates 99 parking positions and maintains the drive aisle along the western wall, at least until the top row of buses are parked (Figure 37). This site concept also enables maintenance and repairs on the electrical system with minimal disruptions while the garage is full.

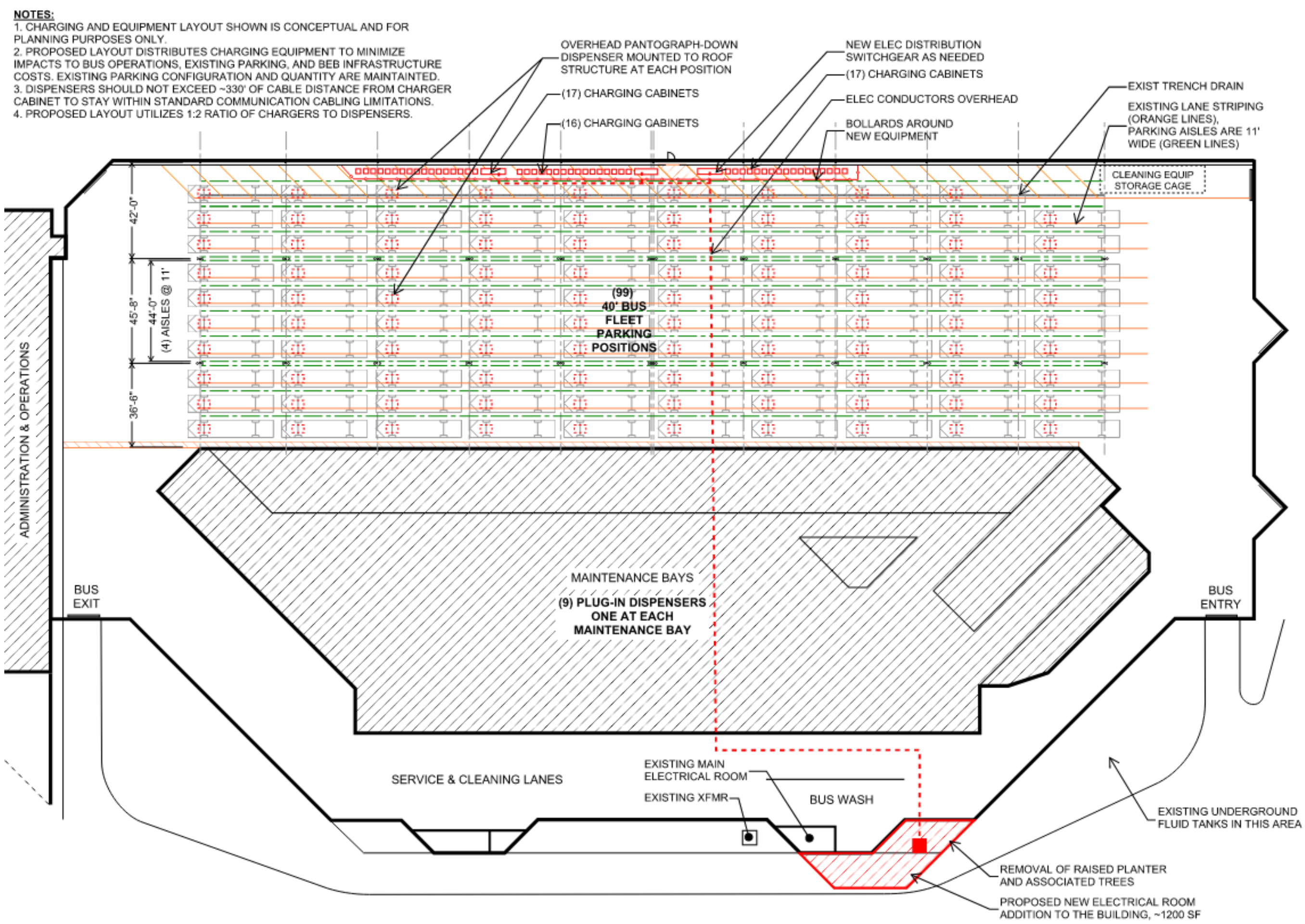


Figure 37: Preferred BEB site concept

5.8.2 Proposed Maintenance Facility Modifications

The modifications to the existing facility for the implementation of charging equipment will generally be limited to the charging equipment itself but there will be significant upgrades to the electrical service for the facility as well as related modifications to the building for the installation of the equipment.

- The proposed concept includes a new/expanded main electrical room for the new facility since the current electrical room is already constrained and in need of an upgrade. The addition is proposed to be about 1,200 sq. ft. and should match the existing masonry architectural envelope of the existing building.
- Three new 2,500 kVA transformers and three 2,500 Amp switchboards to provide adequate additional power to the facility. Alternatively, larger transformers can be installed to coincide with the phased implementation of the BEB fleet. The system can be implemented in stages with each stage being one (1) 2,500 kVA transformer.
- Two new 2.5 MW back-up diesel generators with onsite fuel storage in order to support 100% bus service is recommended. The quantity of fuel maintained on site will depend on the anticipated utility outage duration and the availability of fuel deliveries. Alternatively, the generator could be fueled using pipeline natural gas that is available in the street in front of the facility.
- A minimum of 50, 150-kW vehicle chargers with a 1:2 charger to dispenser ratio to serve a maximum of 99 BEBs.
- Dispensers are proposed to be overhead inverted pantographs attached to the underside of the existing building's roof structure.
- Equipment pads and associated bollard protection around charging equipment will be required.
- Due to length limits for communication and DC-charging cables, the dispensers must be within 100 meters (328 ft.) of its charger, based on total cable length.
- All electrical distribution will be overhead throughout the building and will cause modest impacts to the existing building. Penetrations through existing walls and new support framing for conduits, etc. will be required throughout.
- Modifications to the existing building's overhead systems in the bus parking area, including HVAC ductwork, lighting, etc., may need to be reconfigured based on the fixed locations of the overhead pantographs mounted to the 'ceiling' of the space.
- Supplemental structural framing will be required to be added at each pantograph location to support the new equipment.
- Stantec had discussions with DTE to understand what potential upgrades would be needed for the current electrical system servicing the AAATA facility. While capacity availability can only be confirmed via a formal service expansion request to DTE, Stantec learned that the AAATA facility is located in the South Industrial Zone where large capacities were anticipated for the electrical

grid. While the grid is connected to the nearby mall and other industrial buildings, there is likely available capacity. Therefore, any necessary upgrades to bring power to the facility will likely be limited to behind the meter upgrades (e.g., transformers, switchgears, etc.) and not include substation upgrades, which could cost on the order of millions. Typically, the capital cost of grid infrastructure is borne by the utility, DTE in this case. These costs would be recovered through the increase in power sold to and consumed by AAATA for a BEB fleet.

5.8.2.1 Phasing of Charging Infrastructure

The phasing approach for the charging infrastructure of BEBs is dependent on the vehicle procurement strategy since the chargers and pantographs need to be in place prior to vehicle delivery. As described in Section 8.2, there are different strategies and timelines explored to phase out diesel buses and acquire BEBs. Nevertheless, the following phasing recommendations apply to any of the bus procurement strategies discussed later:

Phase I:

- New/expanded main electrical room for the facility
- Electrical trench and duct banked power feeders to connect electrical room equipment to chargers' location
- Installation of transformers and switchboards. If a larger transformer is selected, it should be installed during this phase
- Installation of generators with onsite diesel fuel storage
- Equipment pads for all future charging equipment, transformers, and switchboards
- If required, modifications to the existing building's overhead systems in the bus parking area, including HVAC ductwork, lighting, etc., could also be completed during this phase
- Double doors for compliance with safety codes
- Upgrades to roof structure and roof drains
- Upgrades to ventilation and extinguishing system
- Upgrades to communication and fire alarms with connections to future phasing
- New full height wall (18 feet) and footing between charging and maintenance bays

Active Phasing (modifications needed to start 18-months prior to the arrival of BEBs):

- Bollard protection for all future charging equipment, transformers, and switchboards
- Modifications to fire protection for pantographs
- Installation of chargers and pantograph dispensers in parking area

- Installation of chargers and dispensers in maintenance building
- Mounted structure and feeder from charger to dispensers
- Feeder to connect power cabinets (chargers) to switchboard
- Modifications to lighting for pantographs
- Installation of supplemental structural framing for each pantograph location to support the new equipment
- Communication connections from pantographs and chargers to main control panel
- Overhead mounted power feeders to connect new chargers to electrical room feeder.

Decommissioning Phase:

- Remove refueling island
- Remove tailpipe exhaust system at maintenance bays
- Remove maintenance equipment related to oil changes and other fluids that are no longer needed in the maintenance cycle of BEBs

5.8.2.2 Modifications to Maintenance Bays

Beyond the facility modifications noted above, there are very few modifications needed to the physical infrastructure of the maintenance area within the garage facility. The primary impacts will be to the maintenance equipment and tooling needed to service a BEB fleet compared to a fossil fuel fleet. The assessment of the actual equipment needed is outside of the scope of this report but can be assumed to be relatively straightforward since it will not be built into the facility. However, following the complete transition to a BEB fleet, maintenance equipment such as vehicle tailpipe exhaust reels can be removed from the maintenance bays to free-up usable space.

The biggest impact to the actual maintenance area would be the installation of at least one charger within the maintenance bays upon initial implementation of electric vehicles. For routine service, diagnostics and to recharge a bus in the event the batteries are depleted during maintenance, a minimum 25-kW charger is recommended to be installed within the building. At full fleet conversion to BEBs, each of the nine repair bays and the one preventive maintenance bay are recommended to be outfitted with charging capabilities. Either at least one high-capacity charger with multiple dispensers or individual charging cabinets for each bay could also be implemented depending on budget and phasing constraints.

Alternatively, mobile charging equipment could also be implemented to use in the repair bays as the technology becomes more readily available. Like the charging equipment in the parking area, the charging cabinets should be remotely located from the dispensers to minimize the consumption of functional space in the repair bays. Remote dispensers could easily be located throughout the bays, mounted to columns or walls as needed to reach the appropriate charge ports on the procured fleet of vehicles.

These chargers could likely be operated on the existing electrical service in the building due to the limited charging demand. However, to potentially take advantage of lower EV electrical utility rates, the chargers could also be connected to the charging infrastructure serving the bus parking to ensure all vehicle charging is connected through one meter.

Figure 38: Charging cabinet and dispenser within maintenance bay

5.8.2.3 Telecom / Low-voltage Infrastructure

Infrastructure for data communications within the charging system will include IP Ethernet wiring between each charger and its associated dispensers, as well as between each charger and a local data switch. The actual wiring will be conventional Cat 5E or Cat 6 Ethernet cable between devices. As the maximum length allowed for Ethernet is 100 meters or 328 ft., the dispensers cannot be too far from their respective charger. And though longer distances are possible with fiberoptic cable, the DC power cables that need to run parallel with the Ethernet cables begin to have problems with voltage drop at this distance, so 328 ft. is a recommended limit.

Once the Ethernet lines from each charger are routed back to the facility's data switch, the data can be contained within AAATA's local network and managed directly by the agency. Alternately, the data can be routed to a cloud-based system—as needed to provide smart-charging and data aggregation—that is managed by a third party and/or is provided by the charger manufacturer. However, this would likely require coordination and approval of security and access, as it would necessitate outside entities operating within AAATA's local network, or an entirely separate network could be established to host this system.

5.8.2.4 Fire Protection Considerations

With the implementation of BEBs, fire protection and life-safety concerns can be significant. However, due to the relatively new advent of these associated technologies, building and fire protection codes have not specifically addressed most of these concerns. National Fire Protection Association (NFPA) 855 'Standard for the Installation of Stationary Energy Storage Systems' is a standard that can potentially be applied to BEB storage, but this particular standard is excessive relative to the capacity of the batteries onboard buses. The need for enhanced fire protection systems has not been determined as a baseline requirement for BEB implementation and would be left up to the discretion of the local fire marshal and the local building officials. The need for additional fire lanes or fire 'breaks' within long continuous rows of bus parking may need to be discussed with the local fire department but since all vehicles are stored indoors the fire department will not need to consider additional fire lanes around the building.

Furthermore, all modifications to the facility should be reviewed with the local Authorities Having Jurisdiction (AHJs), in particular the fire marshal. Fire truck access to the site and hydrant access will need to be reviewed and approved by the pertinent AHJs prior to implementation of any additional infrastructure for charging equipment. However, since the site is already designed for bus/fire truck access and the facility already has a sprinkler system, significant changes to the facility are not anticipated for fire protection.

5.8.2.5 Fall Protection and Safety Infrastructure Considerations

Fall protection systems are recommended for any vehicle maintenance and inspection shop but considering that AAATA has already implemented fall-arrest systems in the facility, it is unlikely that additional fall protection systems would be required to safely access the rooftop of buses for potential battery inspection and maintenance. If considerable rooftop access is necessary in the future, AAATA should consider additional fall protection systems throughout the shop.

5.8.3 Charging Considerations

To optimize BEB charging by minimizing charging during peak times of the day and to restrain the total power demand required for a BEB fleet, transit agencies deploy **smart charging**. Smart charging refers to software, artificial intelligence, and switching processes that control when and how much charging occurs, based on factors such as time of day, number of connected BEBs, and SOC of each BEB. This requires chargers that are capable of being controlled as well as a software platform that can effectively aggregate and manage these chargers. A best practice is to select chargers where the manufacturers are participants in the Open Charge Point Protocol (OCPP), a consortium of over 50 members focused on bringing standardization to the communications of chargers with their network platform.

A simple example of smart charging is if buses A, B and C return to the bus yard and all have an SOC of about 25%, all have 440 kWh battery packs, and all are plugged in in the order they arrived (A, B, C, though within a few minutes of each other). Without smart charging, they would typically get charged sequentially based on arrival time or based on SOC, with A getting charged first in about 2.2 hours, then B would be charged after 4.4 hours, and C about 6.6 hours. But if bus C is scheduled for dispatch after three hours, it would not be adequately charged.

But by implementing smart charging, the system would 'know' that bus C is to be dispatched first and therefore would get the priority, would be charged first in 2.2 hours, and would be ready in time for its 'hour three' rollout.

Another implementation is to mitigate energy demand when possible. For example, if two buses are each connected to their own 150 kW charger and they both need 300 kWh of energy and if the buses do not need to be dispatched for five hours, the system will only charge one bus at a time, thus generating a demand of only 150 kW, while still fully charging both buses in four hours. However, if both buses need to be deployed in two hours, the system would charge both simultaneously as needed to make rollout. A smart charging system would help optimize costs by also avoiding or minimizing charging during the most expensive times of day, and help curb potential demand charges.

Well-planned and coordinated smart charging can significantly reduce the electric utility demand by timing when and how much charging each bus receives. Estimations on the ideal number of chargers is critical to the successful implementation of smart charging strategies.

There are several offerings in the industry for smart charging, charger management, and fleet management from companies such as ViriCiti, I/O Systems, AMPLY Power, Evenergi, and Siemens. Additionally, the charger manufacturers all have their own native charge management software and platforms. These platforms have management functionality and integration that often exceeds the abilities of the other platforms and provide data and functionality similar to that of the third-party systems, particularly in the yard when BEBs are connected to the chargers. However, the third-party platforms provide more robust data streams while the BEBs are on route, including real-time information on SOC and usage rates. These platforms can cost well over $100 per bus per month, depending on the number of buses, and type of package procured.

Three leading charge management system (CMS) providers have been evaluated as shown in Table 19. Information within this table was provided by the providers. This table indicates this point in time—at the time of procurement the features and criteria should be verified with the provider. Note that Viriciti was purchased by ChargePoint in 2021, the intent is to operate Viriciti separately from ChargePoint. A Buy America evaluation will be required for these providers.

Table 19: Charge Management System Vendor Comparison

Item No.	Criteria Description	Amply Power - OMEGA	Viriciti - Agnostic Management Platform	ChargePoint - CMS
1	Number of installations (facilities) with multiple HVDC chargers utilizing the software	14	More than 300	300+
2	Quantify uptime % of cloud base service	99.99%	99.99%	99.99%
3	What networking protocols or modes are supported, i.e., wired Ethernet, cellular, other	Hardwired ethernet is recommended, cellular and facility WIFI are supported	Cellular is recommended, wired Ethernet, and WIFI are supported	Cellular
4	OCPP 1.6 compatibility	Yes	Yes	Yes
5	OCPP 2.0 compatibility	Yes	Yes	Yes
6	List available data fields that can be reported (such as starting and ending SoC, bus ID, charging power, …)	SOC: start and end of charging session, SOC all the time whether bus in plugged in, parked or in the field. Rate of charge (kW) of each charger port. Bus ID all the time whether bus is plugged in or not. Location of bus (in-depot, in field, etc.) Charging session: Energy dispensed Duration of charging, Power and energy consumed at electrical meter and dispensed at each charger port. Charger health: Available Faulted Maintenance needed, etc.	Reports: Uptime, Downtime, and Offline chargers (in hours, percentage, and total for a group) Energy Reports (in kWh and hours of duration) Transactions: Charger OEM, Charger Name, Connector type, Connector/port number (1 or 2) Vehicle Name/Number Start Time and End Time Start SOC and End SOC Power Reason for ending charge session Duration of Charging session kWh Charged Range at start of transaction Range at the end of the transaction A visual graph representation of Power, SOC, and Energy throughout each transaction A complete list of charging transactions (equipped with the data previously stated) A complete list of user logs and documentation of user interactions.	
7	OpenADR2.0b or better common signals	Yes. In addition to OpenADR, also support custom DR integrations including CPower and Leap Energy.		Yes

Item No.	Criteria Description	Amply Power - OMEGA	Viriciti - Agnostic Management Platform	ChargePoint - CMS
8	Support Network Time Protocol (NTP/UTC) time synchronization	Yes	Yes	Yes
9	Describe software security features for system integrity and reliability	AMPLY has implemented security procedures at multiple levels for protecting customer information: • AMPLY databases are encrypted using industry standard AES-256 encryption • Both the database and application are running inside a VPC which has tightly managed access using IAM • The database is accessible only to the application nodes • No passwords are stored in the database and authentication is done using AWS Cognito • Authorization is tightly managed as part of the lower layers of the Amply software framework • Credentials are not stored in the database or code and are managed via the AWS systems manager • Software packages and dependencies are regularly reviewed for security vulnerabilities • Cloud infrastructure, roles & security groups are regularly reviewed for ensuring security		ISO 27000:2015
10	Capable of remote software upgrades	Yes – automatic, over the air updates	Yes – Updates happen though the Cloud	Yes
11	Is user interface web based or is any local app or software required	Web based UI accessible from any web enabled device	The system operates through a cloud-based platform which can be accessed through any web browser on a computer or mobile device. Web base only.	Web based
12	Ability to set charge-power limit to reduce energy charges while also maximizing bus availability	Yes. Pause or curtail charging session during peak energy costs. Optimized charging during off-peak or vehicle dwell times to achieve target SOC by defined roll-out times.	Yes, this is a customizable application which allows the user to create and manipulate charging parameters as needs or schedules change.	Yes
13	Ability to set charging to minimize demand charges while also maximizing bus availability	Demand (kW) management and reduction to achieve roll-out but will spread out charging. Sequential, dynamics and parallel charging capable (limitations are determined by EVSE not AMPLY system).	Yes, this is a customizable application which allows the user to create and manipulate charging parameters as needs or schedules change.	Yes
14	Ability to recognize bus stall and bus number and evaluate charge needs by block and state of charge (i.e., park management)	Yes	Yes	Yes

Item No.	Criteria Description	Amply Power - OMEGA	Viriciti - Agnostic Management Platform	ChargePoint - CMS
15	Manual override (computer/HMI input) for selection of (bus) charging sequence	Yes. Manual override button located within UI accessible by a specific user creditable. Override can also be performed by email, phone call or ticket request.	Yes, users can manually prioritize groups of chargers or single chargers in order to meet the demand as needed.	Yes
16	Describe desktop output/reports for charge telematics	• Energy Report - net (panel) load, modelled load (assuming no CMS), aggregate and individual charger load • Charge Detail Records - plug-in and session start & stop times, session duration, session energy, vehicle start & end soc, vehicle ID • Health Records - % normal, faulted, offline and uptime for EVSEs, controllers, system & software components • Vehicle Logs - Geo location and SOC information • Charge Ready Transport - CRT formatted report for PG&E, SCE and other Utilities Fleet Ready Programs	• Uptime, Downtime, and Offline chargers (in hours, percentage, and total for a group) • Energy Reports (in kWh and hours of duration) • A complete list of charging transactions (equipped with the data previously stated) • A complete list of user logs and documentation of user interactions.	No response
17	Is there a local controller to preserve the same control functionality in case cloud connectivity fails (e.g., WIFI outage)?	Yes, AMPLY Site Controller (ASC) installed at electrical main and is connected to breaker. CT's will meter 3- phases of power for real- time demand management. ASC can be hardwired to each EVSE via CAT6 to send OCPP directly to charger. If CMS cellular connection temporarily down, ASC has programmed commands to continue charging until cellular connection is restored.	With all communications we send to the charger, there are two signals that are sent: The set parameter and a failsafe value. If connection is disrupted for any reason or duration of time, the charger will revert to the failsafe value until connectivity is reestablished.	Yes
18	Other features criteria, or comments	OMEGA supports algorithmic optimization across a wide set of use cases in addition to TOU energy management including load management, tariff-based optimization across usage, demand and subscription charges, factoring in unmanaged loads, demand response signals from OpenADR and other providers. It also offers flexible alerting and notifications for EVSE faults and other conditions.	• Provided system is built to scale. If charging needs change or if a new OEM is desired, the system is able to monitor any charging infrastructure (assuming that charger OEM is OCPP compliant) and easily exchange chargers in the system. • Through an API, there is the ability to integrate with other planning or ITCMS platforms to optimize planning. • Other features may include our agnostic telematics system, which is capable of monitoring any vehicle OEM and operates off the same platform as the charger monitoring infrastructure - decreasing operational complexity by reducing software applications and increasing visibility into energy usage/expenditure.	No response

5.8.3.1 Fleet Tracking Software

Software like Fleetwatch provides agencies with the ability to track vehicle mileage, work orders, fleet maintenance, consumables, and other items. However, with more complex technologies like BEBs, it becomes crucial to monitor the status of batteries, fuel consumption, and so on of a bus in order to track its performance and understand how to improve fuel efficiency. Many OEMs offer fleet tracking software. While AVL and APCs will continue to play important roles in operations planning, tracking fuel consumption and fuel economy will start to form important key performance metrics for fleet management as well as help inform operations planning (by informing operating, among other elements).

The screenshot below is an example of New Flyer's tool (New Flyer Connect 360; Figure 39), but other OEMs also offer similar tools (like ViriCiti) all depending on an agency's preference.

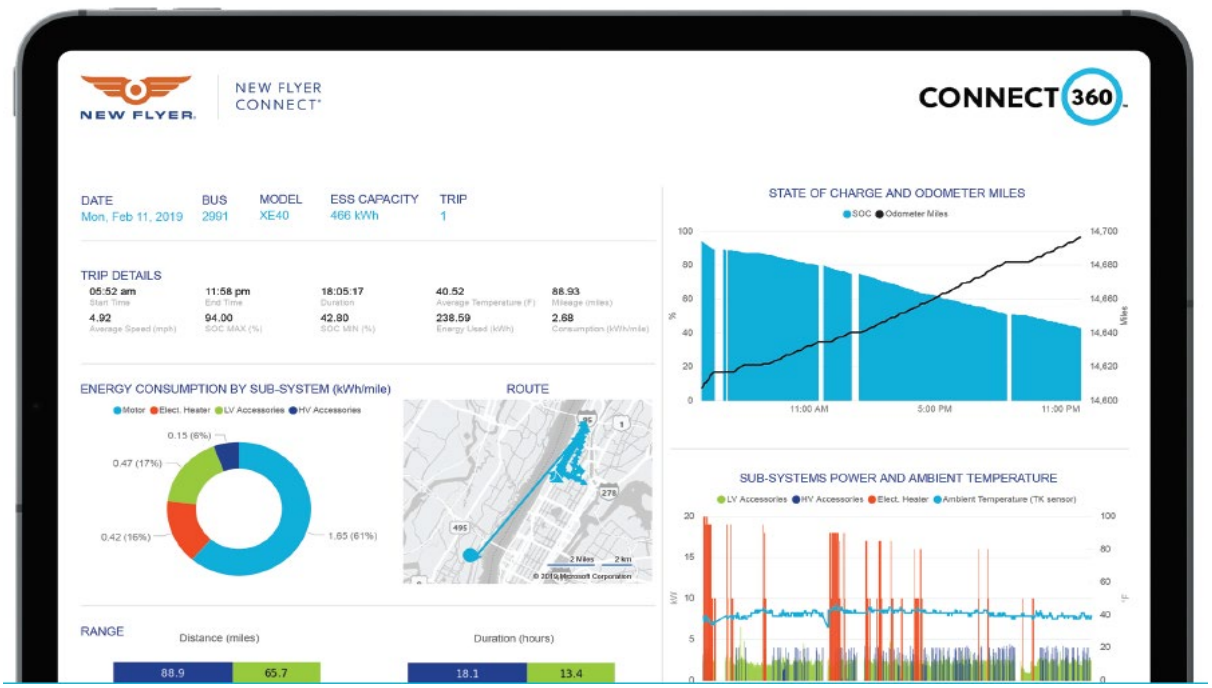


Figure 39: Example of New Flyer Connect 360.[76]

At a minimum, the fleet tracking software should track a vehicle's SOC, energy consumption, distance traveled, hours online, etc. Tracking these KPIs can help compare a vehicle's performance on different routes, under different ambient conditions, and even by different operators.

When looking at other transit agencies, Antelope Valley operates a 100% BEB fleet of over 50 vehicles[77], and during its transition from diesel buses to BEBs, the agency collected and reported the following information at its monthly board meetings:

[76] https://www.newflyer.com/tools/new-flyer-connect/
[77] California's AVTA Becomes 1st North American Transit Agency to Hit 100% Electric Goal - Zero Emissions - Metro Magazine (metro-magazine.com)

- ZEB vs. non-ZEB miles traveled
- ZEB vs. non-ZEB maintenance cost per mile
- ZEB vs. non-ZEB fuel/energy costs by month ($ per kWh vs. $ per gallon)
- ZEB vs. non-ZEB fuel/energy cost per mile
- Average fuel consumption/fuel economy per month
- Total ZEB vs. non-ZEB fuel and maintenance costs per month
- Mean distance between failures
- ZEB vs. non-ZEB fleet availability

The TTC is tracking the following KPIs for its BEBs to compare with its ICE buses (Figure 40).

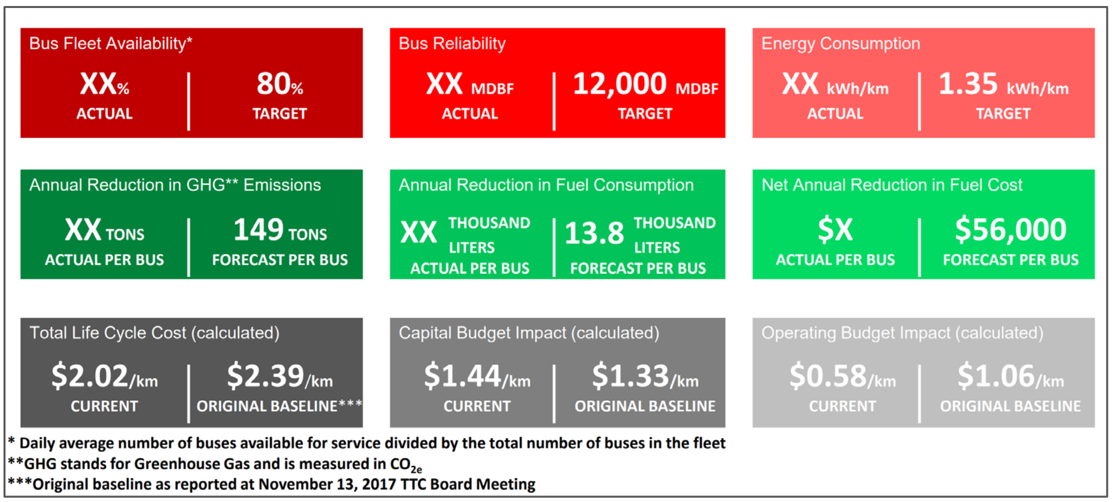


Figure 40: Example of TTC eBus KPIs.[78]

All BEB equipment should be connected to AAATA's current data collection software, networks, and integrated with any existing data collection architecture. All data should be transmitted across secure VPN technology and encrypted.

Beyond the BEB itself, charger data should be collected as well, such as the percentage of battery charge status and kWh rate of charge. Furthermore, it will be important for AAATA to track utility usage data from DTE to understand energy and power demand and costs.

78 https://www.ttc.ca/About_the_TTC/Commission_reports_and_information/Commission_meetings/2018/June_12/Reports/27_Green_Bus_Technology_Plan_Update.pdf

5.8.4 Planning, Scheduling, and Runcutting

BEBs may not have the ability to complete a full block or vehicle assignment, particularly if there have been extensive traffic delays. Rather than a relief operator coming in a shuttle vehicle, he or she may need to bring out a fresh bus for the balance of the day's run and the initial operator return with the first bus to the garage. However, if battery technology improves with a greater capacity/range without an excess gain in vehicle weight, this situation could be mitigated.

Non-revenue tests during vehicle commissioning should be conducted in different parts of AAATA's service area to understand actual range and fuel economy, especially on longer routes, routes with topography variations, and with simulated passenger loads and HVAC testing.

Blocking and runcutting for plug-in BEBs (without on-route charging or midday charging) would need to account for a rather limited range (~150 miles). Training for the scheduling and planning team will also be needed so that they understand the importance of scheduling BEBs to the correct blocks. Training may also be needed in collaboration with AAATA's scheduling software provider to account for a mixed diesel and BEB fleet during the transition, and finally an entirely BEB fleet after the transition. Other key considerations for BEB scheduling and planning include the fact that the usable energy of the battery is 80% of the total battery size (e.g., a 440-kWh battery has a usable capacity of 352 kWh). For example, the TTC, through its BEB testing, has produced general guidelines for blocking BEBs that vary by season—for summer, block length is limited to 124 miles, while for winter, block length is limited to 110 miles—when considering all factors that impact battery usage. The route modeling in Section 5.9 demonstrates that AAATA could start by estimating range thresholds as well—for example, for colder days, limiting blocks to ~170 miles and on warmer days to ~270 miles (for long-range BEBs).

In the long term, it is also important to consider battery capacity degradation early on, as most BEB battery warranties specify the expected end of life capacity is 70% to 80% of the original capacity over 6-12 years. AAATA will need to rotate buses so that older buses are assigned to shorter blocks and newer buses are assigned to longer blocks. Transit agencies can improve battery outcomes with strategies like avoiding full charging and discharging events, avoiding extreme temperature exposures (to the extent possible given an agency's service area), and performing regular maintenance on auxiliary systems that consume energy.

5.8.5 Workforce Considerations

The deployment of a new propulsion technology will require new training regimes for operators and maintenance staff. This section describes some key training considerations as well as the implications of the adoption of BEBs. Some additional information regarding workforce ZEB training is provided in Appendix C Workforce Development.

5.8.5.1 Training

BEBs manufacturers include training modules for bus operators and maintenance technicians that are typically included in the purchase price of the vehicle, with additional training modules and programs available for purchase. AAATA needs to work with its staff to understand how best to approach training for BEBs, and whether in addition to basic training from OEMs, additional training is needed.

BEBs handle and perform differently than diesel buses. Bus operators should understand how to maximize BEB efficiency particularly through regenerative braking and should be trained on BEB operations prior to BEB deployment for revenue service. BEB operators should be able to understand battery SOC, remaining operating time, estimated range, and other system notifications as well as become familiar with the dashboard controls and warning signals. In addition, operators should be familiar with the correct procedures when a warning signal appears.

Driving habits also have a significant effect on BEB energy consumption and overall performance and range (i.e., fuel economy can vary significantly between operators). Operators should become knowledgeable on the principles of regenerative braking, mechanical braking, hill holding, and roll back. Operators should be trained in optimal driving habits including recommended levels of acceleration and deceleration that will maximize fuel efficiency. One strategy could be to implement a positive incentive program that encourages operators to practice optimal driving habits for BEBs through rewards like priority parking in the employee lot, certificates, or other incentives. The Antelope Valley Transit Authority (AVTA) in Lancaster, California (an early adopter of BEBs) has a program of friendly competition between operators where, for instance, and operator with the best monthly average fuel economy (the lowest or most consistent kWh per mile) gets one month of a preferred parking spot in the employee lot.

According to OEMs, BEB maintenance technicians should receive training on:

- Preventative maintenance
- Electrical/electronics
- Multiplexing
- HVAC
- Brakes
- Energy storage systems, lithium-ion battery, and energy management hardware and software
- Electric drive/transmission

The minimum required training recommendations are as follows for operators and maintenance technicians:

- BEB Operator training (total 56 hours)
    - Operator drive training (four sessions, four hours each)
    - Operator vehicle/system orientation (20 sessions, two hours each)

- BEB Maintenance technician training (total 304 hours)
    - Preventative maintenance training (four sessions, eight hours each)
    - Electrical/electronic training (six sessions, eight hours each)
    - Multiplex training (four sessions, each session consisting of three eight-hour days)
    - HVAC training (four sessions, four hours each)
    - Brake training (four sessions, four hours each)
    - Energy Storage System (ESS), lithium-ion battery and energy management hardware and software training (six sessions, eight hours each)
    - Electric drive/transmission training (six sessions, eight hours each)

The priority in maintenance needs will be the issue of safety in dealing with high-voltage systems. All maintenance personnel in the garage, whether doing servicing, inspection, or repairs and those in other routines (e.g., plugging and unplugging BEBs) must be educated on the characteristics of this technology. One essential component is the provision and mandate of additional Personal Protective Equipment (PPE) beyond that which is required by automotive garage workplace legislated standards or AAATA's policies. Examples of such apparel include high voltage insulated work gloves, flame retardant clothing, insulated safety footwear, face shields, special insulated hand tools, and grounding of apparatus that staff may be using. Also, procedures in dealing with accidents and injuries must be established with instructions and warning signs posted.

In terms of preventative maintenance, BEB propulsion systems are more efficient than fossil fuel buses and thus can result in less wear and tear. Without the diesel engine and exhaust, there are 30% fewer mechanical parts on a BEB. BEBs also do not require oil changes and the use of regenerative braking can help to extend the useful life of brake pads. Early studies from King County Metro show that the highest percentage of maintenance costs for BEBs came from the cab, body, and accessories system. It is recommended that AAATA require OEMs to provide a list of activities, time intervals, skills needed, and required parts needed to complete each preventative maintenance task for BEBs.

Many current BEBs also contain on-board communication systems, which are helpful in providing detailed bus performance data and report error messages, which can assist maintenance personnel in quickly identifying and diagnosing maintenance issues.

Finally, it is highly recommended that all local fire and emergency response departments be given training as to the layout, componentry, safety devices, and other features of BEBs. This should reoccur every few years, but the specific frequency can be dependent on agency discretion. In addition, agencywide orientation to familiarize the agency with the new technology should also be conducted prior to the first BEBs deployment.

5.8.5.2 Implications of BEBs on Workforce

Early data suggest that BEBs may require less preventative maintenance than their diesel counterparts since they have fewer moving parts. However, BEBs are so new that there is not enough data to provide detailed insights into long-term maintenance practices for large-scale BEB deployments in North America. One early finding is that spare parts may not be readily available, so one maintenance consideration is to coordinate with OEMs and component manufacturers to develop spare parts inventories and understand lead times for spare parts. Relatedly, AAATA's limited room for growth at its bus facility implies that it will be a major challenge to not only continue stocking parts for the current diesel fleet, but any other propulsion type that it may transition to. This reality could have limitations and require workarounds that may limit the amount of spare part storage, leading to potentially longer down times if AAATA is unable to store sufficient spare parts and needs to order them as needed.

Because BEBs have fewer moving components that can malfunction and require replacement, repair, and general maintenance, transit agencies could theoretically save on maintenance costs because: 1) fewer parts could break and need replacement (capital) and 2) less labor is needed to work on the vehicles (operating). The broader concern is related to a possible reduction in the number of maintenance staff required for an BEB fleet vs. a traditional diesel fleet.

Nonetheless, while a future 100% fleet of BEBs may require a smaller complement of maintenance staff, during the transition period, it is highly improbable that a reduction in staff would be warranted. First, diesel technicians would be required until the last diesel bus is retired; based on the transition schedules explored in this propulsion study, the earliest timepoint would be 2030, and even that is highly unlikely as it is an aggressive timeframe. Second, existing staff can be trained on BEBs to maximize staff retention. As BEB pilots have demonstrated, the learning curve for maintenance as well as the continuing maturity of the technology means that a robust maintenance program is still needed. Indeed, preventative maintenance is still required for a BEB fleet, and experience from a pilot of BEBs revealed comparable labor hours required for work orders across fleets of BEBs, diesel-hybrids, and diesel buses.

Looking further into the future, it is very challenging to predict staffing levels for BEBs. As technology matures and becomes more technological sophisticated, technicians will need to be trained not only on machinery, but also on components that require computer and diagnostic skills.

While the promise of reduced maintenance costs will likely be borne after a full transition to a fully BEB fleet, during the transition period, AAATA will require diesel technicians and train existing staff on the new technology. One potential strategy to manage lower workforce needs is through natural attrition tied to AAATA's implementation schedule for transitioning to ZEBs. If that is not possible, deliberate reductions in maintenance staffing may result ahead of the 100% transition date based on the actual needs and experiences of the agency.

Finally, because a ZEB transition and implementation is an agencywide endeavor that also includes the need to actively consider utilities as a stakeholder and partner, an agencywide approach is required. Additionally, the union representing the bus operators and maintenance technicians should also be included due to the large role they will play in the success of the ZEB transition and implementation. Thus, it would be prudent for AAATA to form a steering committee or task force composed of staff from each major functional department and union representation to help ensure the impact of ZEBs are considered for each. The task force should also name a leader who acts as a champion for the ZEB conversion within the agency and to external stakeholders. Communication will be critical during the transition to ensure customers are made aware of potential disruptions and changes to bus operations. ZEB conversion also offers an excellent marketing opportunity for AAATA to promote its climate commitments.

5.9 BEB MODELING

Computer modeling of bus performance is an important step in determining the feasibility of alternative propulsion technologies, and informing fleet sizing and energy needs, among other elements. Modeling the operational implications of adopting ZEBs is an iterative process including bus scheduling, predictive modeling, and financial modeling. This section focuses on the predictive modeling for BEBs, while Section 6.9 provides the modeling outcomes of FCEB simulations.

Modeling helps:

- To determine the success or pass rate of buses under different ZEB transition scenarios. The pass rate is defined as the percentage of buses in AAATA's fleet that can complete their daily assignments without breaching battery thresholds or hydrogen fuel tank limits.

- To assess the time-of-day energy demand for an all BEB fleet, and the corresponding grid upgrade requirements at the depot to meet the energy demand; to assess the daily hydrogen demand to guide the sizing and needs for hydrogen fueling infrastructure.
- Together, these two modeling results and important inputs into cost estimates in Section 8.0.

5.9.1 Modeling Overview

Based on the schedules provided by AAATA, Evenergi's BetterFleet model emulated each bus in the active fleet. The steps involved in the BetterFleet simulation model at this stage of the bus propulsion study are highlighted in Figure 41.

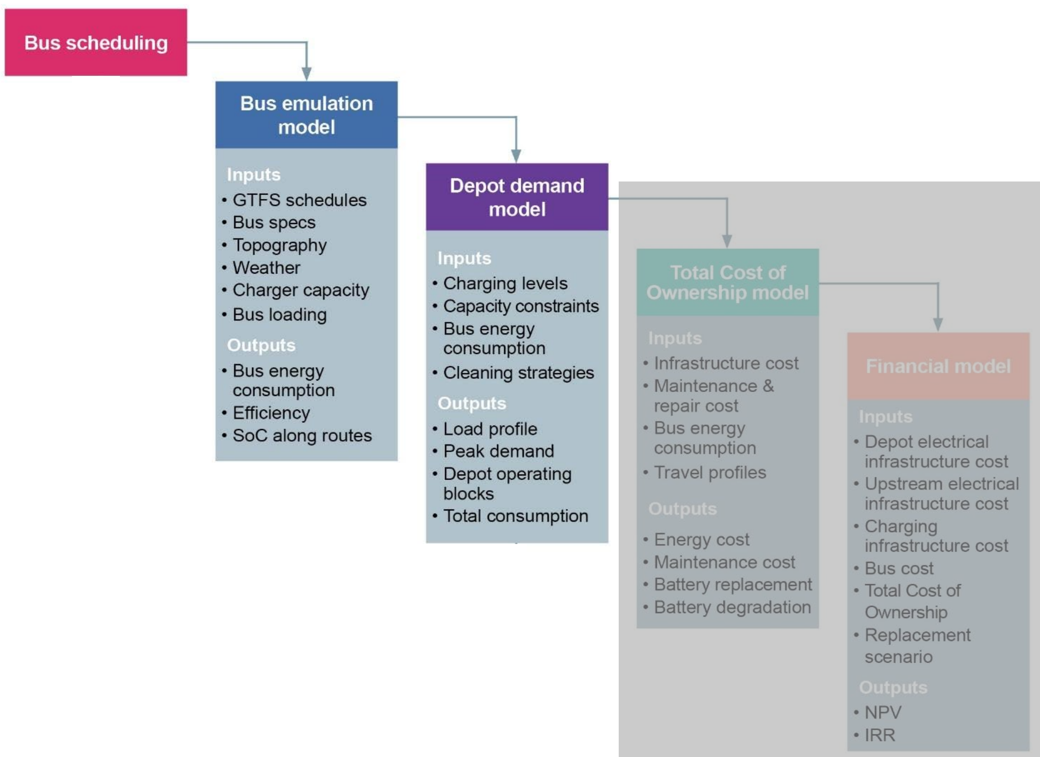


Figure 41: Evenergi's BetterFleet Simulation Model Process

Bus efficiency and range are driven by vehicle engineering specifications, route profiles (traffic conditions, distance, dwell/layover times, sustained top speeds), topography (incline/decline), climate (air-conditioning/heating loads), opportunities for regenerative braking, and operational parameters (such as passenger loading). These values vary by route, by block, by time of day, by geography, etc. To assess the efficiency and range, current vehicle assignments are simulated for each type of ZEB.

The BetterFleet model used GTFS[79] data to simulate AAATA's routes and blocks according to existing terrain and used the agency's schedule data to determine the daily vehicle assignment (i.e., daily mileage

[79] GTFS - General Transit Feed Specification. GTFS is a common format for public transportation schedules and associated geographic information.

of a vehicle on the assigned block). Schedule and GTFS data were provided by the AAATA, which were validated and prepared for use in the BetterFleet model. Appendix D Schedule and Import Data Assumptions shows the key schedule and data import assumptions used in the modeling.

5.9.2 Modeling Scenarios and Key Modeling Assumptions

The key parameters that impact the electrification success of a fleet include the type of ZEB, battery size and battery degradation, type of charging or fueling, and the ambient temperatures considered in the analysis. Table 20 presents the modeled BEB scenarios for AAATA's assessment.

Table 20: BEB Modeled Scenarios Summary

Scenario	Description	Bus	Charging	Ambient temperatures modeled[80]
Battery electric bus - base case	Scenario with standard battery size on a battery electric bus	Standard bus - Proterra ZX5+ with battery capacity of 450 kWh	Depot only (132 kW)	59°F (average) and 10°F (worst case)
Battery electric bus - long range	Scenario considering improvement in pass rate using longer range battery electric bus (larger battery pack)	Longer range bus - Proterra ZX5 MAX with battery capacity of 675 kWh	Depot only (132 kW)	59°F (average) and 10°F (worst case)
Battery electric bus - overhead on-route	Scenario considering improvement in pass rate using pantograph charging on-route	Standard bus (Proterra ZX5+) and longer range bus (Proterra ZX5 MAX)	Depot (132 kW) and pantograph (300 kW) charging	10°F (worst case)
Battery electric bus - battery range improvements	Standard battery electric bus with year-on-year battery range improvements	Standard bus (Proterra ZX5+) and longer range bus (Proterra ZX5 MAX)	Depot only (132 kW)	10°F (worst case)

Average and worst-case ambient temperatures were selected as 59°F and 10°F respectively, based on an assessment of weather data in Ann Arbor, which is presented in Appendix E Weather Data Assessment for Ambient Temperature Estimation.

Table 21 presents the key vehicle, battery, charging and failure vehicle assignment cut-off assumptions used in the model for the BEB scenarios.

80 In this discussion of the results, the average and worst-case ambient temperatures are referred to as average day and cold day, respectively.

Table 21: Key BEB Assumptions in BetterFleet modeling

	Battery Electric - Base case	**Battery Electric - Long range**
Make/Model	Proterra ZX5+	Proterra ZX5 MAX
Dimensions	W: 102″ H: 11′ 1″ L: 41′ 0″	W: 102″ H: 11′ 1″ L: 41′ 0″
Vehicle mass	29,848 lbs	33,149 lbs
Passenger mass	3,748 lbs 20 pass. @ 187 lbs	3,748 lbs 20 pass. @ 187 lbs
Total mass	33,596 lbs	36,897 lbs
Battery capacity	450 kWh	675 kWh
Motor power	410 kW	410 kW
Max charge rate	132 kW plug in 300 kW pantograph	132 kW plug in 300 kW pantograph
Other		
Failed vehicle assignment cut-off	20% state of charge (SOC)	20% SOC
Tire pressure	102 PSI	

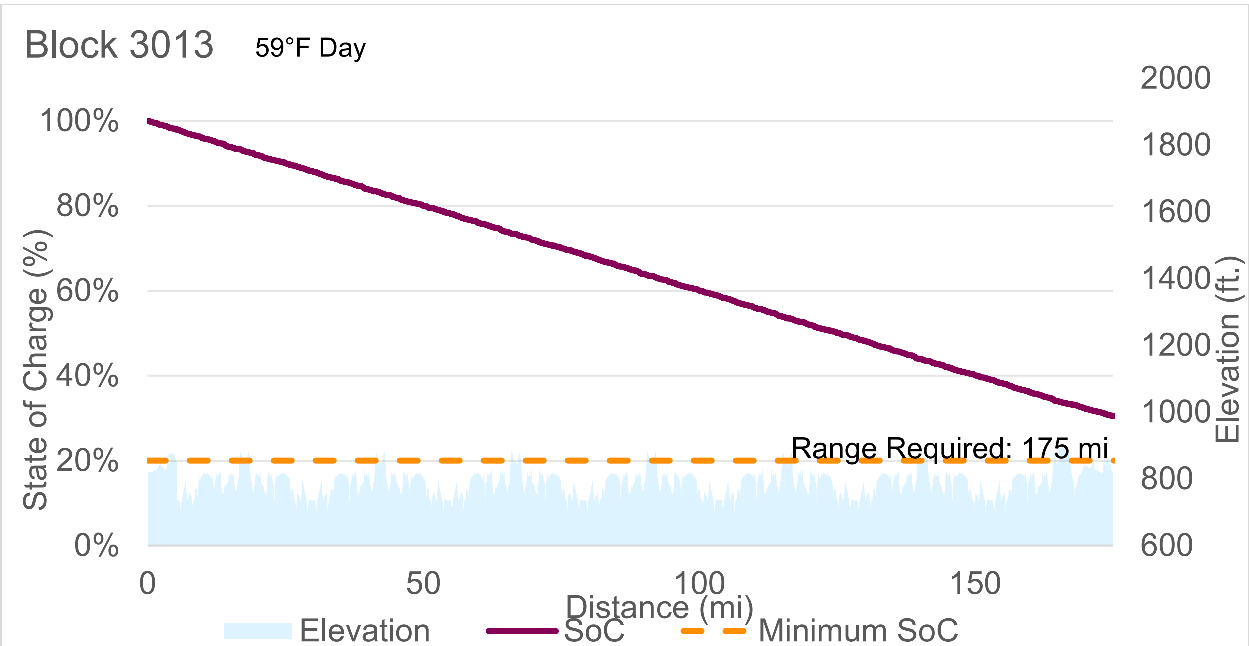
The following key points and assumptions are noted:

- The vehicle makes/models selected were based on commonly available BEB models in the US market. The makes/models selected are for forecasting purposes only and are not a purchasing recommendation.
- Proterra was selected for BEB models due to availability of multiple battery capacities for the same vehicle. These vehicles are also lighter compared to other BEB options in the market, meaning in theory they would have the highest opportunity for a successful pass rate.
- For the assessment of pass-fail rate, a vehicle assignment is considered to have failed if the battery state of charge (SOC) falls below 20% at any point in the day. Twenty percent is a commonly used cut-off point for assessments since it ensures battery health is preserved and to prevent voiding manufacturer warranties on the battery packs. The pass rate does not include mechanical failures.

- For context, the range of a diesel bus is about 400 miles per tank, with a pass rate of 100%.

5.9.3 BEB – Base Case – Range Analysis

The first scenario modeled was the base case which simulates a BEB with a 450-kWh battery pack. Figure 42 provides an example of battery performance for a single vehicle block. The charts show the battery SOC as a function of distance for the average and cold day scenarios for a sample vehicle block (Block 3013). This block requires a bus to achieve a 175-mile daily range.



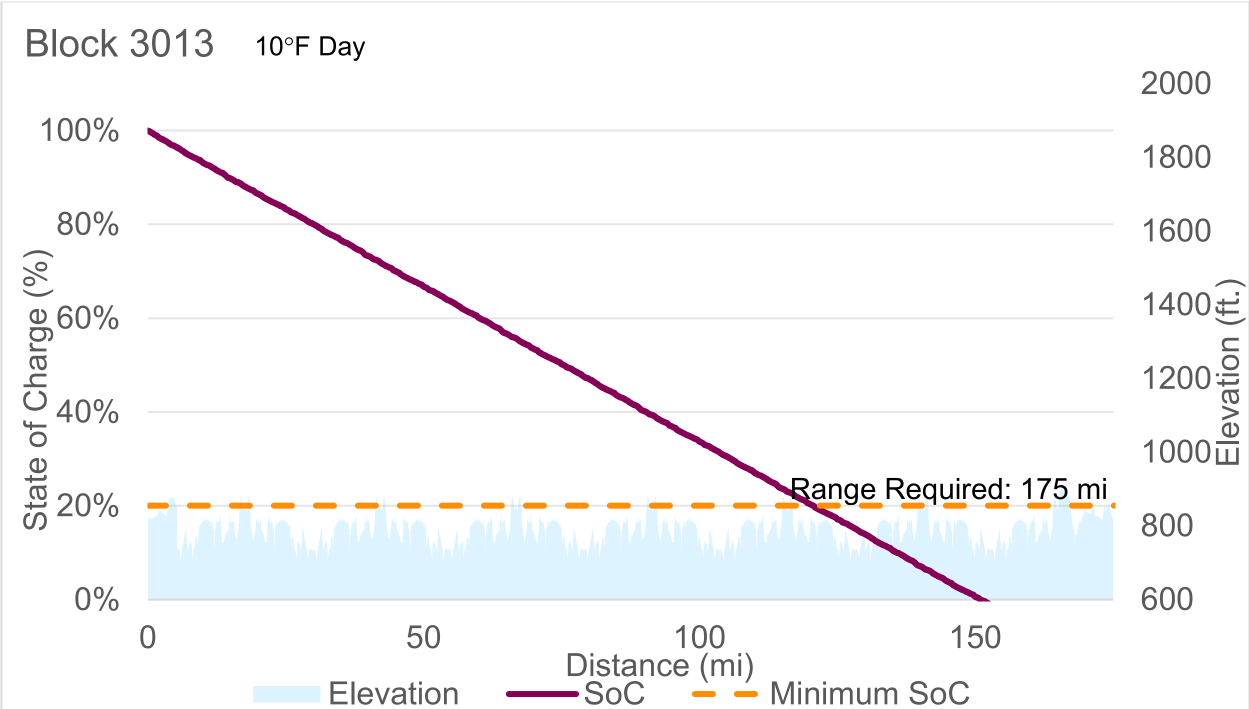


Figure 42: SOC as a Function of Distance for a sample bus in AAATA's fleet – Battery Electric Bus (BEB)

In this example case, a short-range BEB can complete block 3013 in average temperatures (top graph) without the SOC falling below 20%. However, the battery discharge rate is faster on a cold day due to heating the passenger cabin (bottom graph). As a result, the bus is unable to complete its daily vehicle assignment (the battery SOC goes below 20% *before* the completion of the daily vehicle assignment).

A key aspect that impacts pass rate is the number of buses returning to the garage during the day, which can provide an opportunity for refueling/recharging of buses during their vehicle assignment, thereby increasing the daily range capabilities of the buses. Our analysis of AAATA's schedules indicates that a large share of buses _do not_ return to the garage during the day, as seen in Figure 43 below. In other words, as currently scheduled, most buses stay out in service throughout the day, limiting the opportunities for in-depot midday charging.

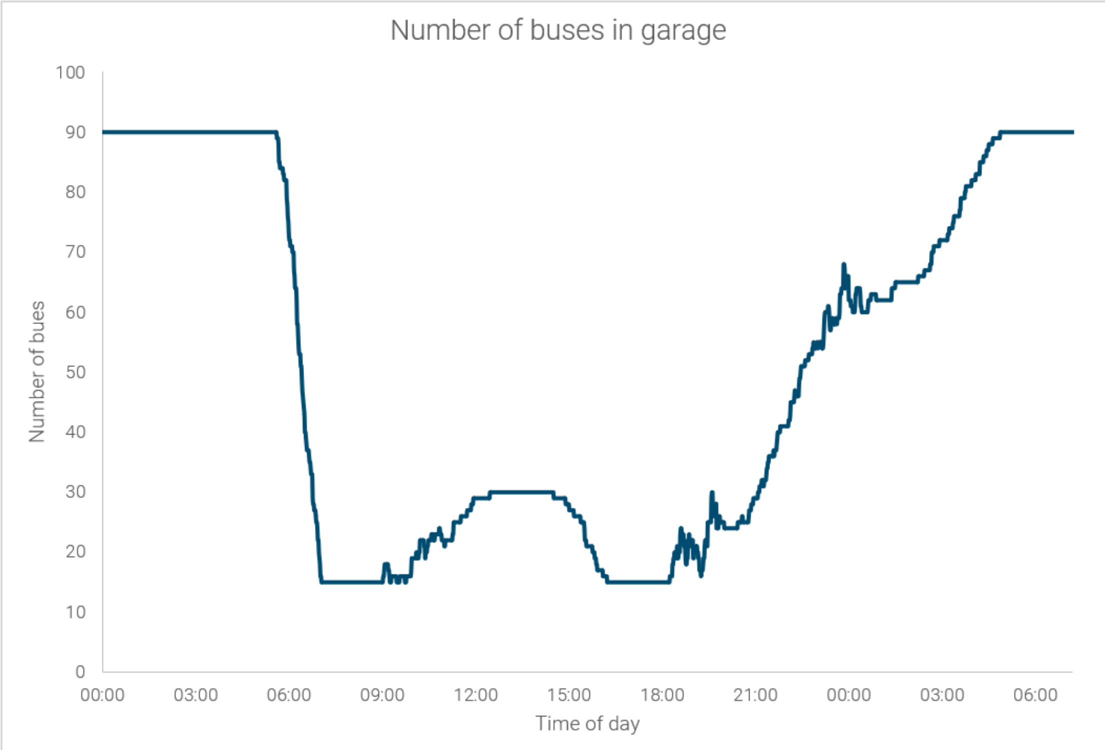


Figure 43: Number of Buses in the Garage by Time of Day

Since the majority of AAATA's buses do not return to the garage once they are in service, coupled with the cold climate of Ann Arbor, the BEBs modeled here suggest that AAATA would face significant challenges in operating range. Given the outcomes of the base scenario, it makes sense to consider and model longer-range BEBs.

Table 22 provides a summary of the modeling results for the BEB base case; it shows the fleet-wide pass rate results for this scenario, in average and worst-case ambient temperature conditions. On an average temperature day, 76% of the standard-range BEBs would be able to complete their daily vehicle assignments with depot-only charging. However, the pass rate falls substantially to 32% under the cold day scenario, due to the impact of energy used for heating, as seen in Table 22.

Furthermore, Table 22 also shows the predicted average, minimum, and maximum fuel efficiency for the different conditions. On an average temperature day, the average fuel efficiency is 2.25 kWh per mile, and this worsens to 3.36 kWh per mile under the cold day scenario. The result of this is that more energy is consumed on a cold day, thus shortening the operating range, meaning that the BEBs modeled would not successfully electrify AAATA's fleet.

Table 22: Pass Rate Results for Battery Electric Bus – Base Case Scenario

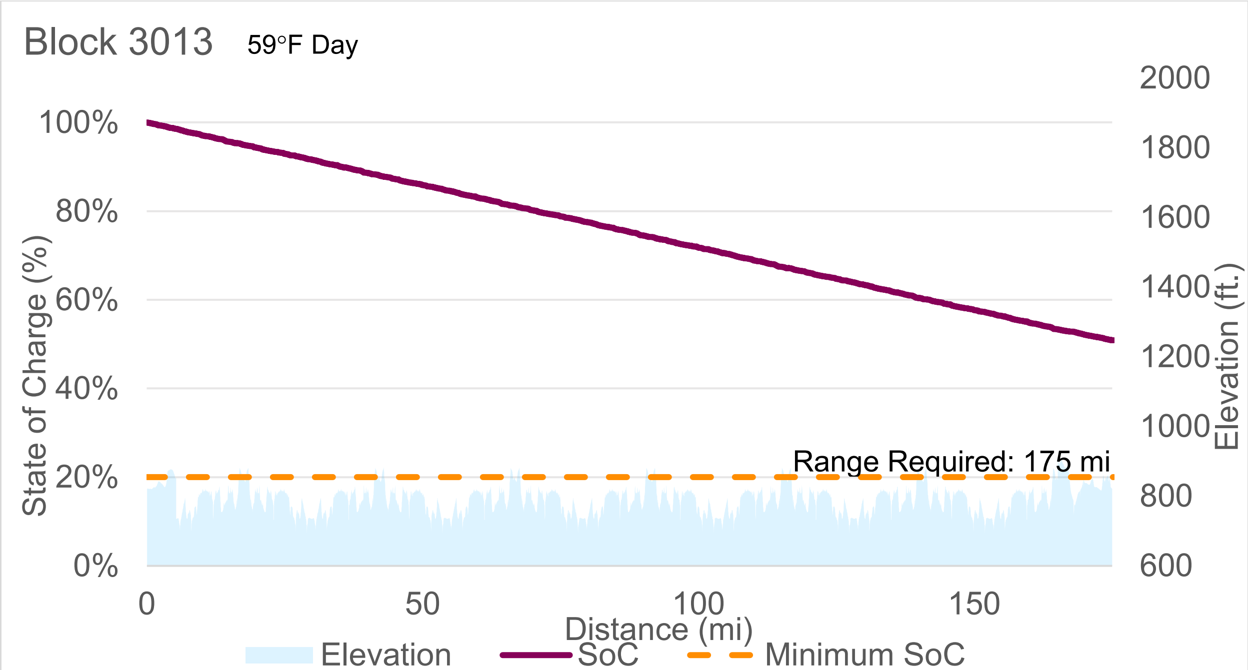
Temperature	BEB	Charging	Pass rate	Pass percentage	Efficiency (kWh/mi)

59°F ambient	Proterra ZX5+ (450 kWh)	Depot only 132 kW	68 / 90	76%	Avg: 1.87 Max: 2.25 Min: 1.61
10°F ambient	Proterra ZX5+ (450 kWh)	Depot only 132 kW	29 / 90	32%	Avg: 3.04 Max: 3.36 Min: 2.70

5.9.4 BEB – Long Range – Range Analysis

To address the range limitations of the base case BEB, long range BEBs were modeled. These BEB as similar to those modeled above but have a larger battery pack—675 kWh instead of 450 kWh.

Figure 44 shows the graphs for the results of the same block (3013) as in Figure 42 but with long range BEBs. On a mild day (top graph), the BEB completes its service with about 50% of its SOC (compared to 30% with the base case BEB). On a cold day (bottom graph), while the base case BEB is unable to successfully complete this block, the long range BEB is able to successfully complete the block but comes close to the 20% threshold.



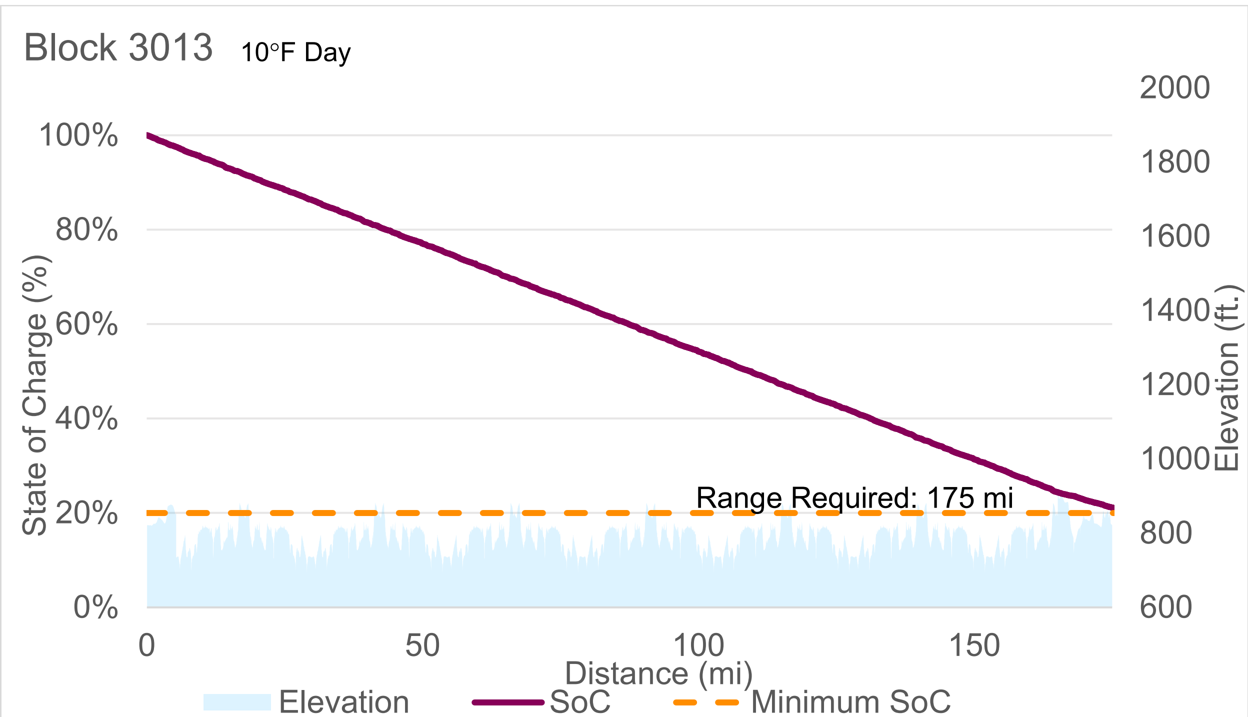


Figure 44: SOC as a Function of Distance for a sample bus in AAATA's fleet – BEB (Longer Range Case)

Overall, modeling long range BEBs demonstrates that the overall success rate is improved for both mild days (97% for long range vs. 76% for base case) and cold days (62% for long range vs. 32% for base case (Table 23 compared with Table 22). Notably, the fuel economy is less efficient for the long range

BEBs due to the additional weight of the larger battery packs compared to the base case BEBs; despite the heavier battery packs and lower fuel efficiencies, the long range BEBs significantly improve the successful electrification of AAATA's services.

Table 23: Pass Rate Results for Battery Electric Bus – Longer Range Scenario

Temperature	Battery Electric Vehicle	Charging	Pass rate	Pass percentage	Efficiency (kWh/mi)
59°F ambient	Proterra ZX5 MAX (675 kWh)	Depot only 132 kW	87/90	97%	Avg: 1.98 Max: 2.41 Min: 1.70
10°F ambient	Proterra ZX5 MAX (675 kWh)	Depot only 132 kW	56/90	62%	Avg: 3.15 Max: 3.49 Min: 2.81

5.9.5 BEB – On-Route Charging – Range Analysis

This scenario considers the implementation of on-route charging (using overhead pantograph chargers) in addition to in-depot charging as a potential solution to increase the pass rates of BEBs. Pantograph chargers were considered at the following on-route locations:

- Blake Transit Centre (BTC)
- Ypsilanti Transit Center (YTC)
- Grove Line - W - Emerick south of Service Dr (Gault Village in Ypsilanti Township)
- Meijer store (Carpenter Road)

Based on the assessment of schedule data, these were the locations found to have dwell times of at least 3 minutes, which was considered as the minimum required time for the vehicles to connect and charge. While scheduling shows at least 3 minutes are available for charging, AAATA will need to validate the actual availability of this time given the operational realities of transit services (traffic, schedule adherence, unexpected passenger events, heavy passenger loading/unloading, etc.).

The specifications of the pantograph chargers[81] considered for the modeling include the following:

- Output: 300 kW
- Connection/disconnection times: 30 seconds each (total 60 seconds)

[81] There are operational considerations with deploying pantograph chargers at public locations. These include property agreements at site hosts, permitting, and accounting for adequate electricity supply at all the sites (i.e., no DTE grid constraints).

Because the biggest challenge as revealed by the modeling is for the cold day scenario, standard and longer-range bus scenarios were modeled with on-route charging for the cold day scenario only.

Figure 45 illustrates the significant benefits that can be achieved through on-route pantograph charging in terms of ensuring adequate battery SOC to complete daily duty cycles. This is particularly important in the case of AAATA's bus operations, where a large share of buses stay in service throughout most of the service day. For example, with depot charging only (top graph, Figure 45), block 4034 (which requires 142 miles) on a cold day would fall below the 20% threshold for success, but on-route charging would be used to top-up the bus throughout the day, allowing it to complete the block with nearly 50% SOC (bottom graph, Figure 45).

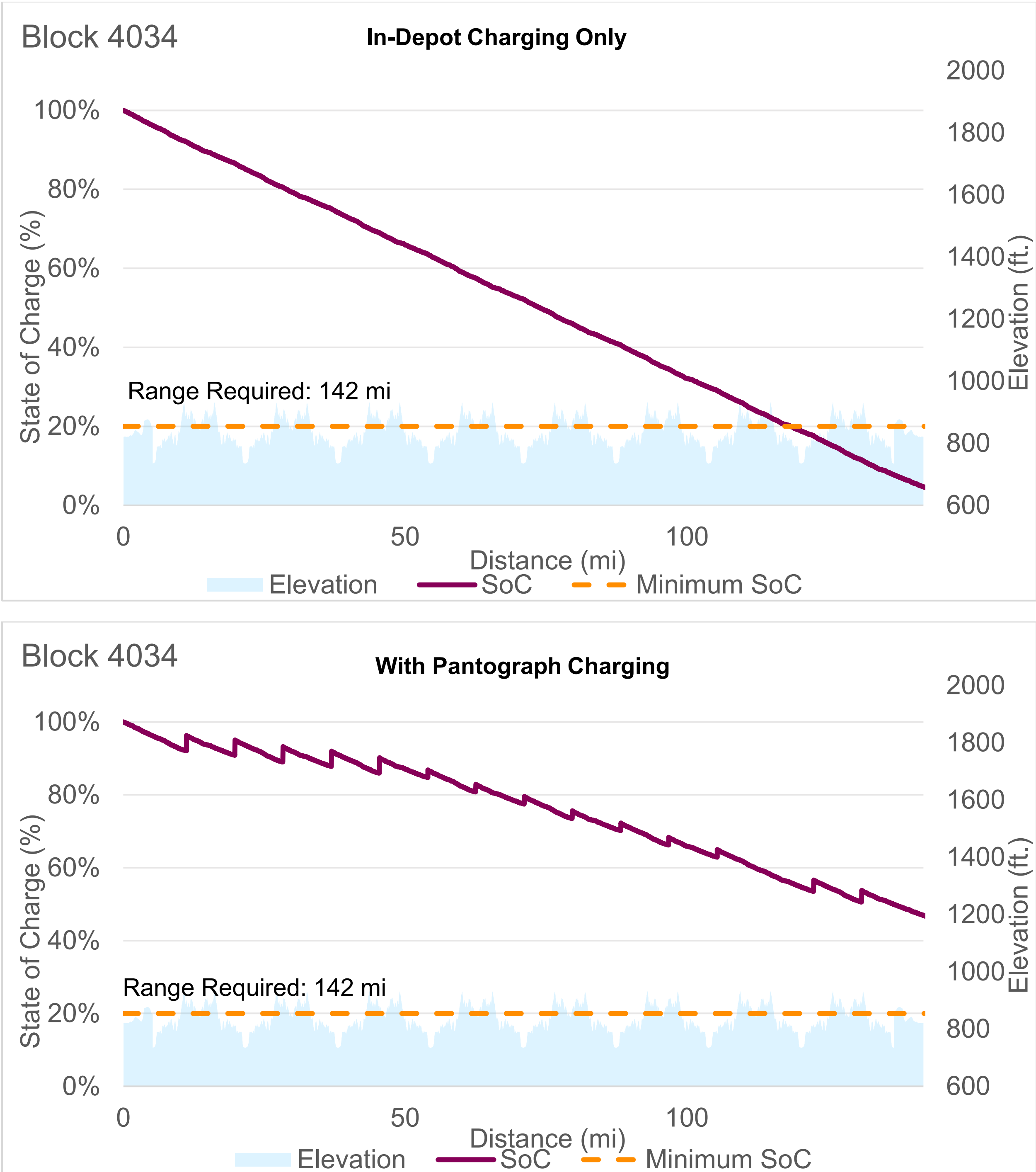


Figure 45: SOC as a Function of Distance for a sample bus in AAATA's fleet – BEB (Pantograph On-Route Charging Case)

Based on our schedule simulations under this scenario, Table 24 presents the number of pantographs that need to be installed at each on-route charging location which is effectively the maximum number of vehicles charging simultaneously at each location throughout a typical day. This is to ensure that multiple buses can charge at the same time, which is the case for the Blake and Ypsilanti Transit Centers.

Table 24: Number of Pantographs and Buses Charging at On-Route Locations

Location	Number of pantographs - unmanaged charging	Number of pantographs - managed charging
Blake Transit Center (BTC)	13	6
Ypsilanti Transit Center (YTC)	5	4
Grove Line - W - Emerick south of Service Dr. (GV)	1	1
Meijer store (MJRC)	1	1
Total	20	12

The rightmost column in Table 24 demonstrates that the total number of on-route bus charger can be further reduced by “coordinated load management” across the bus network. With onboard telematics in the buses and an automated charge controller the system can automatically detect whether a bus has a real need to charge or if it can proceed to the next charging destination, thereby removing charging operations where a bus has arrived at a terminal but may still have a battery that is close to fully charged.

While transfer centers facilitate passenger transfers by having buses of certain routes all at the transfer center at the same time, depending on operating parameters, not all buses need a top-up each time they are at the transfer center. In this way, the total number of pantographs can be reduced by only allocating them to buses that actually need to be recharged, while still facilitating timed passenger transfers. Nonetheless, other complications may arise with this approach, such as the requirement for dynamic bus bay assignment to different routes depending on the bus charging needs and could complicate passenger flow.

To note, while we identify that 13 pantograph chargers are required at the Blake Transit Center, AAATA does not have sufficient bus bays at this transit center to accommodate 13 chargers. On-street space would need to be considered to accommodate a part of these chargers which will be challenging, requiring coordination with DTE, the City of Ann Arbor, as well as entailing disruptive construction. AAATA will have to undertake a subsequent study to determine the feasibility of this approach or coordinated load management.

As seen in Table 25 and comparing with Table 22 and Table 23, the pass rate with on-route overhead charging compared to depot-only charging improves from 32% to 50% and from 62% to 87%, for standard and longer-range buses, respectively. Additional information regarding on-route charging at transit centers can be found in Appendix F Battery-Electric Bus – Pantograph On-Route Charging Scenario.

Table 25: Pass Rate Results for Battery Electric Bus – Pantograph On-Route Charging Scenario

Temperature	Battery Electric Vehicle	Charging	Pass rate	Pass percentage
10°F ambient	Proterra ZX5+ (450 kWh)	Depot 132 kW Pantograph 300 kW	45/90	50%
10°F ambient	Proterra ZX5 MAX (675 kWh)	Depot 132 kW Pantograph 300 kW	78/90	87%

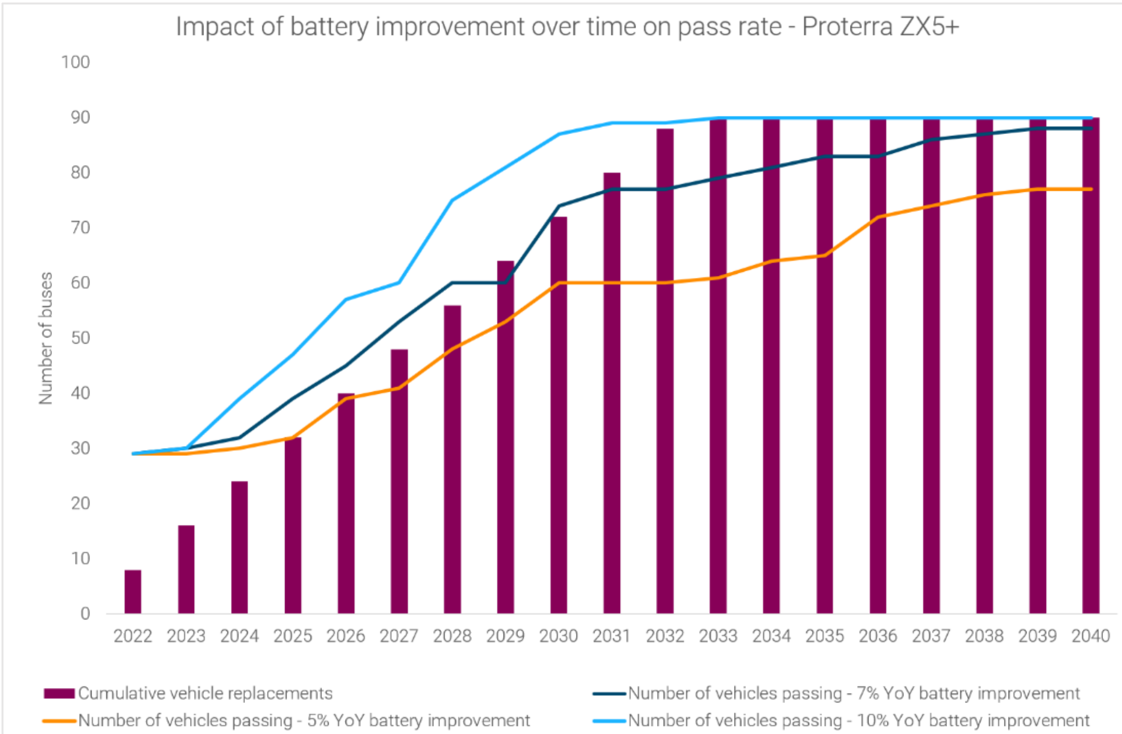
5.9.6 BEB – Battery Range Improvements

Recent improvements in battery technology have led to increased bus range and this is expected to continue. To account for improvements in battery technology, three hypothetical scenarios of year-on-year battery range improvements were modeled: 5%, 7% and 10% improvement in battery capacity for the next 10 years, and then 2% thereafter. Battery range has improved by threefold over the years from 2010 to 2020[82], this equates to a year-on-year improvement of 10%. The three scenarios represent a continuing of this trajectory. Supporting this projection are announcements from manufacturers such as Proterra with a ZX5 bus expected to be released with a 738-kWh battery[83], which is a 10% improvement on the existing ZX5 MAX model.

With battery range improvements, it is anticipated that an increasing number of buses will be able to meet AAATA's range requirements. It is also important to consider the effect of battery degradation over time and how this will impact operations, however, state of health modeling was not in scope for this study. Once operational, BEBs should also be rotated on different routes to make sure that degradation is happening at similar rates across individual buses, and that newer buses with less battery degradation be assigned to longer blocks. This additional complication does not apply to diesel buses or FCEBs.

Figure 46 shows the impact of battery improvements on pass rate for standard (Proterra ZX5+, top) and long-range (Proterra ZX5 MAX, bottom) buses, respectively.

[82] https://cleantechnica.com/2020/02/19/bloombergnef-lithium-ion-battery-cell-densities-have-almost-tripled-since-2010/
[83] https://www.proterra.com/press-release/zx5-electric-bus-738kwh/



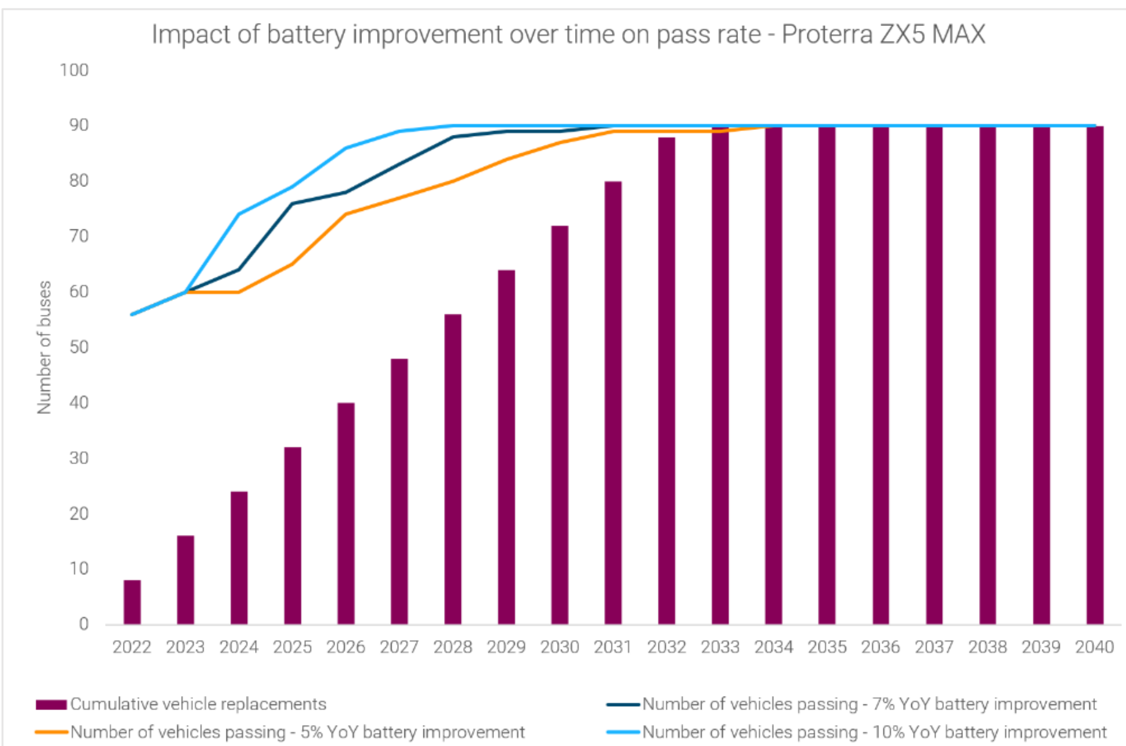


Figure 46: Impacts of Battery Range Improvements of Pass Rate by Bus Type (Base Case, *top* and Longer-Range, *bottom*)

Key insights from Figure 46 include the following:

- Even under conservative range improvement projections (5% YoY), the fleet could start to electrify using standard range vehicles such as the Proterra ZX5+ from today until 2026.
- From 2027 onwards, longer range models would be required and these would comfortably satisfy range requirements as battery technology improves and without relying on on-route charging.
- Having two battery capacities in the fleet reduces interoperability and could cause operational challenges, particularly for vehicle assignments. It was confirmed with Proterra that the battery packs in their buses can be expanded, when required, to avoid operating a mixed fleet. Meaning from 2027 all new vehicles procured will need to be long range and the existing fleet of vehicles fitted with larger batteries to make them of equal range.

Overall, as battery capacity could be expected to improve over time, AAATA would be able to electrify 100% of its service from a range perspective. Other challenges may emerge, including battery degradation, dispatching and vehicle assignments.

5.10 MODELED BEB CHARGING PROFILES

In addition to pass rate analysis, the other important component of predictive modeling is to estimate total power demand (kW) by time of day. Since electricity rates change throughout the day, it is important to understand when the fleet would be charged.

The power demand is assessed in the form of charging profile graphs, which show the power demand by time of day; the area under the curve represents the total daily energy consumption in kWh. In this assessment, both uncontrolled charging (where time of day of charging is not intentionally optimized) and controlled charging (where time of day of charging is optimized to minimize energy demand during the most expensive "network peak" periods) scenarios are modeled for average and cold day conditions. These results are presented below, for standard and longer range BEB scenarios, respectively. While energy costs can be reduced by charging overnight, this approach may increase risks that the fleet may not be ready to begin service in the morning.

5.10.1 Charging Profile for Standard BEB – Proterra ZX5+

The uncontrolled and controlled charging profiles for the standard BEB scenario are shown in Figure 47. In these graphs, the gray charging times are compared with the red area of peak electricity rates as set by DTE. By using an optimized controlled charging approach (i.e., charging overnight, bottom graphs):

- It may not be possible to avoid some charging during the peak period entirely, but it can be minimized.
- The maximum power demand during network peak can be reduced to around 1.5-2 MW by using controlled charging, but maximum demand would still require 5 MW of power. Using controlled charging, this 5 MW maximum power draw would occur from about midnight to about 6 am, and thus avoid DTE peak charging rates.

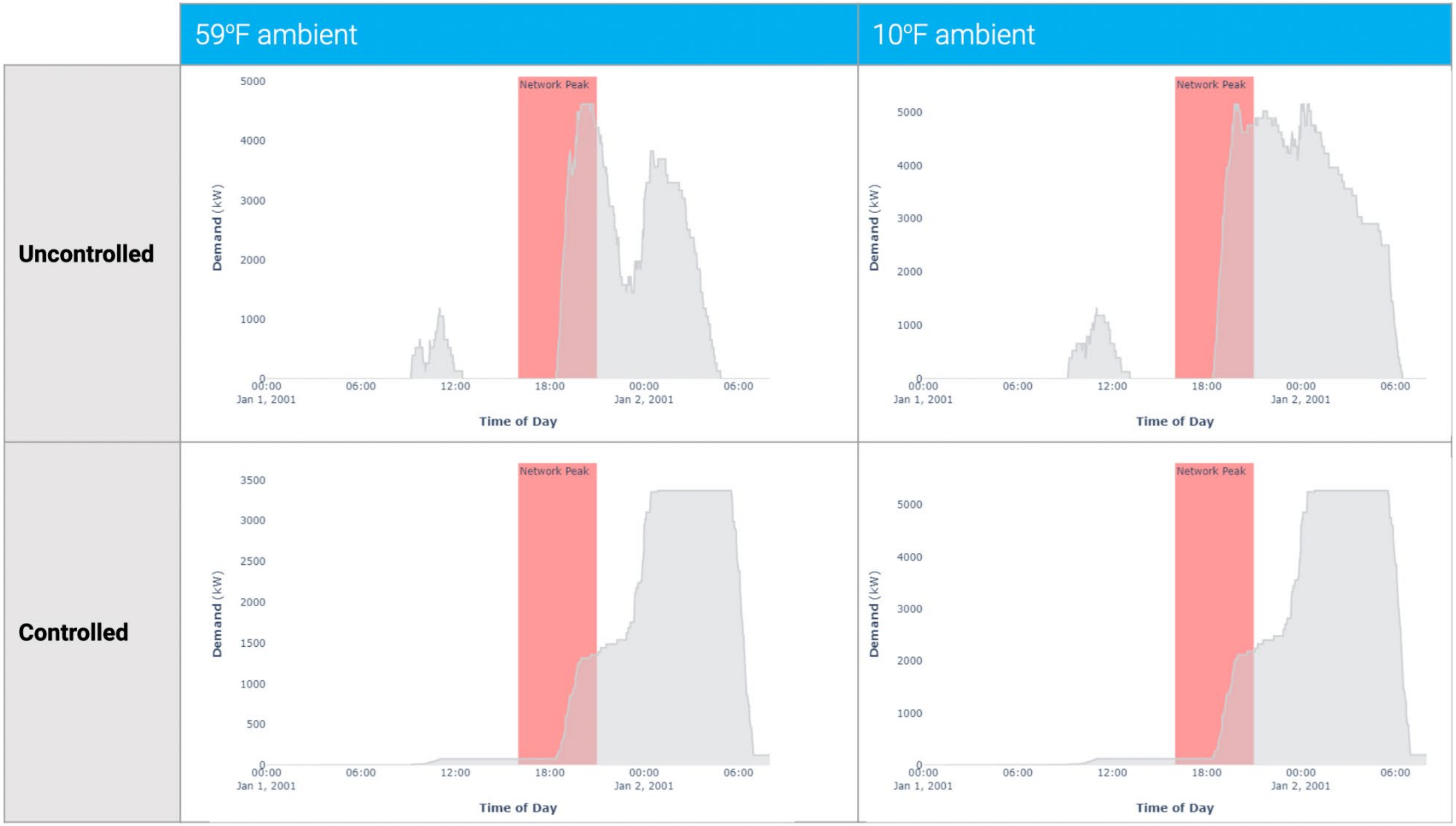


Figure 47: Charging Profile for Standard BEB - Proterra ZX5+

5.10.2 Charging Profile for Long Range BEB – Proterra ZX5 MAX

The uncontrolled and controlled charging profiles for the longer range BEB scenario are presented in Figure 48. Adopting controlled charging in this case can:

- Reduce maximum power demand during network peak periods to 1.5 MW and 2 MW for average and cold day conditions (compared to 4.5 MW and 5 MW for uncontrolled charging), respectively, and
- Reduce maximum power demand under average day conditions to around 3.5 MW compared to around 4.5 MW for uncontrolled charging. For cold day conditions, the maximum power is not impacted due to the increased volume of energy required and time window available to charge overnight

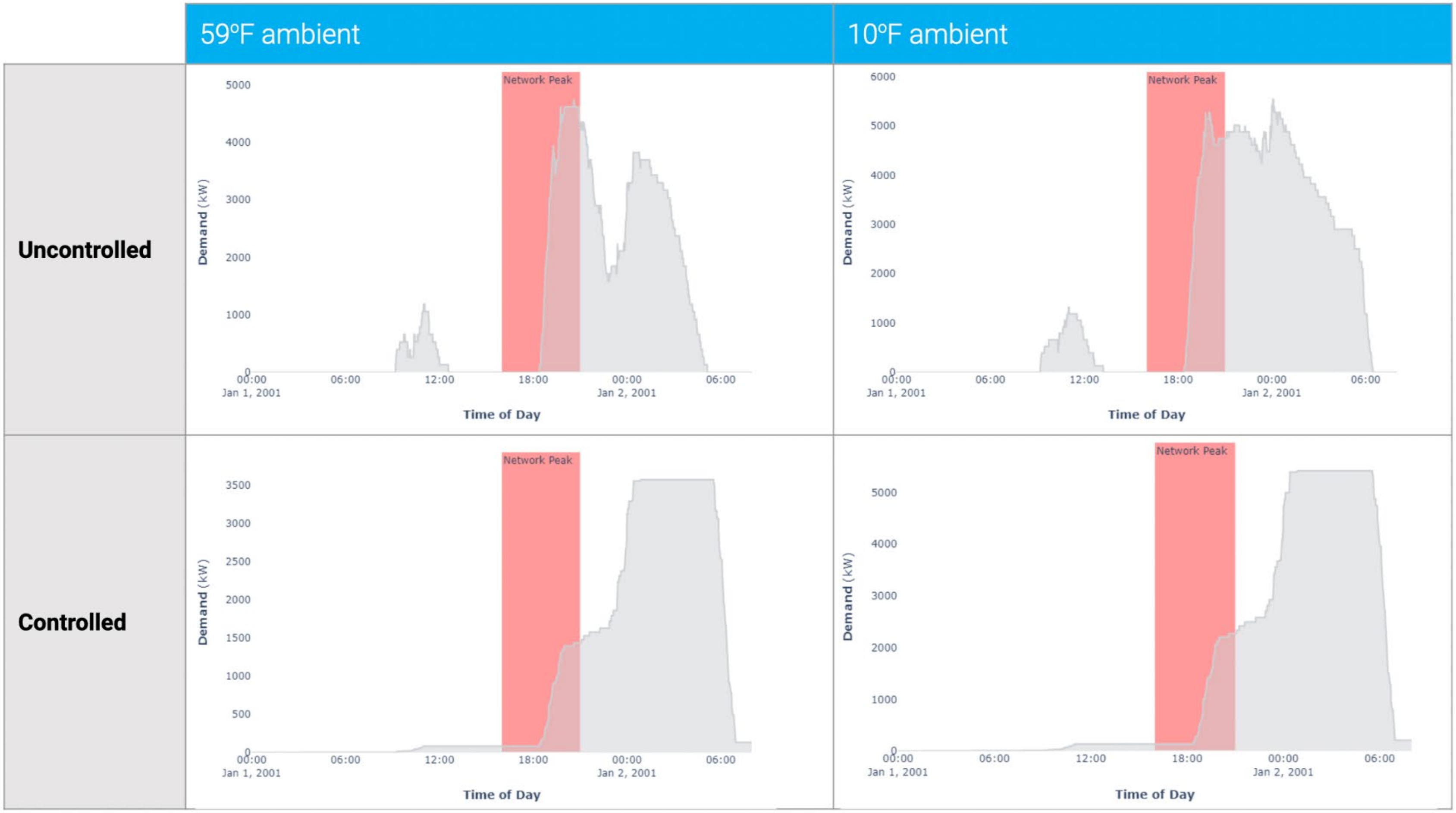


Figure 48: Charging Profile for Standard BEB - Proterra ZX5 MAX

5.11 GRID UPGRADE REQUIREMENTS

The electrical connections serving the existing garage at 2700 S. Industrial Highway would need to be upgraded to handle the large amount of additional power. Based on the power demand analysis presented above, it is estimated that a grid capacity upgrade of 5-6 MW would be required at the garage to satisfy the charging needs of BEBs during cold weather conditions. This is a substantial upgrade, and often upgrades of this magnitude require a dedicated grid line connection to the facility (feeder) to be installed from a nearby electrical substation, likely costing into the millions of dollars. DTE would need to work together with AAATA to understand the demand impacts and implications of a full build-out to support a fleet of BEBs.

A charging management system is recommended to ensure that vehicles are being charged in the most strategic manner to reduce overall electricity costs. The system will automatically shift charging to off-peak periods with consideration for each vehicle's next departure time and energy requirements.

5.12 PREFERRED BEB CONCEPT

Based on the analysis and route modeling, as well as discussions with AAATA, the preferred BEB concept considered in this study is a BEB fleet with long-range batteries that will be charged in-depot. While the modeling demonstrated that a majority of AAATA's service can be successfully operated with BEBs without on-route charging, there is nevertheless a sizable portion of service particularly on very cold days (38%) that would not be feasibly operated with the BEBs modeled without modifying the operating ranges of these blocks and/or using on-route chargers. As well, deploying longer-range BEBs to feasible blocks while operating diesel buses on the most challenging blocks during the transition is another strategy to consider; as battery packs improve, the most challenging blocks can be electrified at a later phase.

Despite on-route charging as a potential strategy for sustaining long vehicle blocks, high-power on-route charging can result in very costly infrastructure and electricity charges that can be significant, particularly at transit centers that involve several vehicles charging simultaneously. AAATA may be able to avoid the deployment of high-power on-route chargers and costly infrastructure investment while still achieving a full conversion to long-range BEBs, but with trade-offs that cause other impacts and costs. To electrify even the most strenuous blocks, AAATA can:

- Explore blocking range limitations for summer and winter weather to reflect the differences in feasible BEB ranges under different weather conditions. The impact of this solution is that AAATA would need to produce vehicle schedules for different seasons, which increases the complexity of transit operations.

- Explore restructuring vehicle blocks and assignments to remain within the BEB operating limitations. This may require a larger fleet to meet the required service levels and introduce additional costs and inefficiencies and requires further analysis.

- Consider procuring BEBs with diesel-fired heaters, such as other bus agencies operating in cold weather climates, to minimize the battery draw for cabin heating. Diesel-fired heaters would typically only need to be used on extremely cold days and while they do emit GHGs, they are an effective strategy to help preserve battery charge for propulsion rather than heating.

- Explore deploying BEBs primarily on blocks within feasible ranges, while keeping diesel buses assigned to longer range blocks until BEB technology matures/improves to accommodate longer ranges.

T A K E A W A Y S

- BEBs have seen consistent improvement to operating ranges and steady reductions to purchase prices, making the adoption of BEBs more accessible for transit agencies.
- BEBs have limited vehicle range and fuel efficiency depending on climates, terrain, and passenger loads. Therefore, the feasibility of transitioning to a BEB fleet needs to be investigated closely according to specific operational conditions and needs of AAATA.
- AAATA's facility will require substantial grid upgrades to handle the large amount of additional power required for a BEB fleet.
- The preferred BEB concept for AAATA is a BEB fleet with long-range batteries that are charged in-depot.
- 38% of service could not be operated without modifying the operating ranges of the blocks or using on-route chargers. High-power on-route charging can result in costly infrastructure and significant electricity charges.

6.0 HYDROGEN FUEL CELL-ELECTRIC BUSES

This section discusses hydrogen fuel-cell electric bus (FCEB) technologies and their implications in public transit. FCEBs are buses that use hydrogen as their on-board energy source. The key advantage of FCEBs over BEBs is their operating range; FCEB operating range is on the order of 300 miles per tank, comparable to fossil fuel-powered buses. Nevertheless, the hydrogen market is still maturing in many parts of the county and a conversion to FCEBs requires costly investment in hydrogen fueling equipment, as well as FCEBs themselves.

This section presents:

- An overview of current FCEB technologies including discussions of key factors for consideration,
- Hydrogen fuel production and supply chain,
- Computer modeling of how FCEB technologies could work in the Ann Arbor/Ypsilanti environment,
- Review and discussion of the changes needed for garage and terminal facilities to use BEBs,
- Implications for transit operations,
- Preliminary workforce implications and training requirements,
- A preferred scenario for how FCEBs could be adopted by the AAATA.

6.1 VEHICLE TECHNOLOGY OVERVIEW

For hydrogen powered vehicles, their energy is primarily stored in on-board liquified hydrogen tanks, much like diesel or gasoline. However, instead of an internal combustion engine to convert the energy into mechanical work, a fuel cell converts hydrogen’s internal energy into electricity which is temporarily stored in smaller batteries before being used to accelerate the vehicle. In this sense, FCEBs are also electric buses and are similar to hybrid diesel-electric buses. Figure 49 shows a technology comparison between BEBs and FCEBs to highlight how hydrogen is the source of energy for the FCEBs.

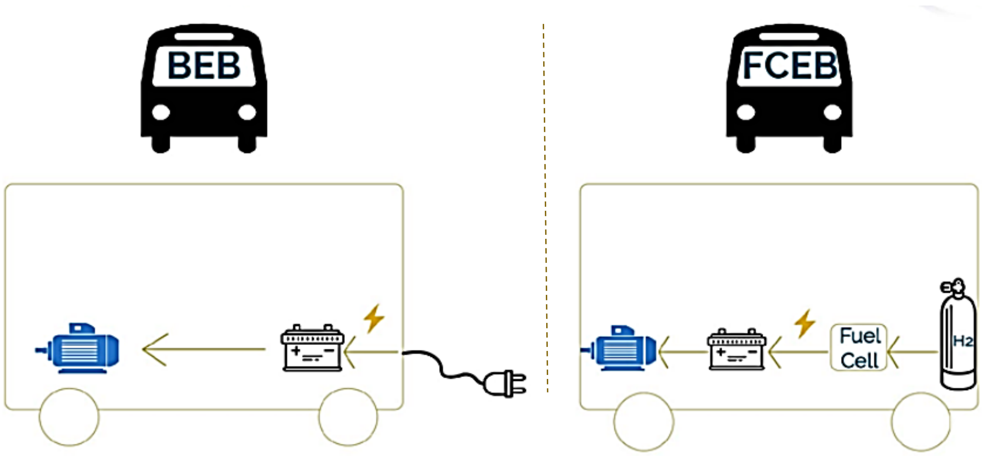


Figure 49: Technology Overview of a BEB versus a FCEB[84].

FCEBs provide operational advantages over BEBs including increased range comparable to fossil fuel buses, reliable service in cold weather conditions, and short refueling times. In addition, fuel cell stacks tend to naturally run 'hot' which is advantageous in winter months to warm the bus cabin through heat capture technologies, and FCEBs are fueled in a way similar to diesel buses in that a dispenser 'pumps' fuel into the onboard fuel tanks.

Figure 50: Hydrogen fuel cell-electric bus from Orange County, California.

Hydrogen has a greater energy density than batteries, allowing more power to be stored on the bus itself. This onboard energy source allows onboard electricity generation, and therefore permits FCEBs to travel greater distances than BEBs, which need to recharge their batteries using an external charger. While the energy conversion cycle (from raw materials to fuel) is less efficient for hydrogen than for the process of

[84] Source: CTE

grid energy conversion and storage in batteries, the energy density of hydrogen (i.e., capacity to carry more energy in the same space) presents a key advantage that allows FCEBs to travel longer distances than BEBs[85]. The range of FCEBs is between 240–325 miles, depending on the hydrogen tank size[86].

Early deployments of this technology struggled to find an economic niche due to the high cost of hydrogen production and the high costs of FCEBs themselves. However, as hydrogen becomes more economic to produce and fuel cell prices drop, the economics for FCEB will improve especially for longer bus routes requiring faster re-fueling times. There is a possibility that hydrogen may find a niche in the heavy-duty vehicle market when battery charging isn't easy, particularly for larger fleets where the fixed costs needed for hydrogen fueling infrastructure is spread out among a larger fleet. While FCEBs have been in the market for over 10 years, only a few bus manufacturer options are currently available in the US. Table 26 presents a list of a sample of available FCEBs models and manufacturers in the US.

Table 26: Non-exhaustive List of Available Transit FCEBs, Battery Capacities, Range, and Fuel Economy

OEM	Propulsion Type	Length(s) (ft)	Fuel Cell Power	Battery Capacity (kWh)	Tank Size (kg)	OEM Stated Range (mi)	Fuel economy (mi/kg)	Estimated purchase cost
New Flyer[87]	FCEB	40, 60	160 kW rate motor power; 85 kW (net)	100, 150	40 ft – 37.5 60 ft – 60 kg	>340	5.8 - 7	40 ft – $1,087,000 60 ft – $1,500,000
ElDorado National	FCEB	40	150 kW rate motor power	11	Up to 50	>260	6.5 - 8	$1,195,000

6.2 FCEB PERFORMANCE

The first FCEB demonstration in the US was in 2007 at SunLine Transit, Thousand Palms, California. This first-generation FCEB was evaluated by the National Renewable Energy Laboratory (NREL)[88] to measure how FCEBs operations compared to the performance targets established by the FTA, as well as compared to fossil fuel buses. NREL continues this evaluation program of FCEBs in head-to-head comparisons with CNG and diesel buses at agencies across the country, providing valuable insights into challenges, performance, and costs.

The NREL technology validation team evaluates FCEBs to provide comprehensive, unbiased evaluation results of FCEB development and performance compared to conventional baseline vehicles. The latest report published in 2021 is the “Fuel Cell Buses in U.S. Transit Fleets: Current Status 2020” and primarily focused on the most recent data on a new generation of FCEBs by New Flyer, from January 2020

[85] https://www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit
[86] Fuel economy of 6.8 mi/kg was assumed for example purposes only. Current hydrogen tank configurations are 37.5 kg and 50 kg capacity and assuming 95% tank consumption.
[87] New Flyer quoted purchase prices for 40-ft FCEB ~$1.01M and 60-ft FCEB ~$1.46M.
[88] Part of the US Department of Energy

through July 2020[89]. The primary results presented in the report are from 25 FCEBs deployed at three agencies:

- Alameda-Contra Costa Transit District (AC Transit) in Oakland, California: 10 FCEBs
- Orange County Transportation Authority (OCTA) in Santa Ana, California: 10 FCEBs
- SunLine Transit Agency in Thousand Palms, California: 5 FCEBs.

The fuel economy for newer FCEB models averages 7.95 mi/kg, which equates to 8.99 miles per diesel gallon equivalent (mpdge). This exceeds the FTA target of 8 mpdge and is more than twice that of the baseline diesel buses. This results in an anticipated maximum range of 350 miles. Figure 51 shows the recorded fuel economy for the FCEBs and comparison against the performance of compressed natural gas, diesel, and hybrid buses.

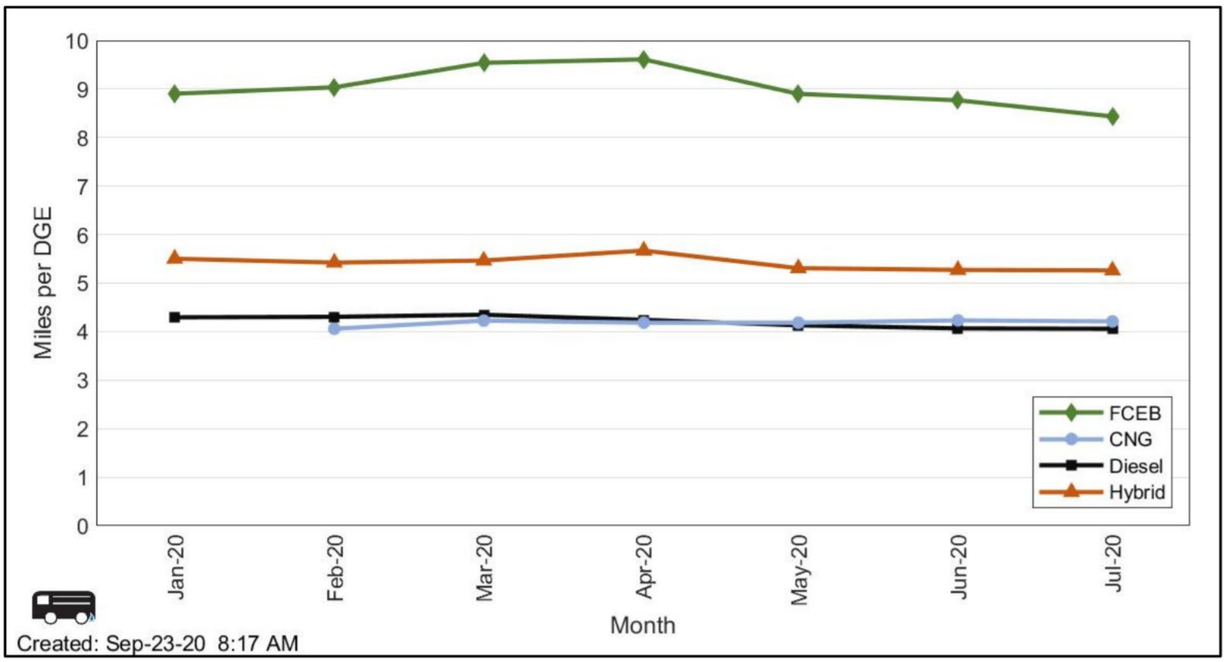


Figure 51: Fuel Economy for FCEBs and Baseline buses reported by NREL[32]

Because the fuel economy of FCEBs depends on duty cycle, ambient temperature, and driver behavior, actual real-world range will differ across agencies (even across routes and time of year) for the same bus. To show the performance of FCEBs in a climate similar to Ann Arbor, results from an NREL report studying 5 FCEBs deployed at Stark Area Regional Transit Authority (SARTA) in Canton, Ohio are presented in Figure 52[90].

[89] https://www.nrel.gov/docs/fy21osti/75583.pdf
[90] https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/134491/zero-emission-bus-evaluation-results-sarta-fta-report-no-0140_0.pdf

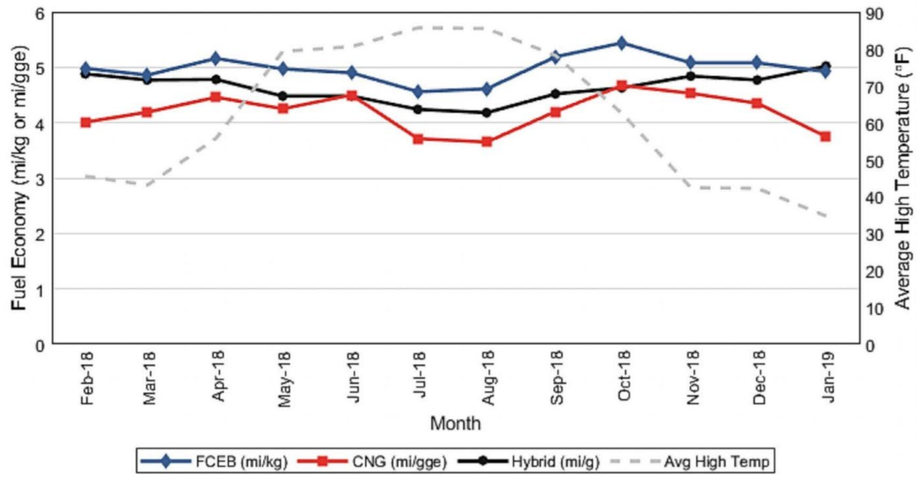


Figure 52: Fuel Economy of FCEBs operation at SARTA

SARTA selected two routes for its first FCEBs, whereas the CNG buses are dispatched on all routes, including commuter runs to Akron and Cleveland. The fuel economy for the FCEBs averaged 5.63 mpdge compared to 4.59 mpdge for the CNG buses. While the fuel economy of these FCEBs is lower than the one observed by the transit agencies in California, the chief factor resulting in poorer performance was the fact that the FCEB deployed by SARTA was a first-generation FCEB manufactured in 2016, while the experience of California agencies is based on newer generation FCEBs (2019 and onwards). Despite the lower-than-expected fuel economy, these values are still 20% higher than the CNG bus fuel economy and 23% higher than the hybrid bus fuel economy.

Additional operational and maintenance cost comparisons between the FCEBs and CNG buses operated by SARTA during the collection period are presented in Table 27. The level of utilization for FCEBs was almost half of the utilization from CNG buses and the availability for FCEBs was only 68% versus 76% for the CNG, mainly due to lead times related to parts and servicing. Nevertheless, the fuel economy for the FCEBs was 20% better than for CNG and the total maintenance costs between both vehicle types was comparable at $0.33 per mile.

Table 27: FCEBs versus CNG buses operated by SARTA[91]

Data Item	FCEB	CNG
Number of buses	5	4
Total mileage in data period	130,798	230,144
Average monthly mileage per bus	2,180	4,795
Availability (85% is target)	68	76
Fuel economy (kg/mile or gge[a]/mile)	4.99	4.21
Fuel economy (mpdge[b])	5.63	4.70
Miles between roadcalls (MBRC) – bus[c]	3,737	7,936
MBRC – fuel cell system only[c]	26,160	–
Total maintenance cost ($/mile)	0.33	0.33
Maintenance cost – propulsion system only ($/mile)	0.15	0.12

[a] *Gasoline gallon equivalent.*
[b] *Miles per diesel gallon equivalent.*
[c] *MBRC data cumulative through January 2019.*

Overall, newer generation FCEBs provide long operating ranges and fuel economies that are better than CNG and diesel buses.

6.3 HYDROGEN FUEL

Hydrogen fuel can be produced in several ways, and different methods use differing amounts of carbon to create the hydrogen. Hydrogen production can be categorized as gray, blue, or green:

- **Gray** hydrogen is created using fossil fuels.
- Hydrogen is labeled **blue** whenever the carbon generated during production is captured and stored underground through industrial carbon capture and storage (CCS). Therefore, blue hydrogen is a "low carbon" solution as 5-15% of the generated carbon cannot be captured.
- **Green** hydrogen is produced without any carbon, is clean and 100% renewable.

Figure 53 summarizes the process and source for each hydrogen type.

[91] https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/134491/zero-emission-bus-evaluation-results-sarta-fta-report-no-0140_0.pdf

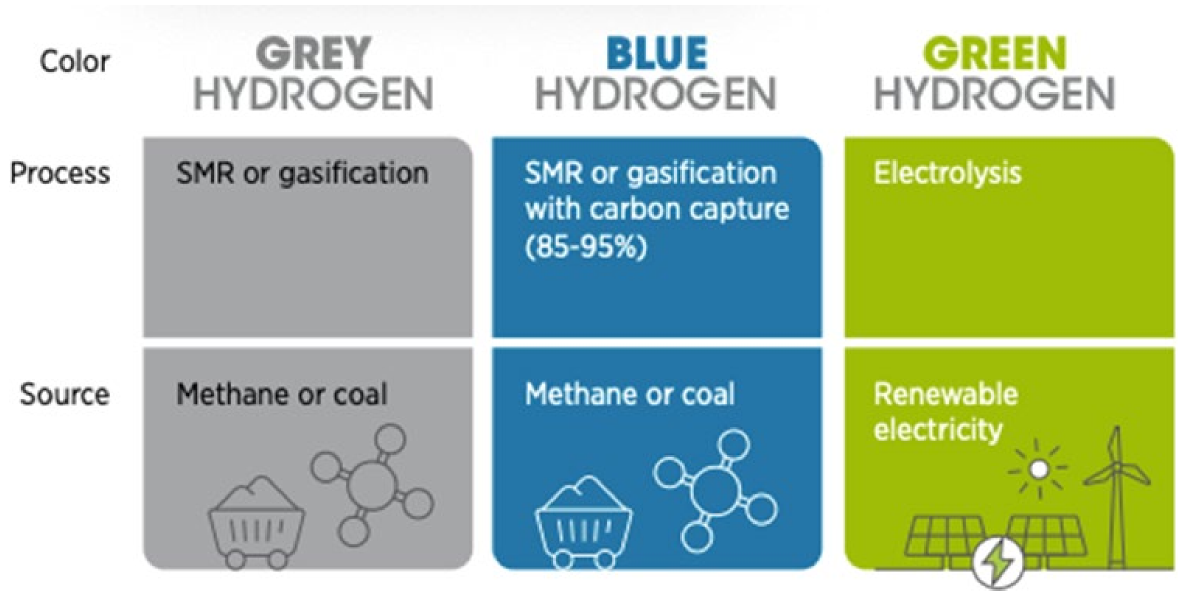


Figure 53: Hydrogen classification based on carbon intensity

Upstream processes and associated economics related to the production of hydrogen are evolving rapidly. The decarbonization of hydrogen is gaining much focus from the gas industry. It is important to understand the impact of scale for onsite generation as well as for carbon capture, which are used to generate clean (green) hydrogen and blue hydrogen, respectively. Storage of captured carbon dioxide will also have to be considered on a local scale. Green hydrogen production is expected to benefit from economies of scale and become more affordable as processing techniques improve.

In addition to the carbon footprint tied to hydrogen production itself, there are varying levels of GHG emissions depending on the supply line used and distances that hydrogen would need to travel before reaching the final user. For example, delivery of hydrogen with a diesel-powered truck would have a larger GHG impact than supply through a fuel pipeline.

Ideally, to maximize the environmental benefits of ZEBs, green hydrogen is preferred to maximize the reduction of GHGs; minimizing the distance that the hydrogen needs to travel is preferred as well. Nonetheless, access to green hydrogen may be limited in certain markets, so it will be important in future steps that AAATA understand the types of hydrogen fuel available for purchase because producing hydrogen on-site can be an expensive endeavor.

6.4 HYDROGEN FUELING INFRASTRUCTURE OVERVIEW

The refueling process of a FCEB is similar to refueling diesel or natural gas buses; a hose or dispenser is connected to the fuel gauge and after 8 to 10 minutes, the tank is full. SAE standard J2601-2 references an upper flow limit for hydrogen dispensing of 7.2 kg/minute.

Figure 54 shows a generalized schematic of a hydrogen infrastructure facility. The Hydrogen Refueling Unit (HRU) refers to all equipment used to directly refuel vehicles and the hydrogen itself can either be produced on-site or delivered from an external location.

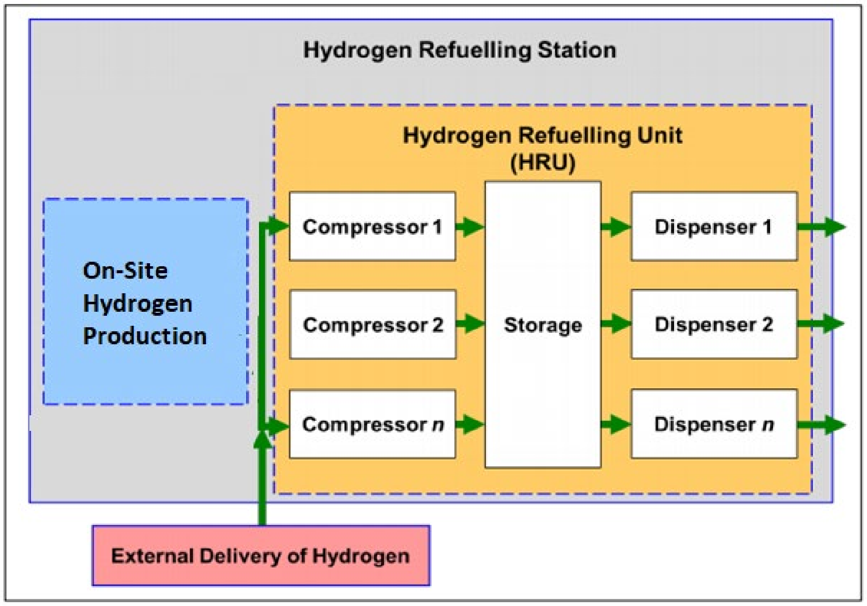


Figure 54: Generalized Schematic of a Hydrogen Infrastructure Facility[92]

Figure 55: Liquid hydrogen storage tank and vaporizers as part of Orange County's hydrogen fuelling infrastructure.

[92] M. Faltenbacher, K. Stolzenburg, S. Eckert, and M. Gallmetzer, "JIVE-Joint Initiative for hydrogen Vehicles across Europe Deliverable 3.1 MEHRLIN-Models for Economic Hydrogen RefueLling INfrastructure Activities 2.4, 3.1 and 3.2 Performance Assessment Handbook," 2018.

The hydrogen dispenser typically includes a nozzle that connects to the vehicle and a user interface (the controls at the dispenser) for initiating fueling (including emergency shutdown controls). The dispenser is usually the only part of the station with which the end users will interact. Details of the connection device (nozzle) are defined by international standards such as ISO 17268:2012 and SAE J2600. The hydrogen refueling process is also standardized with SAE J2601-2. This standardization in hydrogen refueling ensures interoperability and vehicle compatibility—i.e., any hydrogen-fueled bus designed to comply with the standards can refuel at any station also designed according to the standards.

Figure 56: Hydrogen fuelling dispenser, Orange County, California.

The size and configuration of the hydrogen station depends on the number of buses that need to be filled overnight (usually in a seven-hour shift), and the average hydrogen dispensed to each bus (between 30 to 60 kg per bus). Therefore, the daily hydrogen demand and active fleet size will determine the proper configuration of the station, reflected in total number of hydrogen pumps and number of dispensers (or refueling islands). Table 28 presents the illustrative capital cost for different sizes of a hydrogen refueling station. For reference, the existing AAATA fleet size is 103 heavy-duty buses.

Table 28: Estimated capital cost for hydrogen refueling stations of different capacities[93]

Station Capacity		Hydrogen Refueling Station Configuration		Capital Cost ($)
No. of Buses	Kg/day	No. of Pumps	No. Dispensers	
55	1,600	1	1	$3.9 million
110	3,300	2	2	$5.1 million
165	5,000	3	4	$5.8 million

6.5 HYDROGEN SUPPLY CHAIN OVERVIEW

Hydrogen can be acquired through a variety of methods, including the following:

- A tube trailer used to supply gaseous hydrogen
- A tube trailer used to supply liquid hydrogen
- On-site generation of hydrogen using Steam Methane Reformation (SMR)
- On-site generation of hydrogen using water electrolysis (which can be powered by grid electricity or using renewable electricity, such as electricity from solar panels)

The method for hydrogen procurement and fueling will depend on several factors, including reliable access to affordable natural gas, and access to water and affordable electricity, the ingredients for hydrogen production. SMR production would be favored in regions with access to methane/natural gas and other raw materials.

Another key factor is the FCEB fleet size and vehicle assignment mileage for a given transit agency. Smaller FCEB operations tend to favor gaseous hydrogen delivered from a tube trailer due to its lower upfront capital investment requirements, while larger operations favor liquid hydrogen delivery due to the greater volumes and better rates on a cost-per-mile basis. Larger operations (>300 vehicles) with higher capital expense budgets also favor on-site generation of hydrogen using SMR, to achieve further operating cost savings through the elimination of delivery charges.

Electricity-abundant regions favor electrolysis while hydrogen-abundant jurisdictions favor the delivery of gaseous or liquid hydrogen. Jurisdictions without abundant electricity and hydrogen tend to gravitate to on-site generation using SMR, though this is typically only if they have abundant natural gas, which gets converted to hydrogen in the SMR process.

It should be noted that the four methods of acquiring hydrogen are not mutually exclusive, and some regions or agencies may acquire their hydrogen supply through a combination of these methods.

To date, liquid hydrogen delivery and storage is generally the most common model for transit agencies at the moment, followed by on-site generation of hydrogen using SMR. As more agencies deploy larger numbers of FCEBs, the model of hydrogen supply may change. Table 29 is a summary from a Ballard report showing the suitability of different hydrogen sources.

[93] Stantec estimates.

Table 29: Ballard Report of Suitability for Different Hydrogen Sources

	Compressed hydrogen gas	Liquid hydrogen	Local SMR	Local electrolysis
Overall	Good for smaller volumes	Good for large volumes	Good for large volumes	Good for large volumes
Distribution Costs	High; price impacted by location from supply	Nominal; range flexibility	Nominal	Nominal
Price volatility	Dependent on fuel prices; available bulk discounts	Dependent on fuel prices; available bulk discounts	Dependent on maintenance and fuel costs	Dependent on maintenance and electricity
Infrastructure costs	Lower	Higher	Depends on production capacity	Depends on production capacity
Carbon emission reductions	N/A	N/A	Renewable biogas available at higher costs	Clean hydropower available or infrastructure can be installed for local solar or wind electricity generation

While there are a great variety of generation and distribution combinations to establish a hydrogen supply chain, the final design of the supply chain is greatly dependent upon the hydrogen availability in the region and hydrogen demand from the fleet.

6.5.1 Hydrogen in the Ann Arbor Region

While innovations are continually being implemented, the current technical and commercial approaches to producing, compressing, storing and distributing hydrogen are becoming well known. This section presents the main implementation aspects for FCEBs in the Ann Arbor context.

One of the closest sources of hydrogen for Ann Arbor is in Flint, where the local transit agency has deployed several pilot FCEBs, as well as collaborated with Air Products to build an electrolyzer plant in nearby Grand Blanc. Also nearby is an Air Products plant in Sarnia, Ontario where supply lines should not be a problem across the US-Canada border. The Sarnia plant has a capacity of 15 metric tons per day (MTPD) for a possible supply point. The next possible supply site could be the Linde plant in East Chicago, Indiana, with a current capacity of 17 MTPD.

Figure 57 shows the location of current hydrogen manufacturers in the vicinity and Table 30 provides the capacity for each site in the map. It is important to note that in recent years as the hydrogen market has been expanding, the number of hydrogen liquefaction plants continues to grow significantly in North America.

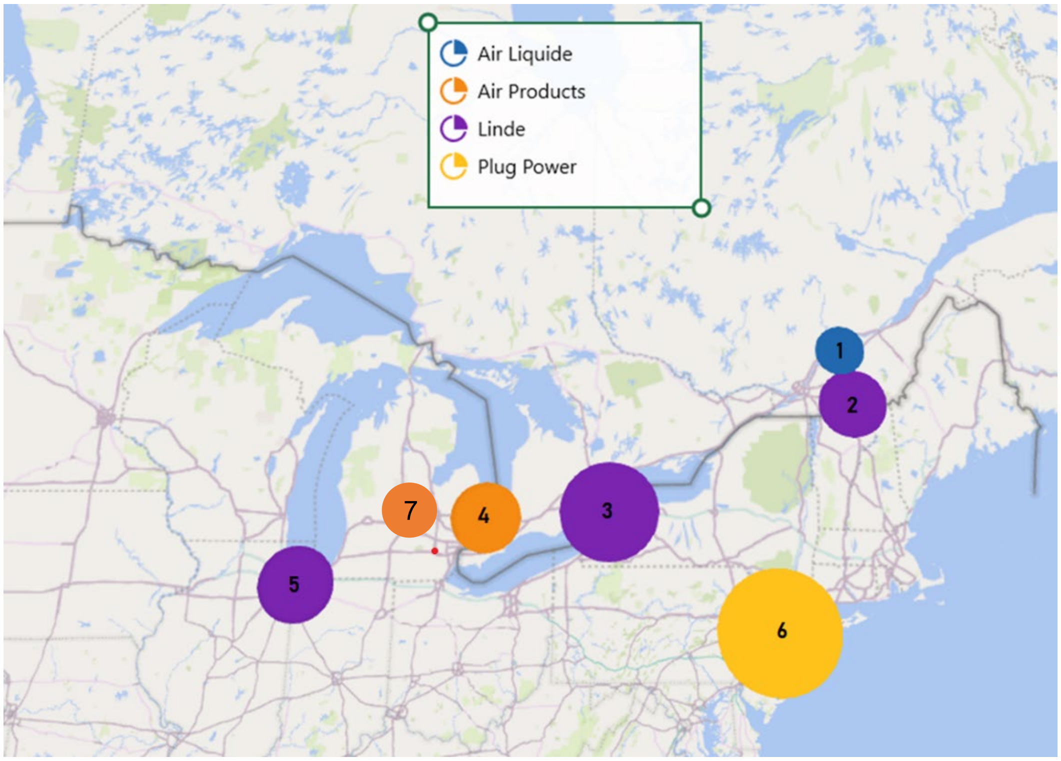


Figure 57: Hydrogen Suppliers in the Upper Midwest and East of the United States and Southern Canada.

Table 30: Capacity of Current Hydrogen Generation Assets in the Nearby Regions

ID	Company	Location	Capacity (MTPD[94])
1	Air Liquide	Becancour, Quebec (clean)	8
2	Linde	Memphremagog, Quebec (clean)	15
3	Linde	Niagara, New York	30
4	Air Products	Sarnia, Ontario	15
5	Linde	East Chicago, Indiana	17
6	Plug Power	New York	45
7	Air Products	Grand Blanc	TBD

[94] Metric tons per day (MTPD).

While an ideal output threshold to justify the investment in a liquefaction plant is 10 MTPD[7], an initial hydrogen demand of as little as 2.5 MTPD from certain region can serve as starting point while the hydrogen market continues to develop, and demand grows outside the transportation sector.

The cost of liquefaction and distribution via tube trucks for distances less than 50 miles has been reported at $1.5 per kg of hydrogen[95]. Figure 58 shows the breakdown for the distribution of hydrogen via gas and liquid tube-trucks. If liquification is not justified, then the cost of hydrogen distribution as a gas could increase to $2.75 per kg considering current gas distribution technologies. However, new technology is rapidly emerging that could justify the use of hydrogen gas as a distribution system with prices between $0.13-1.26 per kg and capacities around 1,200 kg/day at 500 bar[96], which would allow for one tube truck delivery every other day. Nonetheless, these are illustrative values and the costs for the Ann Arbor context will vary depending on local production, delivery costs, and the maturity of the hydrogen market.

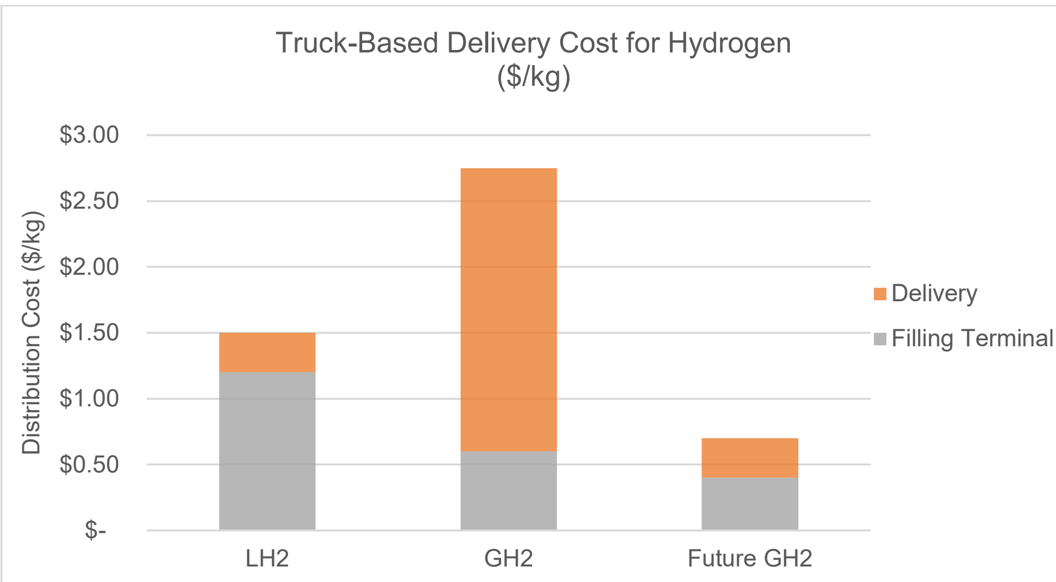


Figure 58: Truck-Based Distribution Costs for Hydrogen Traveling Less than 50 Miles.

Furthermore, even in locations where a robust hydrogen distribution system is under development, hydrogen prices to transit agencies can still be favorable. SARTA reported an average hydrogen cost of $5.27/kg in October 2019 for non-renewable hydrogen[97].

Most recently, an announcement was made that BayoTech Inc., which manufactures hydrogen transport trailers, aims to open a hydrogen production hub at the American Center for Mobility in Ypsilanti Township. This plan is aimed to open in mid-2023 and produce about 1,000 kg per day, or enough to fuel 200 hydrogen vehicles; the type of hydrogen (green, gray, or blue) is unknown at the moment. The town council will vote on approval early in 2023. Projects like these are indications of the development of a

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95 H2A Delivery Scenario Analysis Model by Argonne https://hdsam.es.anl.gov/index.php?content=hdsam
96 Hydrogen Insights Report 2021, Hydrogen Council, McKinsey & Company.
97 SARTA ZEB Evaluation report October 2019: https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/134491/zero-emission-bus-evaluation-results-sarta-fta-report-no-0140_0.pdf

local hydrogen in southeastern Michigan and should AAATA proceed with hydrogen buses, AAATA should explore fueling options and partnerships with firms like BayoTech.

It could be expected that 100% renewable hydrogen in the Ann Arbor region can start around $8/kg of hydrogen with a reduction trend until a price of $4/kg can be reached[98]. While is difficult to say with certainty how much will it cost to fuel a 100% FCEB fleet for AAATA at this exploratory stage, the sensitivity analysis in Section 8.3.2 provides guidance and further detail into how a best- and worst-case scenario of the hydrogen prices could impact the deployment of a pure hydrogen fleet and the following section provides a comparison of financial considerations between FCEBs and diesel buses.

While only local hydrogen sources were explored in this section, is worth noting that liquified hydrogen can travel up to 500 miles, as is the current case for the distribution of hydrogen from Sacramento, California to Irvine and nearby cities in Southern California.

6.6 FINANCIAL CONSIDERATIONS

To provide some illustrative cost comparisons of FCEBs with traditional diesel buses, Table 31 provides an overview of capital costs associated with FCEBs and diesel buses, while Table 32 provides an overview of operating and fueling costs associated with FCEBs and diesel buses. These tables are meant to provide **examples of the costs reported by transit agencies operating these technologies and are based on historical data**. The figures here may differ from what could be expected by AAATA and into the future. Inputs and assumptions used in the financial modeling are presented in Section 8.0 and Appendix B Financial and Emissions Modeling Inputs.

Table 31: Illustrative capital cost comparisons between diesel buses and FCEBs

Item	Diesel	FCEB	Comments
Vehicle	$500,000-700,000	$1.0-1.5 million per bus	• Depends on bus length • Depends on configuration and add-ons • Depends on tank size
Extended warranty	NA	$20,000-40,000 per bus	• Depends on OEM • Depends on battery pack capacity • Depends on duration of warranty
Fueling Infrastructure and Storage – No On-site Production	NA	$5.3-7.9 million for one station	• For a deployment of 50 buses or less, costs are roughly the same • This cost assumes trucked-in liquid hydrogen (i.e., for hydrogen storage and dispensation) and will require minimal electrical upgrades (on par with diesel/CNG storage and dispensation)
On-Site Production Infrastructure	NA	Electrolyzers can cost between $3-4 million per unit Mid-size to large fleet could range over $20 million	• This cost is on top of the fueling infrastructure and storage costs above

98 https://www2.gov.bc.ca/assets/gov/government/ministries-organizations/zen-bcbn-hydrogen-study-final-v6.pdf

Item	Diesel	FCEB	Comments
Facility Modifications	NA	$200,000+ per facility mainly related to gas detection system Other costs may be incurred for other upgrades	• Depends on the state of repair of the bus facility, the space available to accommodate buses and charger infrastructure • Depends also on grid capacity and state of electrical equipment • Depends on the state of repair of the bus facility, the space available to accommodate buses and hydrogen infrastructure. • Depends on whether hydrogen will be generated on-site • A detailed architectural and engineering study is needed to understand true costs in the Ann Arbor context.

Table 32: Illustrative maintenance and fuel cost comparisons between diesel buses and FCEBs

Item	Diesel	FCEB	Comments
Bus Maintenance Cost	$0.19-0.45 per mi	$0.30-$0.40 per mi	• Depends on operating conditions, learning curves for maintenance staff, and bus type • Also depends on operating profile and local labor costs
Fuel Cell Stack Replacement	NA	$20,000 per stack at bus midlife	• Ballard offers refurbished fuel cell stacks at 60-70% of the original price
Battery Pack Replacement	NA	$240-860 per kWh	• Range represents different OEMs and battery pack sizes • Cost range is for a battery replacement not under the extended warranty • Replacement may not be required, depending on battery size/degradation
Midlife Overhaul (body and other related work unrelated to drivetrain)	$50,000-100,000	$50,000-100,000	• Depends on agency policy and practices • Depends on the condition of the bus at midlife • Depends on intended useful life • Depends on whether an agency uses internal or external resources
Fuel cost	$3-7 per gallon $0.70+ per mile	$5-12 per kg $1.25-2.00 per mile	• Depends on supply chain and volatility • Goal is for hydrogen to reach $4 kg or less. Prices given in this table assumed to be for 100% renewable hydrogen delivered as a liquid using tube trucks.

6.7 SUMMARY AND TAKEAWAYS

FCEBs have been operating in the US since 2007, with more than 150 FCEBs that are, or have been, in operation to this day. The FTA has deemed the development of hydrogen bus technology in the latter half of the technology demonstration/commissioning phase, with the final phase being fully commercialized vehicles. And while several demonstrations are active across the US, other large transit agencies have already committed to either 100% FCEBs fleets or a mix with BEBs (e.g., Orange County, AC Transit, and SunLine Transit).

FCEBs have comparable operating ranges and fueling practices to CNG and diesel buses, making this technology attractive for a complete transition to ZEB fleets, particularly if a one-to-one switch is desired between ZEB and fossil fuel buses, with little alterations to operating practices. And while the capital cost of hydrogen refueling stations and bus purchase remain the main obstacles for adoption, once funding is secured, the fast refueling and minimal changes to operational practices offer the flexibility and reliability that transit agencies depend on for their daily operations.

Furthermore, the extended range that FCEBs have compared to BEBs, as well as reliable performance in extreme cold weather, make this bus technology an appealing solution for fleet decarbonization in colder climates. Nevertheless, access to a robust, reliable, and affordable hydrogen supply chain (hydrogen production and distribution) and a comprehensive cost assessment over the lifetime of the project are needed to understand the economic viability of adopting an FCEB fleet.

6.8 FCEB CONCEPT FOR AAATA

Based on the information described above for FCEB technology, the subsequent step in the propulsion study was to develop a potentially viable FCEB deployment concept for AAATA. This step required site planning, bus modeling, and considerations for AAATA's operations.

6.8.1 Preferred Site Concept for FCEBs

To begin developing concepts for a deployment of FCEBs, the following parameters were determined (based on bus modeling) to guide the requirements for hydrogen fueling infrastructure for AAATA:

- Maximum daily hydrogen use of ~2,000 kg/day (average 22 kg/bus)
- Use of liquid hydrogen
- Two fueling lanes, with one dispenser/pump each
- 18,000 gallons for storage

Furthermore, several pieces of on-site equipment are required, such as a hydrogen storage tank, vaporizers, compressors, chillers, and dispensers.

To begin understanding where and how all this equipment can be sited, the following NFPA regulations for liquid hydrogen storage needed to be considered:

- ≤18,000 gallons: 50' to lot line[99]
- >18,000 gallons: 75' to lot line[100]
- Air intake into building: 75'
- Building opening: 75'
- Ignition source: 50'
- Parked vehicles: 25'

[99] Note – proximity requirements may be eliminated using barrier wall with 2-hour rating.
[100] Note – proximity requirements may be eliminated using barrier wall with 2-hour rating.

The production, storage, and dispensing of hydrogen will require significant changes to the existing bus garage at 2700 South Industrial Highway. Initially, four options were considered and abandoned, and a final preferred facilities concept developed. All these explorations are described below.

Given the space requirements for hydrogen fueling infrastructure and based on preliminary discussions with AAATA, four different concepts were considered for possible sites for a hydrogen fueling station: Public Storage Site (Concept 1—north location), adjacent to the railroad (Concept 2—west location), nearby Xfinitiy Site (Concept 3), and employee parking (Concept 4). A summary of the major considerations for each site is outlined in Table 33 with the different fueling station location options in Figure 59. All concepts except for Concept 4 include an offsite refueling station, which would result in significant changes to the vehicle servicing cycle to accommodate this refueling occurring outside of the main building. Namely, vehicles returning from service would need to be taken for offsite fueling, increasing deadheading mileage and the time needed to service (clean, fuel, etc.) each bus.

Figure 59: Initial set of potential site locations for hydrogen fueling station

Table 33: Considerations for initial hydrogen fueling station site concepts

Concept 1 – Public Storage Site	Concept 2 – Railroad Adjacent
Lowest impact to neighbors. 50’ railroad clearance for hydrogen equipment may be difficult to meet. Land acquisition from Public Storage. Significant changes to vehicle servicing cycle to accommodate refueling outside of main building.	Required railroad crossing will be challenging (permits, community outreach/buy-in, etc.), likely expensive, and time consuming. 50’ railroad clearance to H2 equipment unlikely to be met. Special concerns to meet safety codes and standards given proximity to a school and church. Potential land acquisition. Significant changes to vehicle servicing cycle to accommodate fueling outside of main building.
Concept 3 – Former Xfinity Site	**Concept 4 – Employee Parking**
Close proximity to residential zoning needs to be considered for clearance standards. Requires long dispenser-supply lines. Feasibility of piping between equipment yard and fueling station. Land acquisition. Significant changes to vehicle servicing cycle to accommodate refueling outside of main building.	Closest to fueling area. Farthest from residential area. No additional land acquisition. Adjacent areas can be used to relocate the employee parking space.

Concepts 1 and 3, while appealing because they could provide more space immediately next to AAATA’s facility were ruled out primarily because of the need to acquire private land. Concept 2 would incur ~2 mile-round-trip deadhead to drive around the railroad tracks to access the fueling facility and could also raise community concerns due to its location next to a school. Concept 4 would be ideal because it would contain the fueling infrastructure on AAATA’s existing property, but would eliminate much needed staff parking, resulting in the need to find a remote lot for employees and would likely be a non-starter to ask staff to park remotely and then use a shuttle bus to get to the main facility. Finally, while siting the infrastructure remotely and piping the hydrogen to the fueling island could be feasible, the length and cost of piping would be extremely high.

Based on the impracticality of the first four sites, it was decided that a revised concept would look to find space on-site for the hydrogen equipment. Following discussions and workshopping with AAATA staff, Stantec staff developed two subsequent concepts for a FCEB facility. These new concepts identified space on-site that could be reallocated that would minimize disruptions to AAATA operations and parking, nonetheless, because of the constrained nature of the facility, some amount of change would be necessary, regardless of the approach. The goal here is to minimize changes or disruptions.

A site preferred concept, shown in Figure 60, was developed to accomplish the following:

- Consolidate the hydrogen storage equipment into a single yard. All spacing regulations are followed, and to maximize space, a vertical hydrogen storage tank is proposed, as well as a required CMU wall and enclosure.

- Locating the equipment as close as possible to the fueling islands to minimize the distance from the storage to the dispensing equipment to minimizing piping costs.

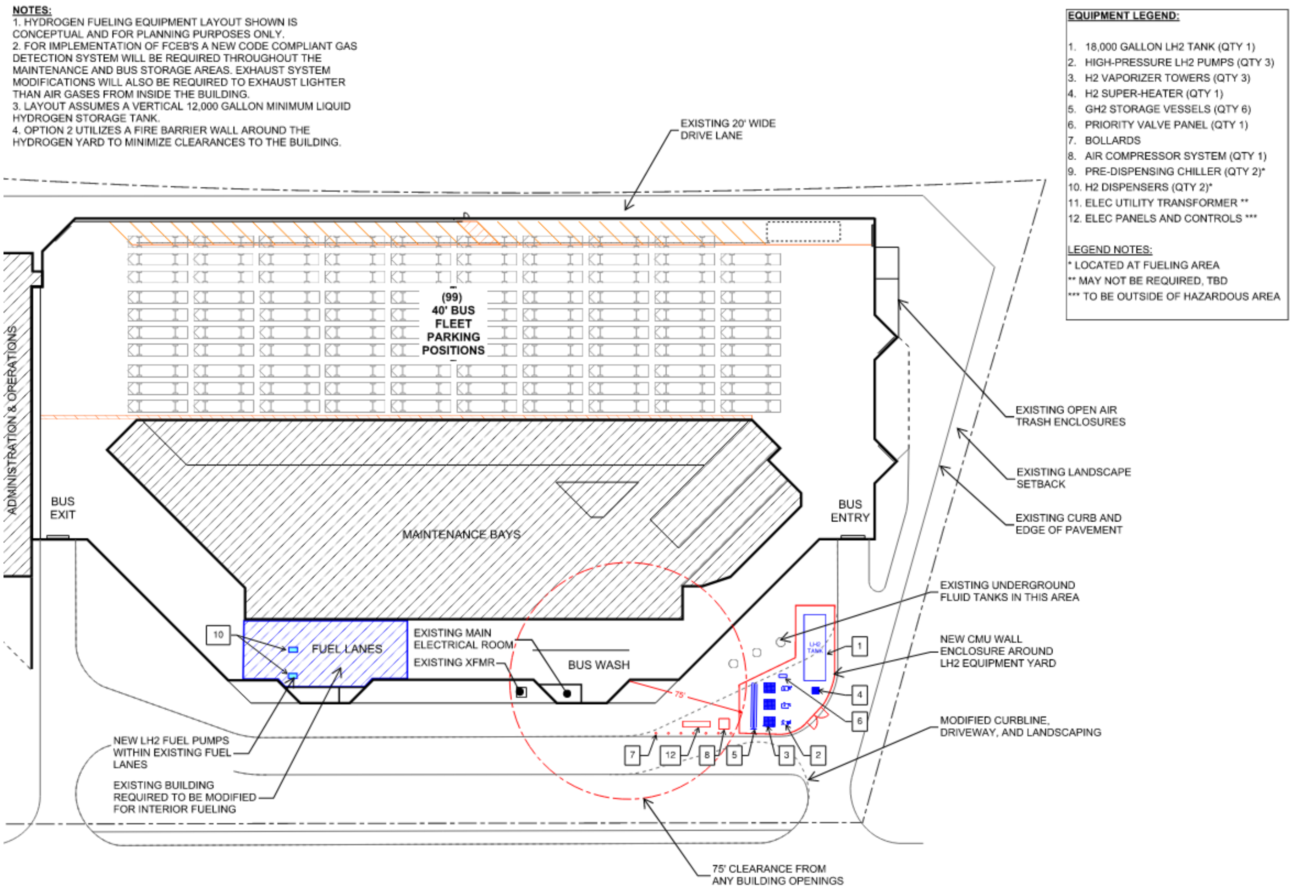


Figure 60: Preferred FCEB site concept

Because of the constrained space of the facility, highly unlikely for AAATA to ever produce hydrogen on-site due to the space requirements of the equipment required. As such, under an FCEB scenario, AAATA would be limited to on-site storage only and require ongoing hydrogen delivery, much as it does now with diesel fuel. This constraint could also limit AAATA's procurement choices for hydrogen to whatever is available in the market, meaning if green hydrogen is not available locally, AAATA's hydrogen source could result in GHG emissions. Alternatively, AAATA could also explore off-site production and delivery.

6.8.2 Proposed Maintenance Facility Modifications and Fueling Infrastructure

- The system will consist of an outdoor hydrogen plant with one 18,000-gallon liquid hydrogen (LH2) storage tank (Chart), three 75 HP duplex LH2 pumps (CS&P or ACD), three vaporizer towers, six high pressure gas storage vessels, one 'super-heater' heat exchanger, one valve panel, a triplex motor starter panel, and one master control panel with PLC. In addition to the above-mentioned equipment that will be in the hydrogen plant at the property yard, two dispensers will be needed in the same fuel lane area where current diesel buses refuel.

- For the hydrogen plant, in order to maintain appropriate clearances while allowing for delivery of liquid hydrogen, modifications to the internal bypass lane would be required to create space for the new hydrogen plant. These modifications would include changes to the curb and gutter, driveway pavement, and landscaping.
- The hydrogen plant would also be partially surrounded by a fire-barrier perimeter wall and partially by chain-link fence to enclose the equipment. This area would be accessed by a large vehicle gate on the driveway side. Equipment not required to be within the fire barrier would be protected by bollards as needed.
- Indoor fuel dispensing of hydrogen for buses requires modification to the building per requirements of NFPA 2. These requirements include gas-detection system in the building (generally one sensor per service bay with master controller), adequate mechanical ventilation with intake at ceiling, heating systems will need to be retrofitted to be non-flame type. Further detail of each requirement from the NFPA 2 are listed below:
    - A hydrogen detection system needs to be installed in the building where hydrogen buses are refueled and when buses are stored/parked indoors. The detection system shall be equipped with audible and visible alarms to announce any event of detected hydrogen at 25% and more of lower flammable limit of hydrogen and should include a connection to the building's IP-data network.
    - Mechanical ventilation is required to be provided in indoor gaseous hydrogen fueling area and maintenance bays. The ventilation rate at normal condition shall be minimum of 1 cubic foot per meter (CFM) per square foot of floor area. In case of gas leak event the ventilation is required to be no less than five air-change an hour. Air-intake of the ventilation system needs to be at the highest point of ceiling. Ventilation discharge point that may convey hydrogen mixture shall terminate at an outdoor location at minimum of 30' from property line, 10' from opening of any building, 6' from exterior walls and roofs. For AAATA, it can be assumed that the existing exhaust system through the entire facility (bus maintenance, parking, and fueling areas) is not adequate to support hydrogen buses. The existing exhaust systems will either require significant modifications or will need to be completely replaced given the age of the facility.
- As a result of the modifications to the HVAC systems, structural modifications for additional framing and/or reinforcement will likely be required for the added or upsized rooftop mounted ventilation and heat recovery equipment.
- The addition of new refueling and ventilation equipment, or upsizing of the existing equipment, will likely require modifications to the electrical system supporting the building.
- Modifications to electrical infrastructure throughout the building for explosion resistance is also assumed to be required. While not all electrical conduits, raceways, etc. will need to be modified, any potential source of ignition within the classified areas under the ceiling of the impacted spaces will need to be thoroughly inspected and modified accordingly.

6.8.2.1 Phasing of Fueling Infrastructure

Hydrogen refueling equipment needs to be in place prior to the arrival of any FCEBs. While there are maintenance and equipment preservation advantages to phasing equipment like pumps, dispensers, vaporizers and chillers, the economic benefit of delaying installation is minimal. As such, the preferred concept proposes building out a hydrogen yard in single phase.

Phase I:

- New/expanded main electrical room for the facility
- Modifications to the existing building's overhead systems in the bus parking area, including HVAC ductwork, lighting, etc.
- Double doors for compliance with safety codes
- Upgrades to ventilation and extinguishing system
- Upgrades to communication and fire alarms
- Conditioning and upgrades to location of fueling facility
- Installation of all equipment for hydrogen refueling station with exception of any n+ pieces of equipment (e.g., if three pressure pumps are needed, only one will be installed in this phase)
- Active Phasing (modifications needed to start 18-months prior to the arrival of FCEBs):
- High-pressure pumps
- Vaporizers
- Pre-dispensing chiller
- Hydrogen dispenser

Decommissioning Phase:

- Remove diesel refueling island
- Remove tailpipe exhaust system at maintenance bays
- Remove maintenance equipment related to oil changes and other fluids that are no longer needed in the maintenance cycle of FCEBs.

6.8.2.2 Telecom / Low-voltage Infrastructure

- Little to no modifications to the telecom systems are anticipated as a result of the implementation of hydrogen fueling.
- Additional security cameras should be considered for the new hydrogen fuel yard.

6.8.2.3 Fire Protection Considerations

- Areas within 15’ of point of transfer while fueling, is considered as hazardous area Class 1, Division 2, Group B. Therefore, ceiling and walls that are within 15’ from hydrogen dispensers need to have fire resistance rating of two hours or more.

6.8.3 Refueling Cycle

Fueling a FCEB is very similar to fueling a traditional CNG or diesel bus. Attaching a dispenser and fueling for ~8-12 minutes will yield a full tank. The hydrogen nozzle is completely sealed to the bus while refueling due to the high-pressure delivery method (above 350 bars). The operation of the nozzle and the pump are virtually the same but specific training needs to be provided to staff for safety reasons. Overall, the design is for two dispensers in the current fueling lanes to minimize disruptions and thus maintain the current servicing and fueling procedures for AAATA. Based on the design of the hydrogen infrastructure and the forecasted demand for hydrogen, we estimate that a delivery of hydrogen fuel would be required every 2-3 days to replenish the storage tank.

6.8.4 Planning, Scheduling, and Runcutting

FCEBs come closest to matching the current diesel bus range and APTA White Book Guidelines for heavy duty bus ranges (280-360 miles). Impacts on planning, scheduling, and runcutting are less severe when compared to BEBs and as range improvements continue over time, can expected to be minimal in the long-term.

AAATA can launch FCEBs first on routes/blocks with shorter daily distances to get a feel for them in terms of range and handling—placing them on routes that remain relatively close to the facility would be a pragmatic strategy at first. As with BEBs, non-revenue tests should be conducted to understand actual driving range and fuel economy. A good starting point for block mileage limits would be the average ranges estimated from the modeling, 400 miles on a mild, average day, and 246 miles on a cold day. Moreover, because a transition will result in the operations of different technologies, dispatching training and instructions to staff on parking routines will be necessary.

6.8.5 Workforce Considerations

The deployment of a new propulsion technology will require new training regimes for operators and maintenance staff. This section describes some key training considerations as well as the implications of the adoption of FCEBs.

6.8.5.1 Training

FCEB manufacturers include training modules for bus operators and maintenance technicians that are typically included in the purchase price of the vehicle, with additional training modules and programs available for purchase. AAATA needs to work with its staff to understand how best to approach training for FCEBs, and whether in addition to basic training from OEMs, additional training is needed.

The minimum required training recommendations are as follows for operators and maintenance technicians.

- FCEB Operator training (total 56 hours).
    - Operator drive training (four sessions, four hours each).
    - Operator vehicle/system orientation (20 sessions, two hours each).
- FCEB Maintenance technician training (total 128 hours).
    - Hydrogen System – Fuel Cell Engine training (six sessions, eight hours each).
    - Hydrogen System training (four sessions, eight hours each).
    - Hydrogen Detection and Fire Suppression Systems training (six sessions, four hours each).
    - Hydrogen Cooling System Package training (six sessions, four hours each).

Moreover, it is highly recommended that all local fire and emergency response departments be given training as to the layout, componentry, safety devices, and other features of FCEBs. This should reoccur every few years, but the specific frequency can be dependent on agency discretion. In addition, agencywide orientation to familiarize the agency with the new technology should also be conducted prior to the first FCEB deployment.

6.8.5.2 Implications of FCEBs on Workforce

The fact that FCEBs have fewer moving components that can malfunction and require replacement, repairs, and general maintenance suggests that transit agencies would save on maintenance costs because: 1) fewer parts could break and need replacement (capital) and 2) less labor is needed to work on the vehicles (operating). The broader concern is related to a possible reduction in the number of maintenance staff required for an FCEB fleet vs. a traditional diesel fleet.

Nonetheless, while a future 100% fleet of FCEBs may require a smaller complement of maintenance staff, during the transition period, it is highly improbable that a reduction in staff would be needed. First, diesel technicians would be required until the last diesel bus is retired; based on the transition schedules explored in this propulsion study, the earliest timepoint would be 2030, and even that is highly unlikely as it is an aggressive timeframe. Second, most transit agencies already operate a minimal complement of staff, so some of the cost savings from maintenance could materialize through reduced overtime, and the ability to be more proactive with maintenance, reducing more costly repairs down the line. Third, existing staff can be trained on FCEBs to ensure staff retention. As FCEB pilots have demonstrated, the learning curve for maintenance as well as the continuing maturity of the technology means that a robust maintenance program is still needed.

Indeed, in the most recent report on FCEB pilots[101], FCEBs accumulated the most labor hours per mile compared to other bus propulsion technologies. As with any new bus order, agencies need to spend extra time to familiarize technicians on the new systems and maintenance procedures. Manufacturer

[101] https://www.nrel.gov/docs/fy21osti/75583.pdf

technicians handle most warranty repair, but agency staff are also being trained; nonetheless, labor hours include time for two or three technicians, which artificially inflates the cost.

Looking further into the future, it is very challenging to predict staffing levels for FCEBs given that the oldest buses in operation are 10 years old, and are outdated models that are not indicative of current models. As technology matures and becomes more technological sophisticated, technicians will need to be trained not only on machinery, but also on components that require computer and diagnostic skills.

Taken together, while the promise of reduced maintenance costs will likely be borne after a full transition to a fully FCEB fleet, during the transition period, AAATA will require diesel technicians and train existing staff on the new technology. One potential strategy to manage lower workforce needs is through natural attrition tied to AAATA's implementation schedule for transitioning to ZEBs. If that is not possible, deliberate reductions in maintenance staffing may result ahead of the 100% transition date based on the actual needs and experiences of the agency.

6.9 FCEB MODELING

To understand the feasibility of FCEBs for AAATA’s operating conditions, fleet modeling and route simulations were conducted with BetterFleet, a computer modeling tool (similar to Section 5.9). This tool is used to mimic bus operations of AAATA as if they were operated by FCEBs. The outputs of this modeling tool include fuel economy, which helps inform bus operating ranges and the degree of successful electrification with FCEBs.

6.9.1 Modeling Scenario and Key Modeling Assumptions

Table 34 presents the modeled FCEB scenario for AAATA’s assessment. The bus modeled in this scenario is the New Flyer Xcelsior Charge H2 40-ft bus with a 37.5 kg hydrogen tank. This model is readily available in the US. Average and worst-case ambient temperatures were selected as 59°F and 10°F respectively, based on an assessment of weather data in Ann Arbor, which is available in Appendix E Weather Data Assessment for Ambient Temperature Estimation.

Table 34: Modeled FCEB Scenario Summary

Scenario	Description	Bus	Ambient temperatures modeled[102]
Hydrogen fuel cell electric bus	Scenario with standard hydrogen fuel cell electric bus	Standard FCEB – New Flyer Xcelsior Charge H2 - 37.5 kg tank	59°F (average) and 10°F (worst case)

Table 35 presents the key vehicle, battery, charging and failure vehicle assignment cut-off assumptions used in the model for the FCEB scenario. This does not include mechanical failures.

[102] In this discussion of the results, the average and worst-case ambient temperatures are referred to as average day and cold day, respectively.

Table 35: Key FCEB Assumptions in BetterFleet modeling

	Hydrogen Fuel Cell
Make/Model	New Flyer Xcelsior CHARGE H2
Dimensions	W: 102″ H: 11′ 1″ L: 41′ 0″
Vehicle mass	32,250 lbs
Passenger mass	3,748 lbs 20 pass. @ 187 lbs
Total mass	35,997 lbs
Tank capacity	37.5 kg
Motor power	160 kW
Other	
Failed vehicle assignment cut-off	5% tank level
Tire pressure	102 PSI

The following key points and assumptions are noted:

- For the assessment of FCEB pass-fail rate, the cut off for vehicle assignment failure is assumed to be 5% of the tank level.
- For context, the range of a diesel bus is about 400 miles per tank, with a pass rate of 100%.

6.9.2 FCEB – Range Analysis

FCEBs were modeled to understand their capability to meet range requirements of AAATA operations. An example of the results from the modeling of an actual vehicle block is shown in Figure 61 at the two tested temperatures. The graph on the top shows the hydrogen fuel level in the tank (dark purple line) over the course of its assignment on a mild day. Over the course of its 175-mile duty, about 40% of the tank of hydrogen is consumed. Compared to the same block but on a cold day (graph on the bottom), nearly 70% of the tank is consumed, demonstrating the impacts of ambient temperature on operating ranges.

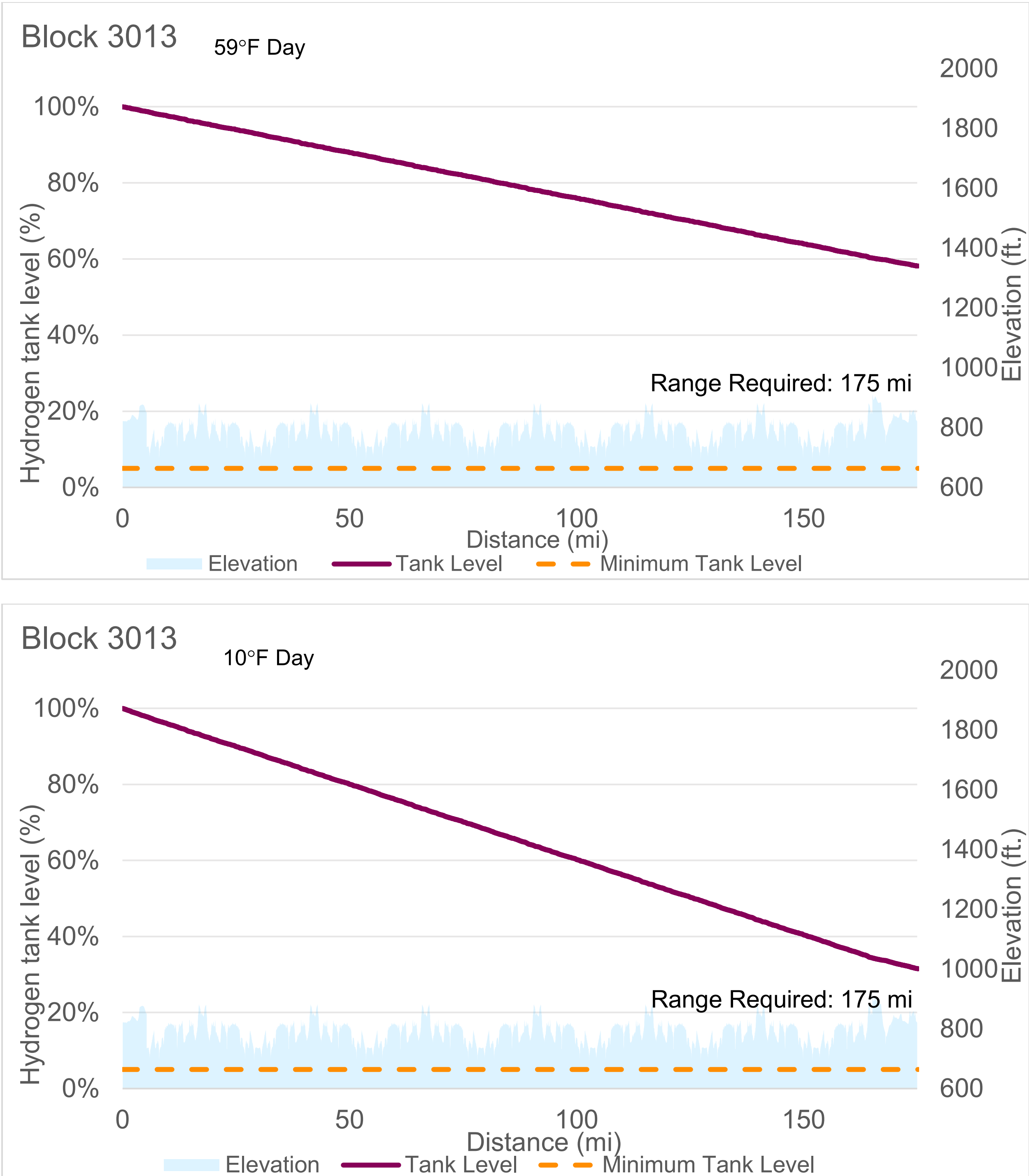


Figure 61: Hydrogen Tank Level as a Function of Distance for a sample bus in AAATA's fleet – FCEB Scenario

Table 36 summarizes the modeling results with FCEBs for the entire of AAATA's current vehicle assignments.

Table 36: Pass Rate Results for Hydrogen Fuel Cell-Electric Bus

Temperature	FCEB	Charging	Pass rate	Pass percentage	Efficiency (mi/kg)
59°F ambient	New Flyer H2 (37.5 kg tank)	6-10 minute refuel	90 / 90	100%	Avg: 10.65 Max: 12.25 Min: 8.90
10°F ambient	New Flyer H2 (37.5 kg tank)	6-10 minute refuel	82 / 90	91%	Avg: 6.58 Max: 7.36 Min: 5.91

FCEBs can meet 100% of the current vehicle assignments on an average day, while in cold conditions (10°F), FCEBs could replace up to 91% of the fleet today. Additionally, the percentage of vehicles that are unable to complete service during extremely cold conditions (10°F) could potentially be quickly refueled during the day with minimal modifications to certain blocks and vehicle assignments.

While FCEBs are a potential solution to range issues, deploying FCEBs must be weighed against the higher capital cost of FCEBs and associated infrastructure requirements. This will be covered in a detailed financial analysis in Section 8.0.

6.9.3 Predicted Hydrogen Demand

Because hydrogen is physically delivered in bulk, stored in tanks, and costs do not change by the hour, detailed time-of-day price modeling is not required. Hydrogen refueling is also much faster than recharging a BEB, and vehicles can be refueled similarly to diesel.

AAATA's operational fleet (i.e., 92 active vehicles) requires 1,200 kg of hydrogen per day on a 59°F day and almost 2,000 kg on a 10°F day (Figure 62). Daily hydrogen demand is important to inform sizing requirements for hydrogen production/storage.

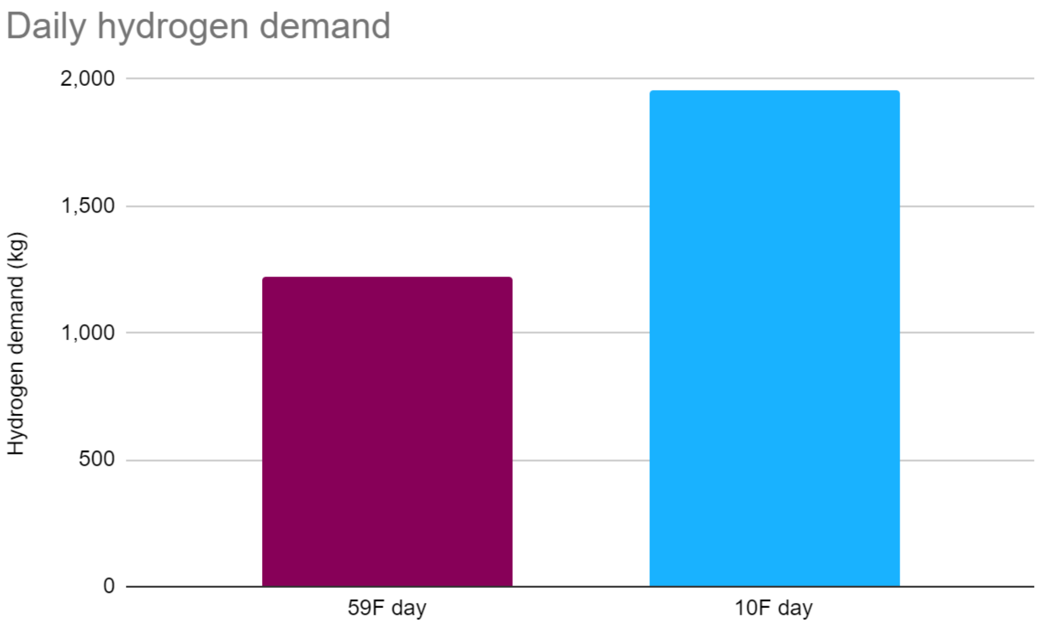


Figure 62: Daily Hydrogen Demand

6.10 PREFERRED FCEB CONCEPT

Based on the analysis and modeling, the preferred FCEB fleet concept will replace diesel buses in a one-to-one manner. FCEBs can complete over 90% of AAATA blocks on cold days and achieve 100% of AAATA blocks on mild days. As such, with a one-to-one replacement, some minor reblocking may be required to achieve 100% of service on cold days.

T A K E A W A Y S

- FCEB operating ranges and fueling practices are similar to diesel buses, making this technology attractive for one-to-one switches between ZEB and fossil fuel buses.
- The capital cost of buses and hydrogen refueling stations is higher than both BEBs and diesel buses.
- FCEBs have longer operating ranges compared do BEBs and more reliable performance in extreme cold weather.
- FCEBs can complete over 90% of AAATA blocks on cold days and 100% of blocks on mild days.
- Because AAATA's facility has limited space, AAATA will be limited to on-site hydrogen storage and require ongoing hydrogen delivery. Alternatively, AAATA could explore off-site production.

7.0 EMISSION ELIMINATION TIMELINES: OPTIONS AND IMPLICATIONS

This section presents the results of modeled emissions reduction. Figure 63 provides a comparison of forecast emissions under four scenarios:

- Diesel (including hybrids)
- BEB
- FCEB using 100% electrolysis
- FCEB using 100% steam methane reformation (SMR)

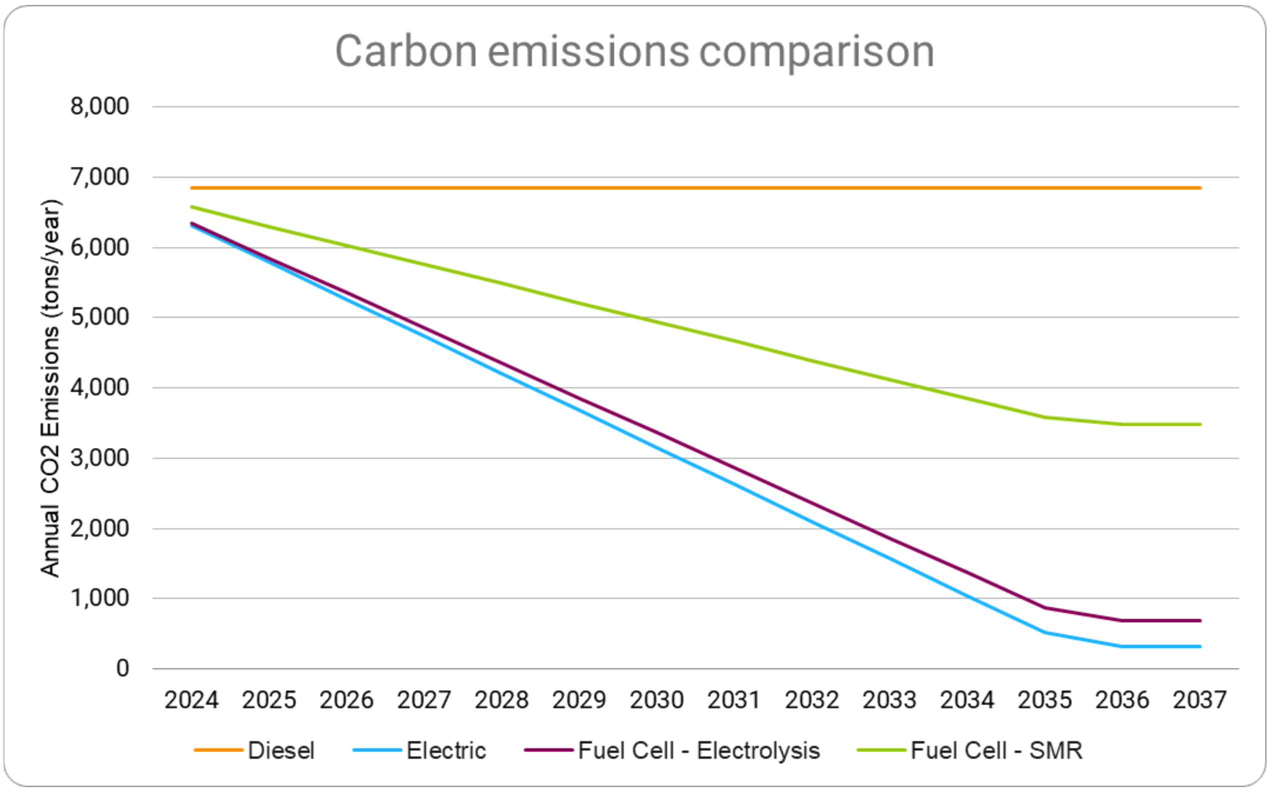


Figure 63: Carbon Emissions Comparison Across Propulsion Type

The modeling found that diesels would produce the most emissions, followed by FCEBs and BEBs. No technology alternative could reach zero emissions by 2036 because of emissions created in the production of electricity or hydrogen. Results are driven by the timeline for implementation of ZEBs and the upstream emissions created by producing electricity or hydrogen fuel. If ZEBs were introduced based on the current fleet replacement schedule—eight buses per year—the fleet could theoretically be converted within twelve years (costs aside), assuming all enablers of such a transition are in place.

Based on AAATA's current diesel operations, we estimated that **AAATA emits nearly 7,000 tons of CO_2 per year from tailpipe emissions.** Hybrids were classified as regular diesel buses. Given historical improvements in diesel technology, it is not unreasonable to assume that future improvements may allow improvements not illustrated here.

BEBs were assumed to be charged using green power to maximize their environmental benefit. Currently the Michigan grid currently has 15% renewable generation in its mix. The balance of 85% can be purchased for an additional 1.9¢/kWh[103], which has been included in the financial analysis.

For FCEBs, the production of hydrogen was modeled for electrolysis using green power and SMR that relies on natural gas. Because emissions will still be created during hydrogen production, total emissions are not expected to reach zero until after 2036.

Apart from upstream GHG emission sources, there may be some minor GHG emissions from ZEBs depending primarily on the source of heat generation. Indeed, several transit agencies operating in cold climates, including the TTC in Toronto and the bus agency in Montreal, are deploying BEBs equipped with diesel-fired heaters to heat the passenger cabin without drawing energy from the battery. While diesel-fired heaters are likely to remain commonplace for the near-term, manufacturers are exploring heat pump technologies as an alternative to diesel-fired heaters. For all assumptions used in the emissions calculations, please refer to Appendix B Financial and Emissions Modeling Inputs.

As seen in Figure 64 below, over the 12-year transition period 2024-2036, if diesel buses continued to be replaced with diesel equivalents, the total cumulative carbon emissions would be over 82,000 tons (Figure 64). If the fleet was replaced with BEBs, then the emissions over that same period would total 41,000 tons, 43,000 tons for FCEB using electrolysis and 61,000 tons for FCEB using SMR. Emissions never reach zero over this timeframe due to emissions created by producing the electricity or hydrogen fuel, as well as the continued operation of diesel buses during the transition. However, production of electricity or hydrogen could become truly zero-emissions sometime after 2036 and an entirely 100% BEB or FCEB fleet will result in additional GHG reductions.

[103] For wind power—https://newlook.dteenergy.com/wps/wcm/connect/dte-web/quicklinks/migreenpower. DTE's MIGreenPower continues to evolve in terms of rate structure so some of the information here may be dated when published.

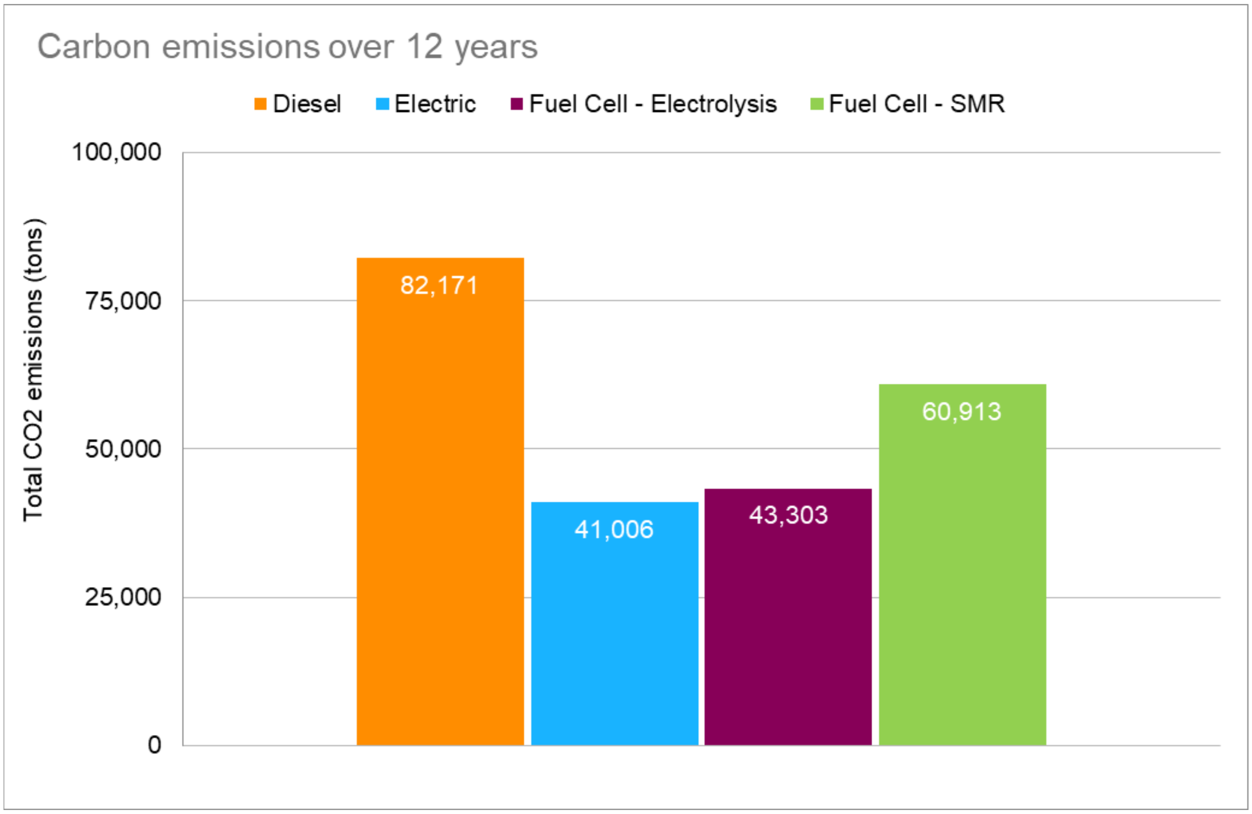


Figure 64: Total Carbon Emissions over 12 Years

Adopting ZEBs could reduce AAATA's fleet-based carbon footprint by between 27% and 50% over the 12-year time frame analyzed. If more renewable energy contributes to Michigan's electrical grid, then AAATA's carbon footprint would be further reduced. If fewer people drive and use TheRide instead—regardless of propulsion technology—then GHG emissions can be further reduced as well[104].

It is also important to consider reductions in harmful emissions such as nitrogen oxides (NOx) and particulate matter (PM). NOx emissions are known to cause acid rain[105] while PM particles are fine droplets suspended in air which can cause serious health problems when inhaled as well as being the main contributor of haze in the United States[106]. **AAATA's existing fleet of diesel buses were estimated to emit over 16,000 kg of NOx and 120 kg of PM per year. If transitioned to any ZEB scenario, these emissions can be eliminated.**

[104] One key strategy of the City's A^{2}Zero Climate Action Plan is to reduce miles traveled by personal vehicles by 50%.
[105] https://www.epa.gov/no2-pollution/basic-information-about-no2
[106] https://www.epa.gov/pm-pollution/particulate-matter-pm-basics

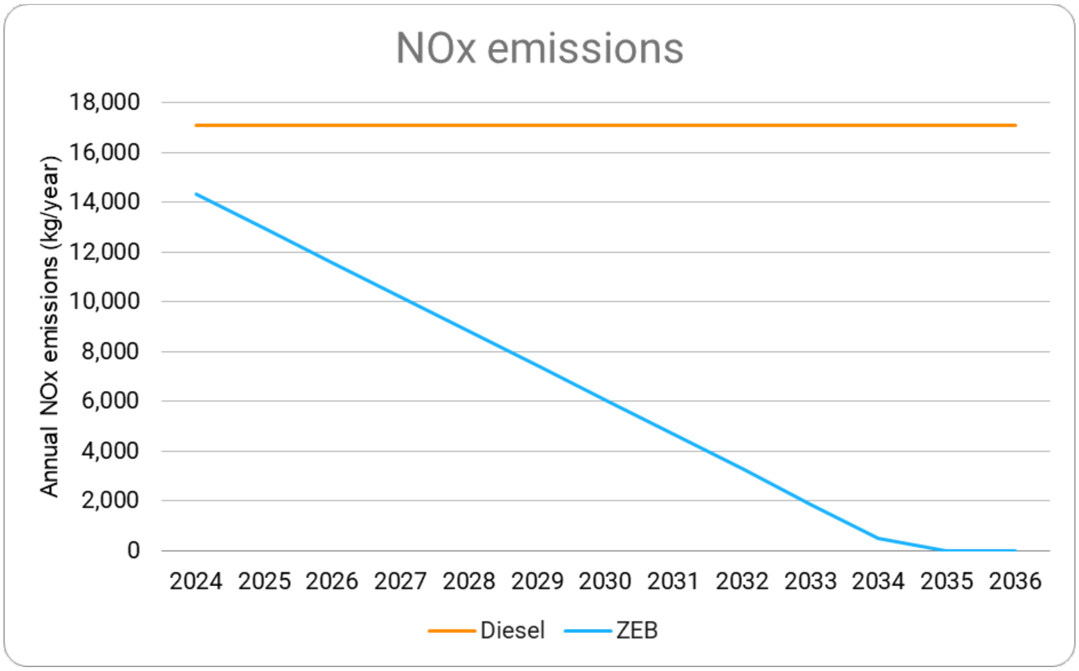


Figure 65: Nitrogen Oxide Emissions Over a 12-Year Period (2022-2036)

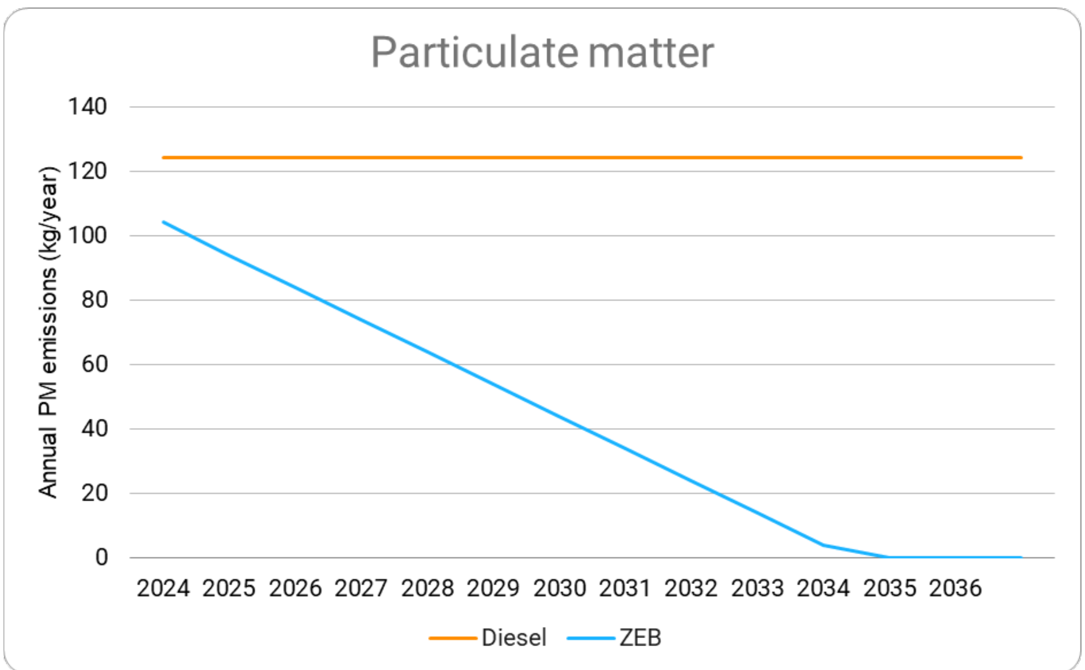


Figure 66: Particulate Matter Emissions Over a 12-Year Period (2022-2036)

While tailpipe emissions are eliminated with ZEBs, the supply chain for either electricity or hydrogen will generate GHG emissions but as the grid becomes cleaner, the “well-to-wheel” carbon footprint will be reduced.

T A K E A W A Y S

- Based on the modeling of emissions reductions, diesels would produce the most emissions, followed by FCEBs, BEBs
- It is estimated that AAATA emits nearly 7,000 tons of CO_2 per year from tailpipe emissions
- Over a 12-year transition period, adopting ZEBs could reduce AAATA's fleet-based carbon footprint between 27% and 50%, and harmful emissions such as nitrogen oxides (NOx) and particulate matter (PM) could be eliminated
- Overall, the adoption of ZEBs would reduce community-wide emissions by less than 0.5%
- Removing 7,000 tons of CO_2 annually represents a potential social benefit of approximately $371,000 per year

8.0 FINANCIAL ANALYSIS FOR ZEB CONCEPTS

This section describes the financial analysis conducted to evaluate the different ZEB concepts developed in this report. These cost estimates have a certain degree of uncertainty as this was study is an initial exploration of ZEB concepts and relies on rough order of magnitude cost estimates for proposed infrastructure.

8.1 ASSUMPTIONS AND INPUTS

Financial analysis, including an evaluation of operating and capital budget and cost impacts, are critical to ZEB planning for two primary reasons. First, it facilitates the ability to make final tweaks to the ZEB scenarios to ensure they are optimized for costs in addition to operational impacts, delivering maximum value for taxpayer dollars. And second, it provides valuable information for AAATA to facilitate future budgeting activities, grant applications, and more informed decision making. At the same time, it must be appreciated that the financial analysis will become more accurate in the future as AAATA determines its ZEB implementation strategy and when detailed design is completed. **Therefore, the financial analysis discussed in this report should be used only for the purposes of evaluating potential ZEB scenario outcomes relative to each other, with the understanding that they are order of magnitude costs estimates subject to change in the future.**

The financial analyses for ZEB operations build upon the predictive modeling for BEBs and FCEBs. Assumptions and inputs are therefore focused on measures such as capital expenditure amounts for vehicles and infrastructure, as well as operations and maintenance cost rates for ICE and ZEB operation, including indication of bus fuel/energy consumption.

To evaluate the financial implications of the transition to ZEBs, the BEB and FCEB scenarios were compared to the “business as usual” scenario of continued ICE bus operation.

Critical assumptions and inputs that have a significant impact on the financial analysis are summarized in the bullets below.

- **Inflation and escalation factors**. Inflation and escalation factors were excluded from the modeling. This is because they tend to apply equally to all costs so there is no relative impact to the modeled scenarios. Further, the presentation of financial impacts in 2022 dollars is more relatable and easier to understand. The financial model only looks at cost curves, i.e., forecasted change in unit costs over time, that are relative to each technology, for example technology improvements in batteries or diesel price variability over time. These have been included in Appendix B Financial and Emissions Modeling Inputs.

- **Bus replacement schedule**. The year-over-year bus replacement schedule is a significant driver of the financial analysis as it impacts the timing of when capital costs are incurred and when operational cost impacts are recognized. Two different procurement strategies were analyzed—procurement-based ZEB transition and accelerated ZEB transition. The lifespan of BEBs and FCEBs is assumed to be consistent with the lifespan of diesel buses, at 12 years as required by the FTA for funding recipients, and therefore only one battery replacement was modeled for each

ZEB. While this is a notable risk, given that we do not yet know how ZEBs will perform as they reach the end of their lifecycle, we can be reasonably confident that a lifespan of 12 years is achievable due to the lesser ongoing maintenance requirements. It is important to clarify also that the bus replacement schedule assumes a 1-for-1 replacement of diesel buses for ZEBs; however, depending on how technologies evolve into the future, it may be necessary to plan for some fleet growth to accommodate ZEB implementation across the blocks that ‘fail’ due to range limitations.

- **Fleet cost**. Capital costs for diesel bus acquisition and overhaul were provided by AAATA. Capital costs for ZEBs were provided by Proterra and are assumed to be $910,000 per long-range (675 kWh battery) BEB and $1,014,000 per FCEB, compared to $600,000 per diesel bus. All battery and powertrain costs, as well as AAATA specs are considered in these estimates. Costs were anticipated to decrease over time as technology matures in accordance with the cost curves shown in Appendix B Financial and Emissions Modeling Inputs.
- **Infrastructure cost**. AAATA’s facility will require upgrades to accommodate the ZEB transition, most notably charging/fueling infrastructure. Different upgrades will be required for each of the BEB and FCEB scenarios. Upgrades will be phased in alongside the fleet transition, ensuring that there is always the infrastructure in place to support ZEB operations, but also not front-end-loading the infrastructure upgrades (and related costs) unnecessarily. The preferred site concepts for BEBs and FCEBs were the basis of design for the rough-order-of-magnitude opinion of probable cost that is presented in Appendix H Independent Cost Estimates. The opinion of probable cost was conducted by a licensed cost estimator.
- **Fuel and electricity cost**. Diesel fuel cost assumptions were driven by a unit price of $5.00/gal (as per EIA) and an average fuel efficiency at 5.74 mpg (as per AAATA), combined with our analysis of vehicle mileage summarized in Section 4.4. Electricity and hydrogen fuel cost assumptions have been determined through reviewing sources such as the EPA and EIA, as well as from proxy data from agencies such as SARTA (Ohio), plus professional judgment to ensure cost estimates are slightly conservative (on the higher end) rather than optimistic (which could lead to an underestimation of unit costs). Cost curves are applied to model how the fuel (diesel and hydrogen) and electricity costs could be expected to change into the future. While these costs are less significant in absolute terms than other costs such as operator wages, they are significant when comparing the BEB and FCEB scenarios to the business-as-usual with ICE buses. As the key objective of this transition is to reduce carbon emissions, electricity and hydrogen prices are for green options which come at a cost premium.

Other assumptions considered in the modeling include the following. A full list of assumptions and inputs has been included in Appendix B Financial and Emissions Modeling Inputs.

- **Vehicle Maintenance**. Vehicle maintenance costs are assumed on a per-mile basis with current year costs modeled at $1.18/mile for diesel propulsion (as per AAATA), $0.64/mile for BEB propulsion (as per the NREL), and $1.30/mile for hydrogen propulsion (an assumed 10% premium on diesel). Notably, maintenance costs for the different propulsion technologies are subject to cost curves, which results in less maintenance costs for hydrogen compared to diesel over the 25-year horizon, as the expected cost of maintenance for hydrogen is expected to decline as the technology matures.

- **Battery replacements**. Batteries were modeled at $455/kWh (2022) as per Proterra pricing. Batteries for BEB were assumed to be replaced every 6 years, based on the manufacturer's standard warranty period. The sensitivity analysis then explored what impact +/- 2 years to the battery life would do to the financials. Battery replacements for FCEB were not costed as manufacturers describe their life to be ~25 years since the full battery capacity is rarely utilized. Battery residual values were assumed to be $72/kWh (2022) as per Relectrify, recognized at the time of battery replacement. Battery cost curves have been included in Appendix B Financial and Emissions Modeling Inputs.
- **Maintenance of charging/refueling equipment**. Equipment maintenance was considered in the financial modeling as $23,000 for existing diesel refueling equipment and 0.5%, and 1% of the installed equipment costs for BEB and FCEB equipment, respectively, as per industry averages.
- **Vehicle disposal**. Residual values for vehicles were assumed to be $3,300 per bus, recognized at the time of the vehicle's retirement. This was the case for each of diesel buses, BEBs, and FCEBs. Note that battery disposal was treated separately, as described above.
- **Grid connection upgrades**. No grid upgrade costs were considered in this analysis—only the costs behind the meter were considered. Section 4.1.5.1 contains details on the facility upgrades that were considered.

8.2 FINANCIAL MODELING SCENARIOS

Four different scenarios were financially modeled for the ZEB transitioning at AAATA. These scenarios included the following:

1. Transition to BEBs, procurement-based approach (8 buses per year, 13 years)
2. Transition to BEBs, accelerated approach (14 buses per year, 7 years)
3. Transition to FCEBs, procurement-based approach (8 buses per year, 13 years)
4. Transition to FCEBs, accelerated approach (14 buses per year, 7 years)

A "procurement-based approach" – applied to scenarios 1 and 3 – involves the annual replacement of 8 diesel buses from 2024 through 2035, with 3 remaining buses replaced in 2036. This is in line with AAATA's current procurement practices of replacing an average of 8 buses per year. Essentially, the procurement-based approach maximizes the value of AAATA's existing fleet assets, and ZEBs are modeled to replace diesel buses only once the diesel buses have reached the end of their useful life. By comparison, an "accelerated approach" (scenarios 2 and 4), with the aim of converting AAATA's entire fleet into ZEBs by the year 2030, was also analyzed. In the accelerated approach, 14 diesel buses are assumed to be replaced per year with ZEBs from 2024 through 2029, with the remaining 15 buses replaced in 2030. As noted above, in both the procurement-based approach and the accelerated approach, we assumed that diesel buses can be replaced by ZEBs on a 1-for-1 basis. A limitation of the financial modeling, therefore, is that it does not capture the possible need (and associated costs) to expand the fleet and to introduce additional deadheading to make the vehicle blocks shorter. In future budget recasts related to the ZEB transition, AAATA will need to revisit assumptions as technology emerges and its implementation approach is confirmed.

Scenarios 1 and 2 assume that long-range BEBs (675 kWh battery) will be implemented. Standard-range BEBs (450 kWh battery) were also considered in the predictive modeling, as were other opportunities such as a mix of standard-range and long-range BEBs, and standard-range BEBs upgradable to long-range BEBs. However, a fleet of exclusively long-range BEBs was modeled for the following reasons:

- To simplify the transition
- To keep vehicle blocks optimized and reduce the likelihood of needing to redo the vehicle blocks on account of the BEB transition. An assumption in the modeling is that BEB technologies will continue to improve, and therefore BEB implementation would begin along the blocks that currently pass, while the blocks that don't pass would be prioritized for later-year implementation. If technologies improve as envisioned, there should not be issues implementing BEBs on the blocks that don't pass today (because they will pass by the time BEBs are implemented); however, if technologies do not improve as envisioned, additional implementation and operations costs will be necessary. These additional costs, such as fleet expansion, are not captured in the financial modeling.
- To minimize the amount of capital, operating, and maintenance costs that are associated with on-route charging equipment.

The capital cost impact of long-range BEB is an additional $100,000 required per bus compared to the standard-range BEB alternative. Also of note, scenarios 1 and 2 assume overhead pantograph chargers implemented at the depot. These are more expensive than plug-in chargers but given capacity and other spatial constraints at the depot, assuming overhead pantograph chargers eliminates the need for significant capital expenses with respect to depot expansion.

With respect to scenarios 3 and 4, these scenarios assume an implementation of FCEBs exclusively, with a 100-kWh battery size and a tank capacity of 37.5 kg of hydrogen.

As noted above, the financial modeling was developed by comparing ZEB transition cases to the business-as-usual case of continued diesel bus operation—this is true for all four scenarios that were modeled.

8.3 FINANCIAL MODELING OUTPUTS

This section provides the results of modeling of the costs of transitioning to ZEBs across the four scenarios identified above. Modeling results can provide important insight, but it should be appreciated that the results may not reflect reality if reality pans out differently from expectations. Therefore, decisions should take this uncertainty into account, notwithstanding the efforts made to be conservative in the financial modeling (i.e., not paint an overly rosy picture of the ZEB transition).

A summary of the key takeaways of the financial modeling are illustrated in the bullets below and are discussed in detail in the following pages. The financial modeling focuses on the incremental costs of transitioning to ZEBs relative to the spending we would expect in business-as-usual. That is, how do the cumulative capital, operating, and maintenance costs for each of the four ZEB implementation scenarios compare to that of the scenario where we continue to operate diesel buses, over the 25-year forecast period (2023-2047).

- The procurement-based approach has lower capital requirements than the accelerated approach. While total capital costs across the 25-year forecast period are comparable due to a consistent number of vehicles needing replacement, incremental spending over the years 2023-2029 is estimated at $28.3M for the procurement-based approach and $72.9M for the accelerated approach for BEBs (scenarios 1 and 2 respectively), and at $34.4M for the procurement-based approach and $73.7M for the accelerated approach for FCEBs (scenarios 3 and 4 respectively). These dollar figures represent the amount of depot infrastructure upgrades required plus the cost premium of ZEB acquisition compared to diesel buses.

- Across the 25-year forecast period, FCEB implementation has lower estimated capital requirements than BEB implementation ($52.2M for the procurement-based approach for FCEBs, compared to $75.3M for the procurement-based approach for BEBs). However, capital requirements for FCEBs are significantly more front-end-loaded, with $19.9M of the $52.2M being required in year 1 (2023), compared to $7.7M in year 1 for BEBs.

- On the operating side, O&M savings potential over the 25-year forecast period is higher for BEBs compared to FCEBs. In the procurement-based approach, $101M in operations and maintenance cost savings is forecasted for BEBs over the forecast period, compared to $51M in savings for FCEBs. These cost savings are driven by forecasted lower commodity prices for electricity (and hydrogen) compared to diesel fuel, as well as lesser maintenance costs that are expected. While there is a degree of uncertainty around the extent to which these cost savings will emerge, we can be reasonably confident that the cost savings will be greater in BEB implementation than they will be in FCEB implementation.

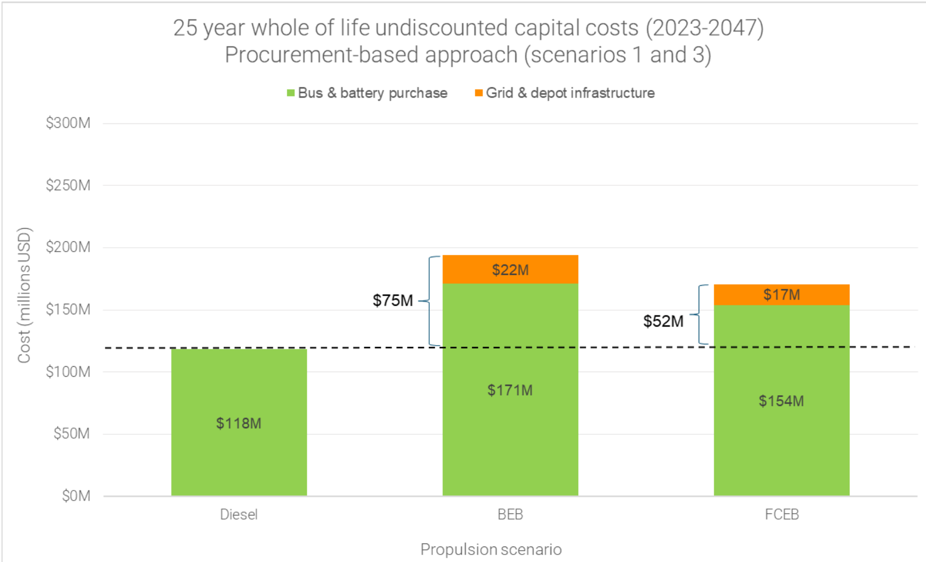
8.3.1 Cost Components

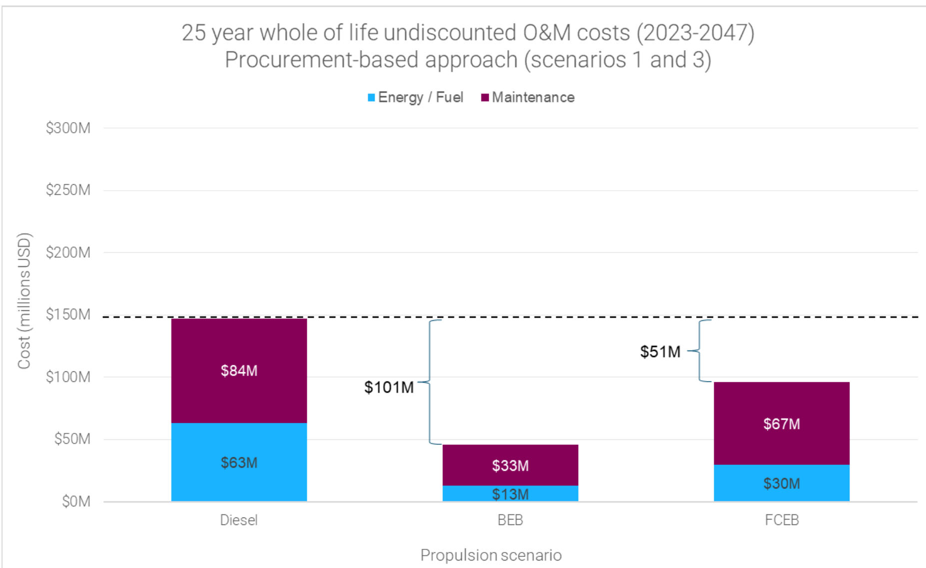
The cost figures presented in this section includes the following vehicle and depot costs.

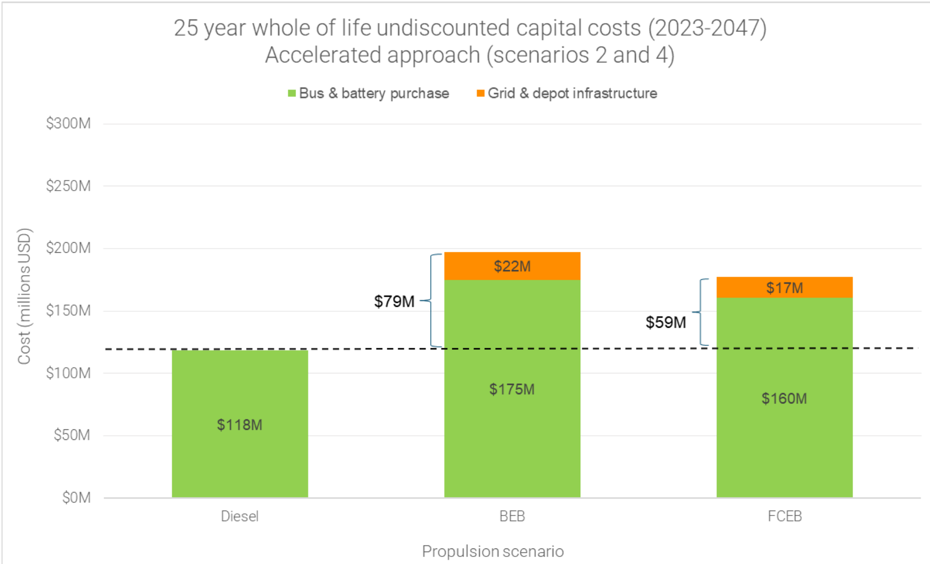
Vehicle Costs:	Depot Costs:
• Vehicle purchase and disposal • Battery purchase and disposal • Maintenance costs (including vehicle overhauls) • Energy/fuel costs • Pantograph connector costs	• Charging equipment costs • Civil and other backbone infrastructure costs • Costs related to electrical connections • Onsite costs for hydrogen refueling include costs for compressors, waste treatment plants, storage tubes, and dispensers • Cost to use spare space to extend parking areas

Excluded are the social costs of air and climate pollution, as well as the cost categories which are not anticipated to be impacted by ZEB transitioning, for example salary and wage costs, and the operating costs of diesel buses present in both the ZEB transitioning scenarios and the business-as-usual.

In comparing the BEB scenarios with the FCEB scenarios, it is important to appreciate that different cost components are involved. Some items are more costly in the FCEB scenarios while others are more costly in the BEB scenarios. Additionally, the timing of expenditures varies between the BEB and FCEB scenarios. The major cost components of each of the four scenarios compared to business as usual are highlighted in Figure 67 below. This figure also illustrates the estimated incremental capital funding requirements of $75M for scenario 1, along with an estimated operations and maintenance cost savings potential of $101M. Importantly, due to different funding sources, the operations and maintenance cost savings is not a true offset of the $75M in capital funding requirements, and it is further reliant on the “best guess” assumptions of technological improvement, which may not come to fruition in actuality. Further, the $101M in estimated operations and maintenance cost savings is more back-end loaded across the 25-year forecast period as it depends on implementation being completed and unit costs becoming more favorable over time, whereas the $75M in estimated incremental capital costs is required to facilitate the transition to BEBs and is therefore more front-end loaded.


25 year whole of life undiscounted capital costs (2023-2047)
Procurement-based approach (scenarios 1 and 3)
Bus & battery purchase
Grid & depot infrastructure
$300M
$250M
$200M
$150M
$100M
$50M
$0M
Cost (millions USD)
$118M
$75M
$22M
$171M
$52M
$17M
$154M
Diesel
BEB
FCEB
Propulsion scenario


25 year whole of life undiscounted O&M costs (2023-2047)
Procurement-based approach (scenarios 1 and 3)
Energy / Fuel
Maintenance
$300M
$250M
$200M
$150M
$100M
$50M
$0M
Cost (millions USD)
$84M
$63M
$101M
$33M
$13M
$51M
$67M
$30M
Diesel
BEB
FCEB
Propulsion scenario



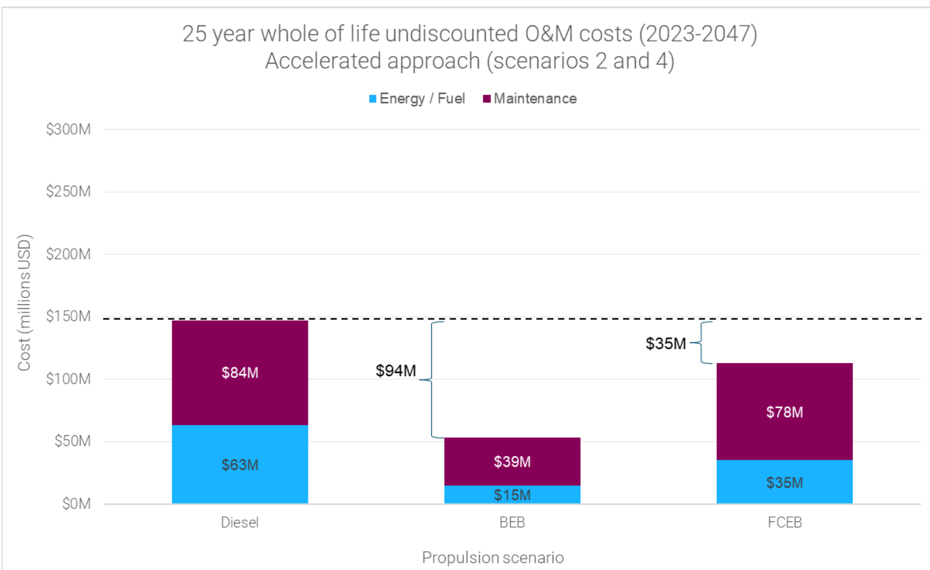


Figure 67: Cost components of the four scenarios

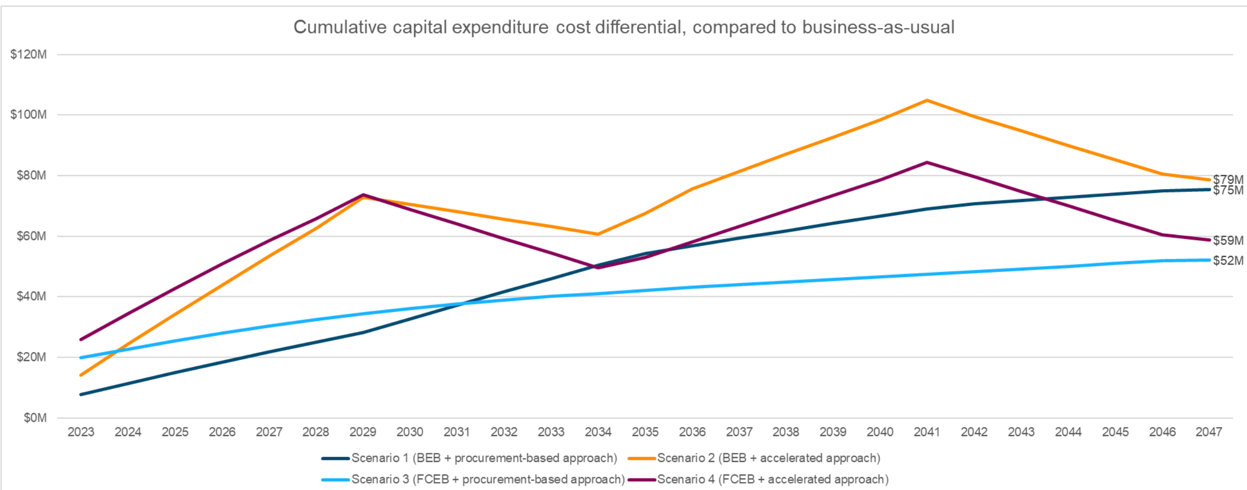
There is a significant difference between the costs of different components across systems within each scenario. Some important observations include the following:

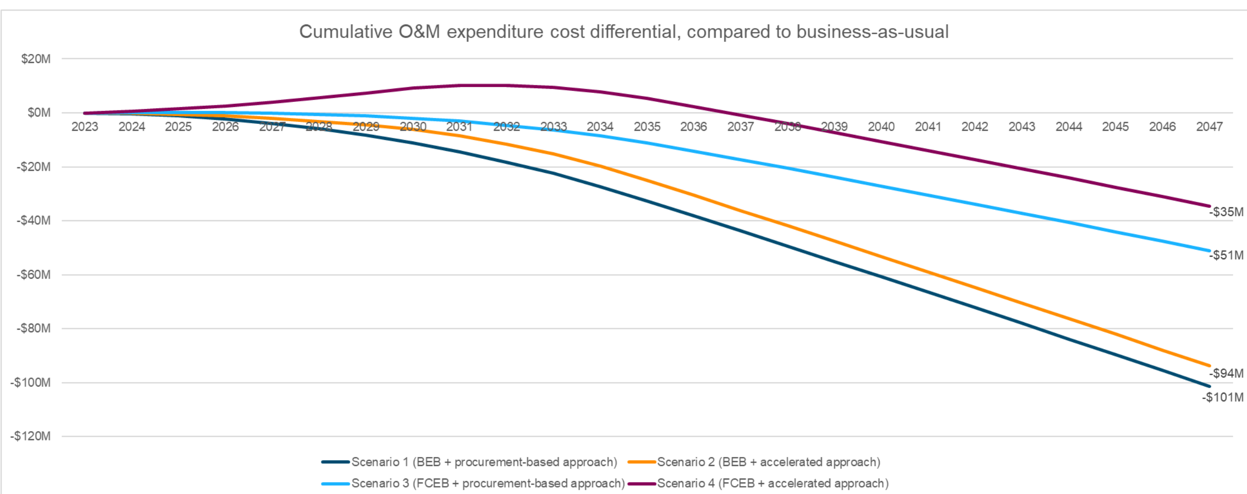
- Vehicle purchases (excluding batteries) are higher for FCEBs compared to BEBs
- The costs of upgrading the depot with pantographs in the BEB scenarios are more significant compared to the cost of FCEB infrastructure
- Although the cost of BEB infrastructure is higher than for FCEB infrastructure across the forecast period, the upfront (year 1) capital requirements for FCEB infrastructure are much higher. The entire $17M of depot infrastructure shown in the graphs above is required in the first year for both

of scenarios 3 and 4. By comparison the year 1 infrastructure requirements for BEB are $5M (scenario 1) or $6M (scenario 2).

- The fuel and maintenance costs for BEBs and FCEBs are both significantly less than that for diesel buses. Bus overhaul costs are also lower for BEBs and FCEBs.
- While fuel and maintenance costs are lower for BEBs compared to FCEBs, battery replacement costs are anticipated to be a significant expense as the batteries are assumed to need to be replaced after 6 years of operating a BEB, as a conservative value based on Proterra standard warranty.

These observations are unpackaged further in the graphs below which summarize the cumulative O&M, capital, and total spending over time compared to the business-as-usual, for each of the four scenarios. Incremental costs compared to business-as-usual are shown as positive dollar values, and cost savings compared to business-as-usual are shown as negative dollar values.





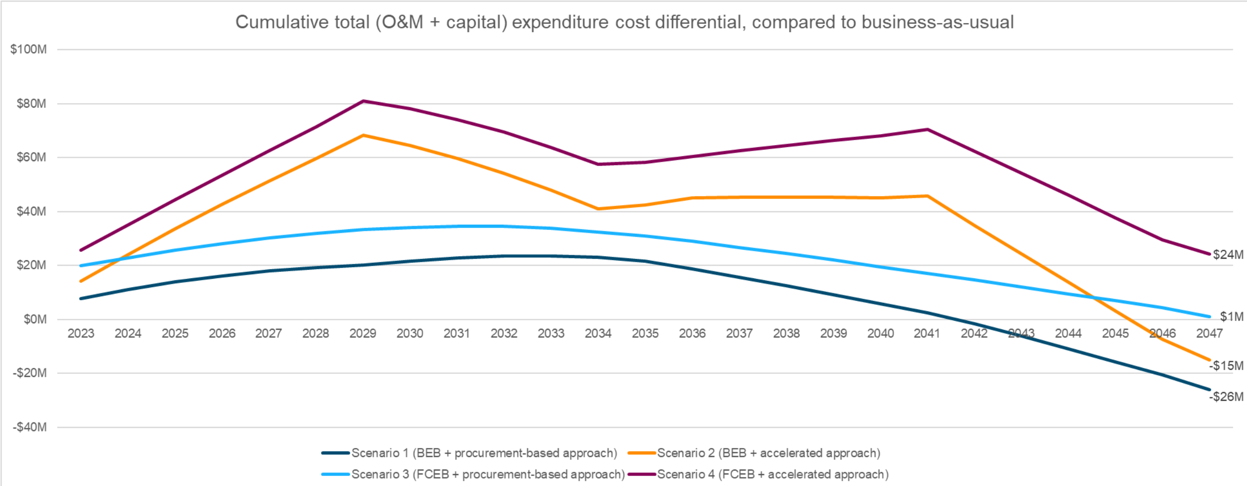


Figure 68: Anticipated changes in cumulative capital, O&M, and total expenditures for each of the four scenarios, compared to the business-as-usual case of continued diesel operation

The graphs above illustrate additional capital funding requirements for ZEBs compared to the business-as-usual, while also illustrating the cost savings that may be realized on the operating side. Scenario 1 represents the biggest opportunity for potential cumulative cost savings over the 25-year horizon ($26M in savings), contingent on technology and price maturation in accordance with the cost curves and other assumptions included in the financial modeling. A sensitivity analysis is included in the following sub-section to discuss the impacts of key assumptions on the total cost of ownership, i.e., the cumulative operating and capital costs over the 25-year forecast period.

To evaluate the scenarios relative to one another, the total cost of ownership (TCO) was evaluated for each of the four scenarios across the 25-year time horizon (2023-2047 inclusive). In doing so, future cash flows have been discounted using a 7% discount rate, consistent with the discount rate used by federal agencies such as the USDOT, and consistent with standard financial modeling practice. What this means is that cash flows in 2023 have been divided by a factor of 1.07 to restate them as a present (2022) value, and cash flows in 2024 have been divided by a factor of 1.07^2, so on and so forth. As a result of the discounting, the early-year cash flows (for example the infrastructure capital expenditures) are weighted more heavily in the analysis than the operating cost savings and other later-year cash flows.

The purpose of this TCO analysis is not to quantify absolute costs, but rather to illustrate the *relative* magnitude of the TCO across the four scenarios. As scenario 1 has the lowest TCO value of the four scenarios, at $115M, this suggests that scenario 1 has the strongest business case and should be explored further by AAATA for next steps after the completion of this study.

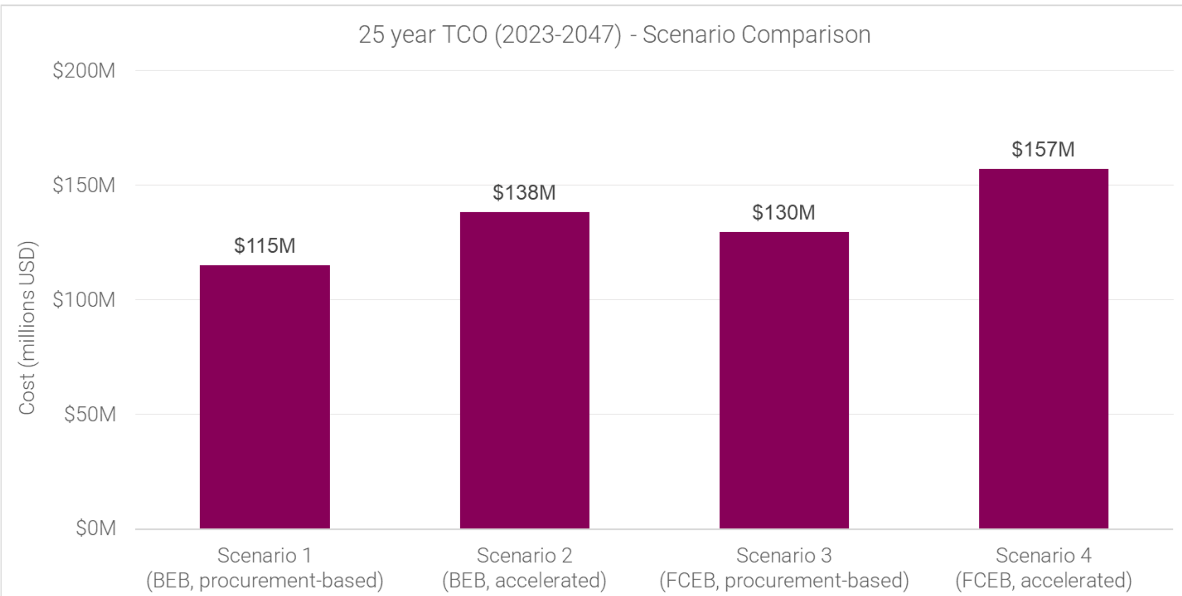


Figure 69: Total Cost of Ownership (TCO) comparison across the four scenarios

As noted earlier in this section, an estimated $75M in incremental capital funding is required over the 25-year horizon to implement scenario 1. Although this is greater in magnitude than the 25-year capital funding requirements estimated for scenarios 3 and 4, the cost savings potential is greater, and the upfront capital requirement in the year 2023 is lower, which contribute to the lower TCO measure for scenario 1.

8.3.2 Sensitivity Analysis

Notably, this financial analysis includes judgments about future prices and asset costs. While the assumptions included in this financial analysis are our best guess at present day, there is inherent risk if prices and asset costs evolve to be greater or lesser in magnitude than envisioned. To ensure the results are robust, a sensitivity analysis was conducted on the TCO. Variability in input parameters has been selected based on technology maturity and market conditions.

The sensitivity analysis shows that changes in capital costs such as bus purchase price and infrastructure upgrades have the biggest impact on TCO. As is shown in the graphs below, if FCEB vehicle costs turn out to be 30% greater or 30% lesser than modeled in this analysis, the 25-year TCO will be either $23M greater or $23M lesser accordingly, for the procurement-based approach. By comparison, if BEB vehicle costs turn out to be 15% greater or 15% lesser than modeled in this analysis, the 25-year TCO will be either $11M greater or $11M lesser accordingly, for the procurement-based approach. The percentage variance is lower for BEBs in the sensitivity analysis because vehicle capital costs does not have the same level of uncertainty that is present in FCEBs.

In general, it is worth noting that BEB options (including consideration of fuel and infrastructure) are less sensitive to price fluctuations than FCEB options. Furthermore, it is important to note that if battery life is 30%, or 2 years shorter or longer than the modeled 6 years, it does not have a material impact on TCO. The following charts show the effect of swings in input parameters on TCO for procurement-based and accelerated approaches.

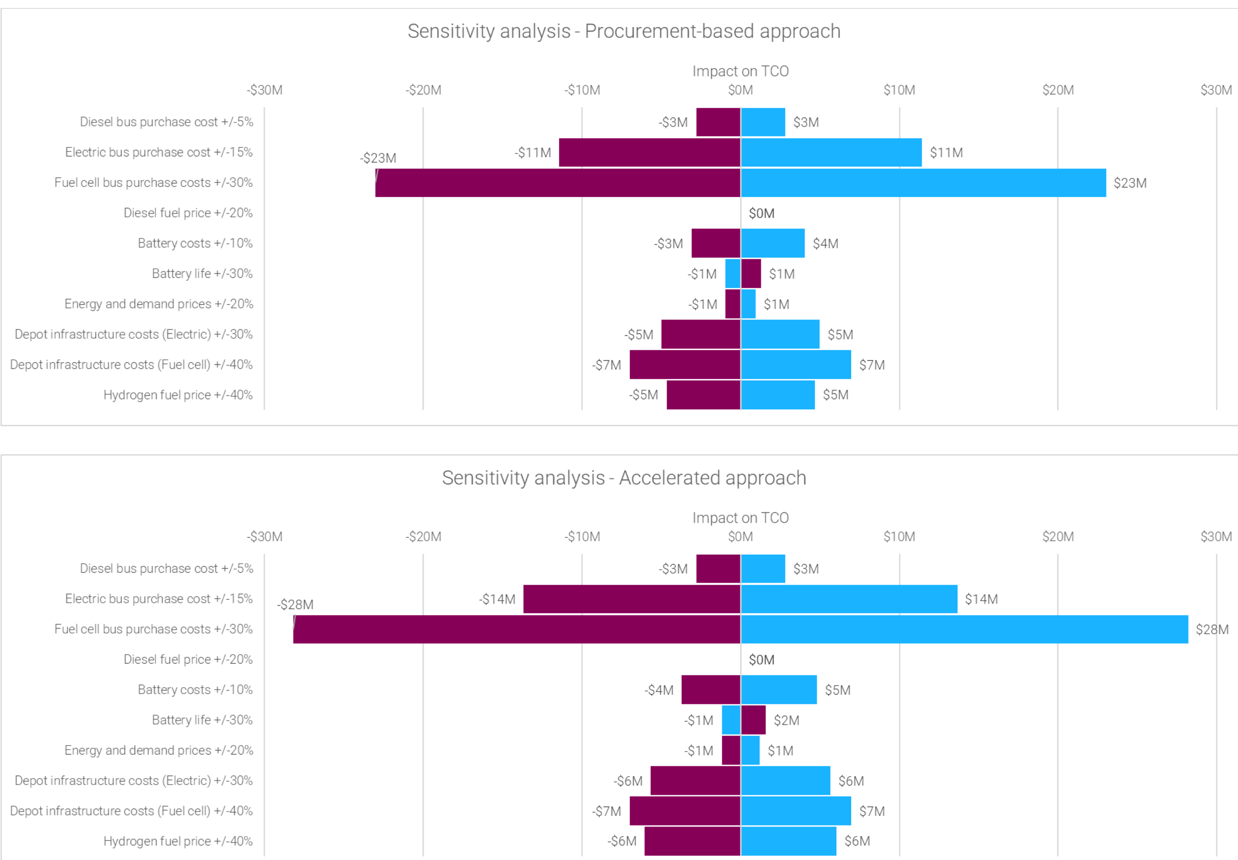


Figure 70: Sensitivity analysis of key variables of uncertainty

Finally, it is important to note that an additional layer of uncertainty is with respect to the quantity of ZEBs that will be required to replace the diesel fleet. Presently, the fleet size of ZEBs is assumed to be equal to the current diesel fleet size, however, additional capital and operating dollars may be required in the event that diesel buses cannot be swapped out for ZEBs 1-for-1, which may be the case if technology doesn't improve at the rate it is envisioned to. This level of analysis was beyond the scope of this study, but will require further investigation prior to AAATA's initiation of a ZEB pilot, and a revision of the costing will be required at this time accordingly.

8.3.3 Capital Funding Requirements

As alluded to above, it is important to appreciate that capital and O&M funding sources are different and that capital requirements for implementing scenario 1 (and the other scenarios) are significant. To aid in implementation planning, the following table breaks down the total incremental capital requirements (i.e. incremental capital funding needs) year-over-year, compared to business-as-usual for each of the four scenarios. This table also illustrates the extent to which the upfront (2023) capital requirements are higher for the FCEB scenarios despite smaller capital requirements over the 25-year horizon.

Table 37: Year-over-year incremental capital funding requirements for implementation

	Scenario 1 (BEB + procurement-based approach)	Scenario 2 (BEB + accelerated approach)	Scenario 3 (FCEB + procurement-based approach)	Scenario 4 (FCEB + accelerated approach)
2023	$7.7M	$14.2M	$19.9M	$25.8M
2024	$3.7M	$10.1M	$2.9M	$8.7M
2025	$3.6M	$9.9M	$2.7M	$8.4M
2026	$3.5M	$9.7M	$2.5M	$8.0M
2027	$3.4M	$9.5M	$2.3M	$7.7M
2028	$3.3M	$9.3M	$2.1M	$7.3M
2029	$3.2M	$10.2M	$1.9M	$7.8M
2030	$4.5M	-$2.4M	$1.7M	-$4.8M
2031	$4.4M	-$2.4M	$1.5M	-$4.8M
2032	$4.4M	-$2.4M	$1.3M	-$4.8M
2033	$4.4M	-$2.4M	$1.1M	-$4.8M
2034	$4.3M	-$2.5M	$0.9M	-$4.8M
2035	$3.9M	$6.7M	$1.2M	$3.3M
2036	$2.5M	$8.2M	$0.9M	$5.1M
2037	$2.5M	$5.7M	$0.9M	$5.1M
2038	$2.5M	$5.7M	$0.9M	$5.1M
2039	$2.4M	$5.7M	$0.9M	$5.1M
2040	$2.4M	$5.6M	$0.9M	$5.1M
2041	$2.4M	$6.4M	$0.9M	$5.8M
2042	$1.6M	-$5.2M	$0.9M	-$4.8M
2043	$1.1M	-$4.8M	$0.9M	-$4.8M
2044	$1.1M	-$4.8M	$0.9M	-$4.8M
2045	$1.1M	-$4.8M	$0.9M	-$4.8M
2046	$1.1M	-$4.8M	$0.9M	-$4.8M
2047	$0.3M	-$1.8M	$0.3M	-$1.8M
TOTAL	**$75.3M**	**$78.7M**	**$52.2M**	**$58.7M**

8.4 SUMMARY

The financial modeling, when completed over a 25-year forecast period, illustrates that scenario 1 (transition to BEBs, procurement-based approach) has the most favorable business case, with a TCO of $115M, compared to $138M, $130M, and $157M for scenarios 2, 3, and 4 respectively. This suggests that a fleet replacement schedule that dovetails with AAATA's current procurement schedule is ideal, and ensures that AAATA's current diesel buses can continue to be utilized for their full 12-year lifecycle. Exploring a faster transition plan, for example full fleet conversion by 2030, or exploring different ZEB technologies such as FCEBs would make for a more complex transition, would necessitate additional costs, and would result in an underutilization of existing assets.

The major cost drivers of a transition to BEBs include the capital cost of infrastructure (approximately $22M of incremental costs) and the capital cost of the vehicles (approximately $310,000 of incremental costs per bus, compared to diesel buses). However, there are significant cost savings opportunities presented on the operating and maintenance side, with a "best guess" estimate at $101M in savings over the 25-year forecast period through the implementation of scenario 1. However, to achieve these cost savings, AAATA will require an additional $75M in capital funding throughout the forecast period, and an initial $7.7M investment in year 1 (2023).

In reviewing the financial modeling outputs, and evaluating next steps, it is important to also consider the limitations of the modeling. While a sensitivity analysis was undertaken to estimate the impact that different capital costs, fuel prices, and other factors would have on the financials, it is not possible to undertake a sensitivity analysis for every single variable. This includes sensitivity on the price curves, as it is difficult to predict whether BEB and FCEB prices will decrease in accordance with the curves illustrated in Appendix B Financial and Emissions Modeling Inputs. This also includes sensitivity on fleet size, which would require an additional level of analysis which was outside of the scope of this study. Additionally, the factors below have not been considered in the modeling and would impact the financial results in a manner that are difficult to foresee, and therefore difficult to consider in a sensitivity analysis:

- Future changes in traffic volumes and road conditions can affect the driving efficiency of the routes.
- Routes and blocks may need to change as a result of future AAATA transit planning activities, which would change the underlying duty cycles and operating procedures.

T A K E A W A Y S

- Four different scenarios were financially modeled, including a procurement-based approach for both BEBs and FCEBs, and an accelerated approach for BEBs and FCEBs.
- Over a 25-year period, the procurement-based transition to BEBs was the most favorable business case, with a total cost of ownership (TCO) of $115M.
- The major costs for a transition to BEBs include the capital cost of vehicles, chargers, and facility modifications. For the procurement-based transition to BEBs scenario, we can expect incremental capital costs of approximately $75.3M.
- The major costs for a transition to FCEBs include the capital cost of vehicles, the construction of a hydrogen fueling yard, and facility modifications.
- When considering next steps, it is important to understand the limitations of modeling as it is not possible to undertake a sensitivity analysis for every variable.

9.0 CONCLUSIONS AND KEY FINDINGS

This chapter summarizes the results of the earlier sections of this report, the analyses conducted, and discusses implications around benefits, readiness, costs, and risks for potential alternative bus propulsion technologies.

9.1 STUDY OVERVIEW

The AAATA Alternative Bus Propulsion Study was conducted to explore ZEB propulsion technologies and assess the benefits and challenges of transitioning from fossil fuel bus fleet to a ZEB fleet.

Public transit agencies across the United States have started to adopt and transition to ZEB fleets to reduce emissions. As of 2021, 1,287 ZEBs have been deployed in the US, roughly 2% of the ~66,000 transit buses nationwide. In Michigan, 15 BEBs and 2 FCEBs are currently in operation.

The increase in transitions to ZEB fleets is driven by several factors, including:

- Regulation for cleaner transportation
- Rapid advancements in bus and battery technologies
- Favorable fiscal incentives
- New funding programs
- Maturing electric vehicle market providing lower costs
- Reduced technological risks.

The two technologies analyzed in detail in this study are hydrogen fuel cell-electric buses (FCEB) and battery-electric buses (BEB). Diesel and diesel hybrid technologies were used for comparison and to create baseline scenarios.

The study comprised of six main components to evaluate the benefits, opportunities, challenges, risks, and costs of adopting different propulsion technologies:

1. Overview of current bus propulsion technologies
2. Assessment of AAATA's current bus operations
3. BEB technology assessment and modeling
4. FCEB technology assessment and modeling
5. BEB and FCEB fleet transition financial analysis
6. BEB and FCEB emission reductions analysis

9.2 BEB AND FCEB GENERAL CONSIDERATIONS

BEBs and FCEBs are considered ZE technologies. Both use electricity to power their traction motors but require different fueling methods. BEBs use batteries to store electricity and typically require numerous charging stations. FCEBs use fuel cells to generate electricity by combining hydrogen and oxygen. They are fueled by filling a storage tank, and typically require only one fueling station.

When comparing BEB and FCEB technologies, there are several tradeoffs that should be considered. First is range. BEBs have a range of around 100-250 miles, and FCEBs have a range of about 200-300 miles; actual driving range depends on a host of factors, including battery size, passenger loads, duty cycles, and temperature. For comparison, the range of operation for fossil fuel buses is about 400 miles. Generally, BEBs are better suited for agencies with short routes and frequent service due to range limitations. FCEBs are more suitable for long routes with frequent service (Figure 71).

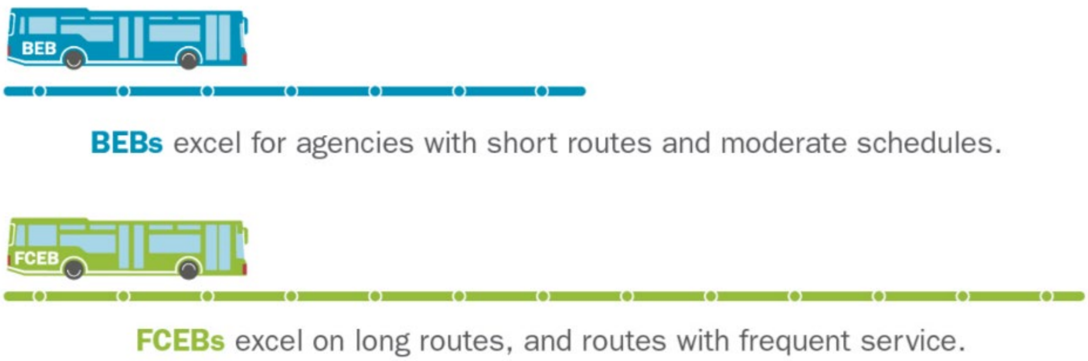


Figure 71: BEB and FCEB range comparison (Source: Ballard)

Relatedly, energy density is a key factor to consider. The energy density of the fuel directly impacts the range of the vehicle. Different types of fuel have different relative energy densities, and some require more storage space and are heavier. Gasoline and diesel require less storage space, are relatively light weight, and have a high energy content per unit volume. Batteries and hydrogen fall lower on these scales, as illustrated in Figure 72 below.

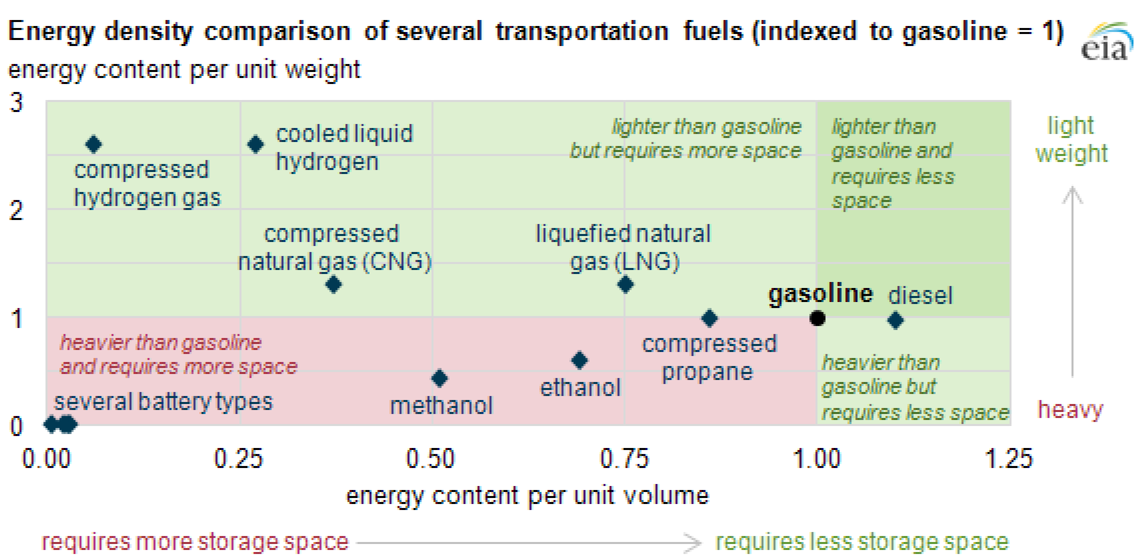


Figure 72: Energy density of transportation fuels. (Source: EIA)

Figure 72 illustrates how much more energy-rich fossil fuels like diesel tend to be by volume. Furthermore, on the graph, diesel fuel sits to the right of batteries as a fuel, meaning that diesel fuel requires less storage space for a greater amount of energy per unit volume. Put another way, batteries need to be very large to carry the same amount of energy as diesel fuel. The implication of this for a transit bus is that battery packs carry significant weight, which may in turn reduce fuel efficiency as well as limit potential route alignments based on weight restrictions for certain roadways like bridges or overpasses. Similarly, compressed hydrogen gas is less energy dense than diesel, but slightly more than batteries. However, because compressed hydrogen gas is much lighter weight than diesel fuel, more of it can be stored onboard a bus without excessively increasing the weight compared to batteries. Overall, the notion of energy density helps explain some of the trade-offs associated with ZEBs and their operating range characteristics.

Depot and fleet size are also important considerations. Because of the charging infrastructure space requirements, BEBs require more space. FCEBs are generally better for depots that are space constrained, as illustrated in Figure 73 below. For AAATA, the current facility is very limited in space and the plans developed in this report are illustrative and attempted to minimize modifications to accommodate alternative propulsion technologies. Regardless of the alternative propulsion selection, mitigating mechanisms will be required to minimize disruptions during construction.

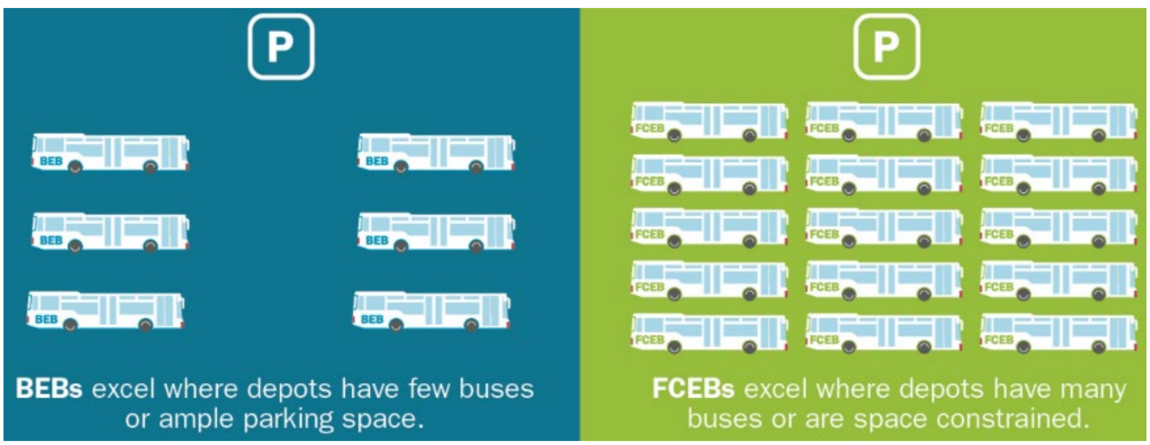


Figure 73: BEB and FCEB depot and fleet size constraints (Source: Ballard)

In addition, reliable and convenient access to fuel helps inform technology feasibility. Discussions with DTE indicate that significant electrical upgrades would be needed at the AAATA facility to enable BEB deployment. Meanwhile, the hydrogen market in the Ann Arbor area is limited, but new developments suggest a potential hydrogen producing plan in Ypsilanti coming online in 2023.

Lastly, scalability is a crucial factor to take into consideration. With a small fleet, a BEB implementation is less expensive and simpler. However, a larger bus fleet will require more chargers and utility upgrades, increasing the price and complexity of the implementation. Conversely, FCEBs can be a more cost-effective option for larger fleets. The larger fixed cost of hydrogen fueling infrastructure becomes cheaper on a per bus basis (Figure 74).

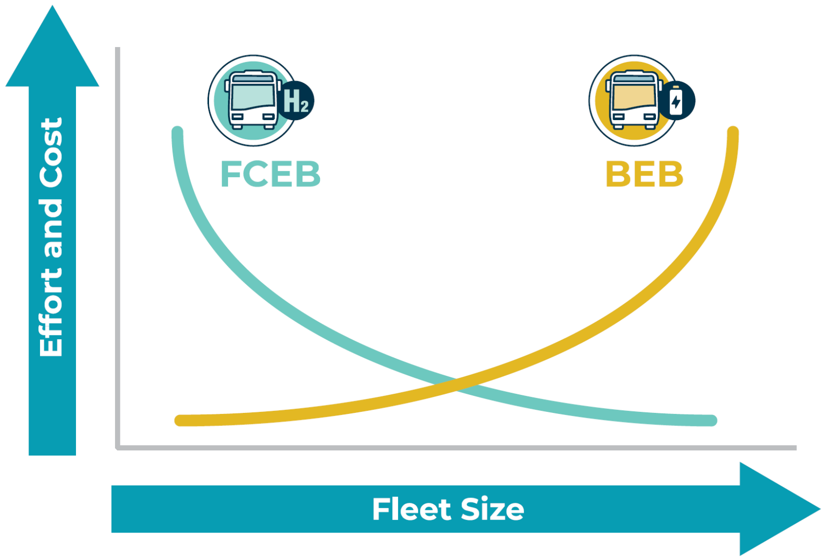


Figure 74: Scalability of FCEBs and BEBs (Source: TCRP, CTE)

9.3 AAATA BEB ASSESSMENT AND MODELING

AAATA and Stantec developed a preferred BEB concept based on workshops and conversations with AAATA staff, service analysis, and route modeling. The preferred concept is a BEB fleet with long-range batteries that will be charged in-depot. BEBs with 675 kWh batteries could successfully deliver 97% of service on mild days (59°F), but only 62% on cold days (10°F). Deploying on-route opportunity chargers at transit centers could elevate that success rate to 87%, but may introduce other operational challenges, as well as capital and operating costs.

The preferred site concept uses an overhead pantograph charging arrangement while clustering charge cabinetry remotely. While pantograph chargers are most expensive than plug-in chargers, the space limitations at AAATA's facility requires an overhead approach to minimize the footprint and maximize space for vehicles. A BEB implementation will require electrical service upgrades because the existing electrical system is not adequate to serve the loads that will result from the full build out of BEB charges.

With a BEB fleet, a portion of service will require restructuring of vehicle assignments that exceed the operating ranges of BEBs. Furthermore, AAATA can explore other options such as considering blocking range limitations for summer and winter weather, procuring BEBs with diesel-fired heaters, or deploying BEBs primarily on blocks within feasible ranges while keeping diesel buses assigned to long range blocks. As battery technology improves, the operational alterations required are likely to shrink in the longer-term. However, additional analysis would be required to map out the scheduling of BEBs for AAATA's future service plans.

9.4 AAATA FCEB ASSESSMENT AND MODELING

The preferred FCEB concept will replace diesel buses one-to-one. Route modeling demonstrated FCEBs can achieve 100% of AAATA blocks on mild days, and 91% of blocks on cold days. Therefore, minor re-blocking will be required to achieve 100% service on very cold days. However, additional analysis would be needed to consider the impacts of FCEB scheduling with regard to AAATA's future service plans.

The preferred site concept requires site alterations to accommodate hydrogen fueling infrastructure. If FCEBs are implemented, major HVAC system upgrades and a new gas detection system will be required. Additionally, building retrofits will be necessary to facilitate indoor hydrogen fueling.

9.5 TRANSITION COSTS

Financial analysis, including a total cost of ownership (TCO) analysis as well as an evaluation of operating and capital budget impacts, is critical to ZEB planning for two primary reasons. First, it facilitates the ability to make final tweaks to the ZEB scenarios to ensure they are optimized for costs in addition to operational impacts, delivering maximum value for taxpayer dollars. Second, it provides valuable information for AAATA to facilitate future budgeting activities, grant applications, and more informed decision making.

Four different scenarios were financially modeled for the ZEB transitioning at AAATA. These scenarios included the following:

1. Transition to BEBs, procurement-based approach (8 buses per year, 13 years to complete)
2. Transition to BEBs, accelerated approach (14 buses per year, 7 years to complete)
3. Transition to FCEBs, procurement-based approach (8 buses per year, 13 years to complete)
4. Transition to FCEBs, accelerated approach (14 buses per year, 7 years to complete)

A "procurement-based approach" – applied to scenarios 1 and 3 – involves the annual replacement of 8 diesel buses from 2024 through 2035, with 3 remaining buses replaced in 2036. This is in line with AAATA's current procurement practices of replacing an average of 8 buses per year. Essentially, the procurement-based approach maximizes the value of AAATA's existing fleet assets, and ZEBs are modeled to replace diesel buses only once the diesel buses have reached the end of their useful life. By comparison, an "accelerated approach" (scenarios 2 and 4), with the aim of converting AAATA's entire fleet into ZEBs by the year 2030 was also analyzed. In the accelerated approach, 14 diesel buses are assumed to be replaced per year with ZEBs from 2024 through 2029, with the remaining 15 buses replaced in 2030.

The financial modeling, when completed over a 25-year forecast period, illustrates that scenario 1 (transition to BEBs, procurement-based approach) has the most favorable business case, with a TCO of $115M, compared to $138M, $130M, and $157M for scenarios 2, 3, and 4 respectively. This suggests that a ZEB replacement schedule that dovetails with AAATA's current procurement schedule is ideal, and ensures that AAATA's current diesel buses can continue to be utilized for their full 12-year lifecycle.

Exploring a faster transition plan, for example full fleet conversion by 2030, or exploring different ZEB technologies such as FCEBs would make for a more complex transition, would necessitate additional costs, and would result in an underutilization of existing assets.

The major cost drivers of a transition to BEBs include the capital cost of infrastructure (approximately $22M of incremental costs) and the capital cost of the vehicles (approximately $310,000 of incremental costs per bus, compared to diesel buses). However, there could be cost saving opportunities on the operating and maintenance side, with a "best guess" estimate at $101M in savings over the 25-year forecast period through the implementation of scenario 1. However, to achieve these cost savings, AAATA will require an additional $75M in capital funding throughout the forecast period, and an initial $7.7M investment in year 1 (2023). It is important to also appreciate that capital requirements may end up being larger than $75M in the event the transition to BEBs necessitates additional vehicle purchases, or in the event that unit costs do not decrease over time to the extent envisioned.

9.6 KEY CONSIDERATIONS

9.6.1 Benefits and Opportunities

Despite the considerable increase in costs associated with the adoption of and transition to a BEB or FCEB fleet, there are several benefits to adopting a ZEB fleet.

Greenhouse Gas (GHG) Emissions Reduction

The chief benefit of transitioning to a ZEB fleet is the reduction of the region's GHG emissions. Four scenarios were modeled over 12 years to understand how ZEB technologies will impact emissions. Based on the agency's current diesel operations, the modeling estimated that AAATA emits approximately 7,000 tons of CO_2 annually, slightly lower than the GHG emissions estimated by the A^2ZERO Plan.

While BEBs and FCEBs are zero-emissions at the tailpipe, the electrical grid in Michigan isn't 100% green (although 100% renewable energy from DTE is available for a cost premium), and hydrogen sources vary in their carbon neutrality. Nonetheless, by assuming that AAATA would purchase green energy from DTE and green hydrogen produced through electrolysis, over a 12-year period of ZEB replacement, a BEB transition would result in 41,000 tons of GHGs, 43,000 tons for FCEBs using electrolysis and 61,000 tons for FCEBs using steam methane reforming methods of hydrogen production. Emissions never reach zero in this timeframe due to emissions created by the continued operation of diesel buses during the transition to ZEBs. However, a fleet of entirely ZEBs together with green electricity or green hydrogen would virtually eliminate the carbon footprint of AAATA's fleet.

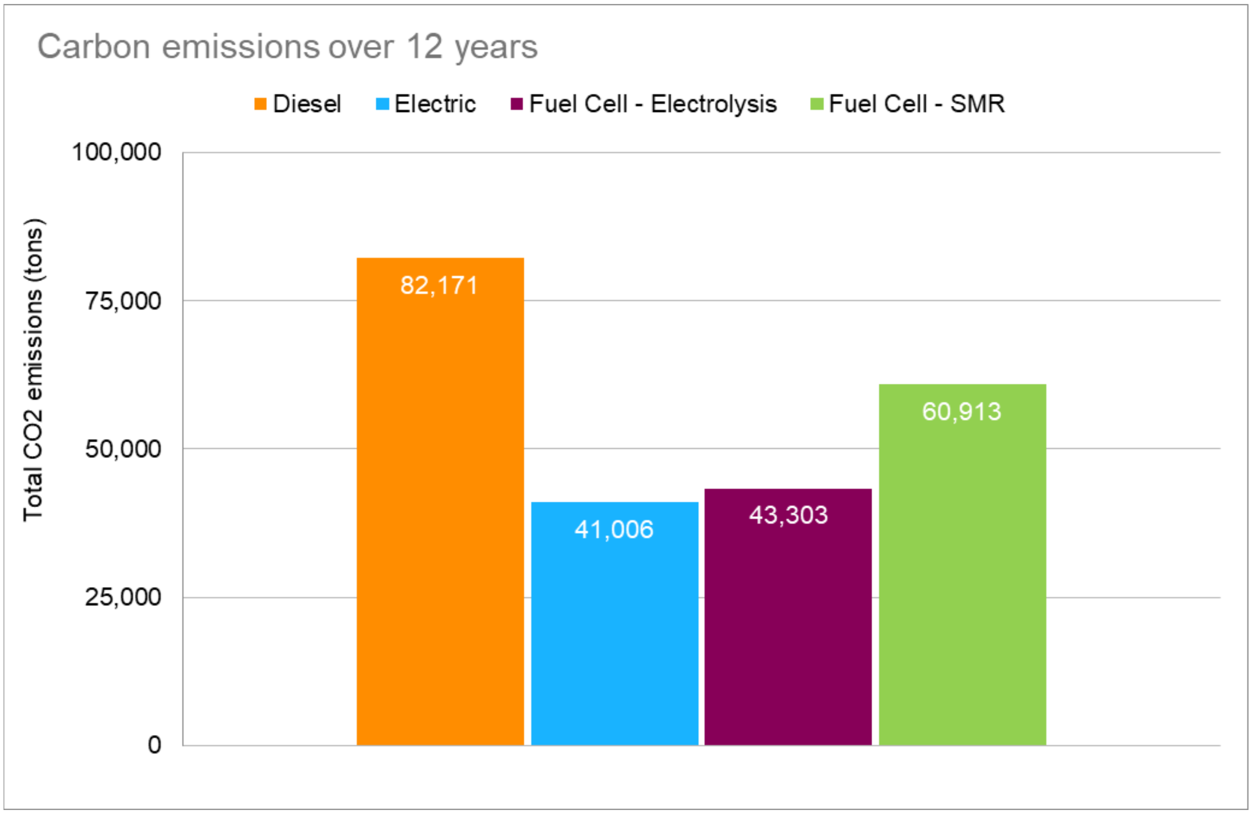


Figure 75: Total Carbon Emissions over 12 Years

Overall, adopting **ZEBs can reduce AAATA's fleet-based carbon footprint by 27-50% over a 12-year transition timeframe, which translates to a community-wide emissions reduction of less than 0.5%.** This aligns with the fact that the mileage AAATA's buses travel is also less than 1% of all vehicle miles traveled in the region. SEMCOG estimates that in 2019, there were 3.95 billion total vehicle miles driven in Washtenaw County. AAATA's fixed-route buses traveled slightly more than 4 million miles that same year (0.1% of all vehicle miles traveled). Even if only half the total miles can be attributed to the Ann Arbor/Ypsilanti area, AAATA bus mileage would only be 0.2% of the total. Also in 2019, there were 173,441 vehicles registered in the cities of Ann Arbor and Ypsilanti, while AAATA had 103 buses (0.06%).

While AAATA is a small emitter, more localized benefits of ZEB conversion can help improve air quality where buses operate, particularly in communities with existing air quality issues, as well as at bus stops and at transit centers where buses generally idle while serving passengers. For example, diesel buses have been estimated to release between 2,700-3,500 grams of $CO2_e$ per mile along a corridor (depending on operating conditions like traffic, frequency, dwell times), and up to 300 grams of $CO2_e$ while at a bus stop[107]. And importantly, interior cabin air in ZEBs will also be cleaner and more healthful for passengers and bus operators. It is unclear whether these levels are significant and further study may

[107] Alam, A. and M. Hatzopoulou. 2014. Reducing transit bus emissions: Alternative fuels or traffic operations? Atmospheric Environment, 89: 129-139; https://www.sciencedirect.com/science/article/pii/S1352231014001393
Alam, A., E, Diab, A. El-Geneidy, M. Hatzopoulou. 2014. A simulation of transit bus emissions along an urban corridor: Evaluating changes across several years and under various service improvement strategies. Transportation Research Part D, 31: 189-198. http://tram.mcgill.ca/Research/Publications/Bus_emissions.pdf

be warranted. In addition, the conversion could also eliminate 16,000 kg of nitrous oxide (NOx) and 113 kg of particulate matter (PM) per year. Further greening of the electrical grid, as well as green hydrogen sources, together with a 100% ZEB fleet will reduce the carbon footprint even further.

Cost Savings

During the COVID-19 pandemic, diesel fuel prices were about $3 per gallon, but as of August 2022, diesel fuel now hovers around $5 per gallon. The volatility of diesel fuel prices, coupled with the predictability and lower costs of electricity could translate to future cost savings with a BEB fleet. And while hydrogen fuel is more expensive than electricity or diesel fuel, costs are expected to decrease over time to provide a cost savings compared to diesel fuel.

Additionally, the propulsion of systems of ZEBs involve fewer moving parts than a traditional diesel engine, which could result in reduced maintenance needs and cost savings. The learning curve for the new technologies will be steep and retraining of existing staff will be required for a ZEB fleet, but is expected to level off with technology maturation and increased experience from maintenance staff.

Funding Programs

As the push to cleaner transportation becomes a broader policy priority at the national level, numerous funding opportunities are available to transit agencies pursuing ZEB transition. One case in point is that the FTA announced that available Section 5339 funding that AAATA and peer agencies use for bus purchase would total over $2 billion in FY 2022, an almost doubling of the $1 billion enacted in FY 2021. This level of funding is a clear signal of the commitment of the FTA and federal government to provide financial support through the Buses and Bus Facilities Formula, Competitive, and Low-No Program for the adoption of ZEBs. Moreover, these programs also provide funding for ZEB-associated infrastructure and training programs for workforce development. These funding opportunities provide AAATA a potential mechanism to procure and deploy ZEBs in a financially sustainable manner. Table 38 provides an overview of the authorized funding for the 5339 program[108] through FY 2026, demonstrating the significant investment from the federal government to support ZEB transitions.

Table 38: Authorized Funding for Section 5339 Program

Program component	FY 2021 Enacted	FY 2022 (in millions)	FY 2023 (in millions)	FY 2024 (in millions)	FY 2025 (in millions)	FY 2026 (in millions)
Formula	$582.61	$603.99	$616.61	$632.71	$645.78	$662.20
Buses and Bus Facilities Competitive	$414.04	$375.70	$383.54	$393.56	$401.69	$411.90
Low or No Emissions Competitive	$180.00	$1,121.56	$1,123.06	$1,124.96	$1,126.51	$1,128.46
5339 Program Total	$1,176.65	$2,101.25	$2,123.21	$2,151.23	$2,173.98	$2,202.56

[108] https://www.transit.dot.gov/sites/fta.dot.gov/files/2022-03/FY22-Low-No-Bus-Public-Webinar.pdf

Social

There are also social benefits to transitioning to a ZEB fleet through the reduction of negative externalities like health impacts related to GHG reduction. The US Department of Transportation estimates a monetized value of the social costs of carbon emissions at $53 per ton. Therefore, removing 7,000 tons of CO_2 annually represents a potential social benefit of approximately $371,000 per year.

Other Benefits

Other factors, such as improved cabin air quality and near-silent operations, make riding the bus safer and more pleasant for both operators and passengers. In addition, the cachet of ZEBs could be leveraged as a marketing tool to grow ridership by offering green transit.

9.6.2 Risks and Challenges

There are multiple risks associated with ZEB technologies related to planning/scheduling, operations maintenance, cost, safety, and human resources, all of which should be carefully considered.

The first risk is cost. ZEBs are more expensive than diesel buses and require expensive fueling infrastructure. AAATA's facility will require costly upgrades to accommodate charging and fueling infrastructure. Maintenance costs might be lower in the future, but this is not yet definitive. Although some ZEB fuel costs might translate to cost savings, energy costs can depend on rate structures and savings are not guaranteed.

Uncertainty about new technologies also poses a potential risk. ZEB technologies are relatively new, and there is insufficient data and information to make strong conclusions about how well ZEB technologies perform over the long-term life cycle of a fleet. While both technologies are being deployed around the world, it isn't clear if they will completely replace diesel, or if one will displace the other.

Execution is another risk that should be taken into consideration. A transition to a ZEB fleet will require 1-2 years of up-front planning before implementation. Overall operations will require significant changes, including scheduling, maintenance, purchasing, and staff training.

Staff resources also present potential risks. AAATA has several projects and initiatives that could potentially compete against a transition to a new propulsion system. Therefore, it will be necessary to understand and set agency priorities and assess the realities of resources.

The risks with the highest likelihood and impact are summarized below:

- Service changes and the impacts on fleet size and scheduling
- Uncertainties in bus and battery performance and life
- Availability of resources for unexpected maintenance/ repair requirements
- ZEB life cycle is not fully proven out
- Unknown long-term commodity prices for fuel (electricity, hydrogen, etc.)
- Battery replacement costs
- Bus and battery residual value
- Hydrogen fuel cell replacement/ refurbishment costs

- Workforce training and retention
- Execution and deployment of ZEBs
- Balancing competing capital needs for AAATA

AAATA will encounter agency-specific challenges while transitioning to ZEB technologies. AAATA's current operating base and maintenance facility lacks the space needed for future growth and for ZE charging and fueling infrastructure. This will require facility upgrades that are carefully planned and phased to not impact the agency's day-to-day operations. The facility was designed for the operation and maintenance of diesel buses and has reached its design life even for that purpose. Retrofitting is required to first bring the building up to current code for diesel operations (such as additional ventilation systems that exhaust at the floor level), and second to successfully accommodate a new propulsion technology.

Throughout a transition, AAATA will need to accommodate existing diesel technology as well as a ZEB technology. To deploy a ZEB fleet at the existing facility, significant investment in infrastructure and planning will be required. Beyond the costs that can be more easily calculated, other challenges are extensive such as the need for space to house spare parts and tools for multiple propulsion types and bus models.

There are also several industry-wide challenges common to ZE fleet transitions. Short term, the global supply chain is driving up the costs of vehicles and manufacturing, while also increasing lead time for parts and vehicles. In addition, agencies need to ensure that staff is appropriately trained for the deployed ZEB technology and enough lead time for training is available. Maintenance can also be challenging as maintenance activities shift from the manufacturer to the agency. Lastly, ZEB and infrastructure procurement requires a large capital outlay. Although the FTA has demonstrated its support for ZEB transition by doubling funding for bus acquisitions, future funding levels may not be sufficient to support industry-wide transition to ZEBs.

9.6.3 Timeline

The full transition to a ZEB fleet is at least 12 years. Diesel buses will be phased out strategically and gradually, so AAATA does not have to repay the federal government for them. Actual implementation might take longer due to funding availability, competing capital projects for AAATA, and service changes.

9.7 NEXT STEPS

With a preliminary understanding of ZEB technologies and the potential transition, necessary next steps include:

1. Determine the preferred fleet technology for AAATA. In the interim, AAATA will continue to procure the newest and cleanest diesel buses to minimize emissions.

2. Determine necessary modifications to the current facility, or if a new facility will be required. If a new facility is determined to be more cost-effective strategy, the location of the new facility will also need to be determined. Either technology will require significant lead time to prepare.

3. As an interim step before committing to a ZEB technology, AAATA may benefit from a short term ‘pilot’ or ZEB borrow from peer transit agencies/ZEB OEMs to test both BEBs and FCEBs vehicles in its service area. Other transit peers across the country have been using this interim to aid them in decision making. Regionally, the City of Detroit[109] continues to deploy BEBs, while Flint has FCEBs in its fleet; AAATA staff could hold field trips to these communities to learn directly from their ZEB deployments.

4. Determine the relative priority of capital funding to put towards propulsion vs. other needs like transit centers and customer-facing projects. This will affect grant applications and timeline of the transition. AAATA recently published a Long-Range Development Plan aimed at not only improving service by frequency enhancement and longer service spans, but also proposing new routes such as express service between Ann Arbor and Ypsilanti. In addition, several capital projects were also identified in the Long-Range Development Plan. There are several implications for a ZEB transition, including the fleet needs for service expansion, operational parameters that need to be worked out for ZEBs, and the capital projects that will be competing for funding and local matches. For comparison, eliminating 7,000 tons of CO_2 equivalents could also be accomplished by diverting 1,500 cars from the road for one year[110] on to more attractive public transit. AAATA will need to set priorities as it may be unable to implement both a full-scale transition and its long-term strategies.

5. It will be imperative that AAATA develop a ZEB transition plan to guide the ZEB rollout. This transition plan can leverage much of the information and analysis presented here, including the route modeling and cost estimates. Further details and strategies will need to be fleshed out in terms of timing and phasing of vehicles and infrastructure, as well as workforce training information and facility modifications. By developing a ZEB transition plan, AAATA will not only have a playbook for the technology transition, but it can also use the resulting transition plan to meet that requirement to apply for competitive FTA funding.

6. Determine if additional consulting work is needed to reach decisions about transition.

7. Take steps towards filling grant applications such as the FTA Low-No program. This should begin in early 2023, as the deadline for the Low-No grant program is typically in April/May.

8. Assess staffing requirements to oversee and manage a successful transition and ensure adequate resources. Workforce training should also be considered.

9. Begin planning for future garage expansions that take into consideration the specific requirements of the ZEB technology.

[109] https://detroitmi.gov/news/ddot-deploys-four-electric-buses-part-charge-greener-operations
[110] Greenhouse Gas Equivalencies Calculator | US EPA

9.8 CLOSING

This report is the first step for an eventual transition to ZEB technologies for AAATA. It provides the foundation for a full transition plan and strategy that will detail phasing and implementation of the preferred technology or technologies. Since bus technology continues to evolve at a rapid pace and transit service design and delivery is dynamic, AAATA's ZEB transition plan should be a living document with a clear, yet flexible path to 100% ZE operations.

Whichever technology or technologies AAATA decides to pursue, there will be risks and challenges as with any change from business-as-usual. As this Study has outlined, a change in propulsion technology will have ramifications throughout AAATA's business, from operations and planning, to operator scheduling, to workforce training, to budgeting and procurement. One real and pressing challenge is AAATA's aging facility that is nearly at capacity; adding more vehicles and fueling equipment will require careful and deliberate planning. Nonetheless, the environmental benefits of a clean technology fleet will aid in Ann Arbor's push to carbon-neutrality, helping to remove harmful emissions from vulnerable neighborhoods that transit services, but at a cost. AAATA will need to work together with the community it serves to determine the right balance of capital investments for its long-term projects that will continue AAATA's along its mission to provide reliable, safe, affordable transportation services.

APPENDIX A BATTERY SECOND LIFE AND RECYCLING

Lithium batteries have the potential to be used in other applications once they have reached the currently acceptable electric vehicle battery usage limits. Generally, it is considered that when an Li-ion battery degrades to 70-80%, from its original maximum capacity, it is not usable for vehicle driving purposes, and batteries can be either recycled, dispatched as waste, refurbished or reconditioned (for reuse on EV applications) and repurposed (for other uses than vehicle driving). The figure below gives a high-level illustration of the battery life process (without dispatching as waste)[111].

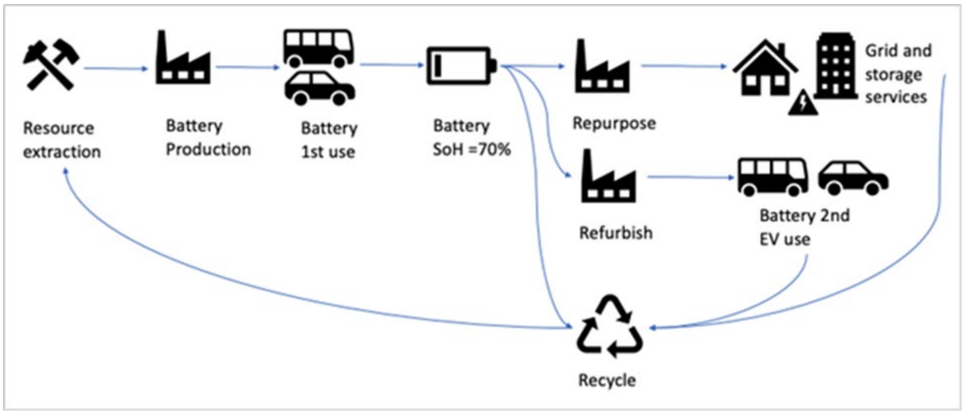


Figure 76: Battery life process

There is increasing discussion about recycling, refurbishing and repurposing batteries, as it would benefit the environmental profile of the EV life cycle as well as their economic business case—if the battery, which is the most expensive element of the vehicle, can be sold at an attractive price after its initial EV usage, it would benefit the vehicle's total cost of ownership dynamics. Though the second life market(s) of electric batteries remains nascent, particularly for heavy vehicles, it is expected to pick-up as substantial volumes of second life batteries are expected to come into the market in the next few years coupled with the industry's focus on developing innovative models of application. It has been suggested that the correct path for recycling depends on the chemistry and that batteries that contain cobalt should be recycled or otherwise repurposed[112].

[111] Source: Adapted from
1. https://www.sciencedirect.com/science/article/pii/S0301479718313124
2. https://www.nrel.gov/transportation/battery-second-use-analysis.htm

[112] Gaines, Linda. "Lithium-Ion Battery Recycling Processes: Research Towards a Sustainable Course." Sustainable Materials and Technologies 17 (2018)

APPENDIX B FINANCIAL AND EMISSIONS MODELING INPUTS

Static assumptions –

Variable	Value	Units / Notes	Source
General			
Discount Rate	7.00%	percent	Consistent with the discount rate used by federal entities such as USDOT
Transition start date	2024	year	Provided by AAATA
Bus Average Annual Driving Distance	39,000	miles	From Bus Mileage data provided by AAATA
Bus weekend duty intensity	50%	of weekday	From Bus Mileage data provided by AAATA
Total buses in fleet	99	buses	Provided by AAATA
Bus costs			
All powertrains			
Extra Specs	$75,000.00	$	Provided by AAATA
Bus lead-time	1	year(s)	Used to trigger cash outflow prior to delivery
Bus residual value	$3,300.00	$	From industry averages
Mid life overhaul at	6	years	Provided by AAATA
Holding period	12	years	Provided by AAATA
Batteries			
Bus Battery Costs	$455.00	$/kWh, 2022	Proterra pricing
Residual Battery Value	$72.00	$/kWh, 2022	Relectrify Provided value, indexed per cost indices
Battery replacement at	6.00	years	Proterra warranty
Diesel	Standard		
Diesel Bus body cost	$490,000.00	$	Provided by AAATA
Diesel Bus Powertrain Costs	$35,000.00	$	Provided by AAATA
Total Diesel Bus Cost	$600,000.00	$	Provided by AAATA
Electric	Standard range	Long range	
Electric Bus body cost	$495,000.00	$495,000.00	Proterra pricing
Electric Powertrain cost	$30,000.00	$30,000.00	Proterra pricing
Electric motor size	410 kW	410 kW	Proterra pricing
Battery Size	450 kWh	675 kWh	Proterra pricing
Pantograph cost	$7,000.00	$7,000.00	From industry averages
Total Electric Bus Cost	$810,000.00	$910,000.00	Proterra pricing
Fuel Cell Vehicle	Standard		
FCEV Total Cost	$1,014,000.00	$	New Flyer pricing
FCEV battery size	100	kWh	New Flyer pricing
Infrastructure costs			
Infrastructure lead time	1	year(s)	Used to trigger cash outflow prior to being in service
Battery electric			
Grid and backbone infrastructure upgrade	$3,873,102	upfront	Jacobus & Yuang Inc
Depot upgrades	$187,396	per bus	Jacobus & Yuang Inc
Fuel cell			
Grid and backbone infrastructure upgrade	$16,746,827	upfront	Jacobus & Yuang Inc
Depot upgrades	$11,771	upfront	Jacobus & Yuang Inc

Variable	Value	Units / Notes	Source
Bus Efficieny			
Diesel efficiency	5.74	MPG	Provided by AAATA
Diesel efficiency	0.17	G / mi	Converted from MPG
Fuel cell efficiency	0.09	kg/mi	Evenergi BetterFleet model
Maintenance Costs			
Diesel Bus	1.180	$/mi	Provided by AAATA
Electric Bus	0.640	$/mi	https://afdc.energy.gov/files/u/publication/financial_analysis_be_transit_buses.pdf
Fuel Cell	1.298	$/mi	10% premium on diesel
Emissions			
Diesel Fuel	10180	g/CO2 / gallon	https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references
Standard Grid Electricity	499	g/CO2 / kWh	https://www.eia.gov/electricity/state/michigan/
Green Electricity	40	g/CO2 / kWh	https://www.nrel.gov/docs/fy13osti/56487.pdf
Hydrogen - Electrolysis using green power	1960	g/CO2 / kg	https://bcbioenergy.ca/resources/bcbn-publications/british-columbia-hydrogen-study/
Hydrogen - Steam methane reforming	10000	g/CO2 /kg	https://bcbioenergy.ca/resources/bcbn-publications/british-columbia-hydrogen-study/
Diesel NOx Emissions	4.43	g/NOx / mi	Euro 4/5 average NOx limit
Diesel PM (tailpipe) Emissions	0.03	gPM / mi	Euro 4/5 diesel heavy vehicles
Other Fuel Costs			
Diesel Fuel Cost	5	$/ga	https://www.eia.gov/petroleum/gasdiesel/
Hydrogen Fuel Cost (offsite electrolyser and delivery)	8	$/kg	SARTA (Ohio)
Electricity Costs			
Network Charges			
Network Peak - tariff	56.28	c/kVA/day	DTE
Network Anytime - tariff	13.84	c/kVA/day	
Energy Charges			
Power supply energy charge - On peak	4.261	c/kWh	DTE
Power supply energy charge - Off peak	3.261	c/kWh	
Power supply energy charge - Off peak	3.261	c/kWh	
Green electricity markup	1.9	c/kWh	
Environmental and other charges			
Power supply cost recovery	0.322	c/kWh	DTE
Nuclear surcharge	0.0842	c/kWh	
Transitional recovery	0.1794	c/kWh	
Refuelling Equipment OPEX			
Electric Charging Equipment	0.50%	of installed equipment per year	From industry averages
Hydrogen refueling equipment	1.00%	of installed equipment per year	From industry averages
ICE refuelling equipment	$23,000	per year	From industry averages

Time-series assumptions –

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Infrastructure upgrades													
Infrastructure annual escalation	8.5%	8.5%	8.0%	8.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%
Infrastructure index	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Battery Price Indices													
Battery New Cost	1.00	0.94	0.89	0.84	0.79	0.75	0.71	0.67	0.63	0.62	0.61	0.61	0.60
Battery Second Life Value	1.00	0.94	0.89	0.84	0.79	0.75	0.71	0.67	0.63	0.62	0.61	0.61	0.60
Electric Bus	1.00	0.98	0.96	0.95	0.93	0.92	0.90	0.89	0.88	0.87	0.87	0.87	0.87
Electric Bus maintenance cost	1	0.9756	0.9512	0.9268	0.9024	0.878	0.8536	0.8292	0.8048	0.7804	0.756	0.7316	0.7072
Electricity Indices													
Peak	1	0.97	0.95	0.94	0.94	0.94	0.94	0.95	0.94	0.95	0.95	0.95	0.95
Shoulder (time Weighted)	1	0.97	0.95	0.94	0.94	0.94	0.94	0.95	0.94	0.95	0.95	0.95	0.95
Off Peak	1	0.97	0.95	0.94	0.94	0.94	0.94	0.95	0.94	0.95	0.95	0.95	0.95
Green Power Surcharge	1	1	1	1	1	1	1	1	1	1	1	1	1
Demand Charges - Peak	1	0.97	0.95	0.94	0.94	0.94	0.94	0.95	0.94	0.95	0.95	0.95	0.95
Demand Charges - OffPeak	1	0.97	0.95	0.94	0.94	0.94	0.94	0.95	0.94	0.95	0.95	0.95	0.95
Fuel Cell Price Indices													
Fuel Cell Cost	1	0.9756	0.9512	0.9268	0.9024	0.878	0.8536	0.8292	0.8048	0.7804	0.756	0.7316	0.7
Hydrogen Cost	1	0.9623	0.9259	0.8910	0.8574	0.8250	0.7938	0.7639	0.7351	0.7073	0.6806	0.6549	0.6302
H2 Maintenance Cost	1	0.9756	0.9512	0.9268	0.9024	0.878	0.8536	0.8292	0.8048	0.7804	0.756	0.7316	0.7072
ICE Price Indices													
Diesel Engine Cost	1	1	1	1	1	1	1	1	1	1	1	1	1
Diesel Cost	1	1	0.96	0.96	0.96	0.96	0.96	0.97	0.97	0.97	1.00	1.00	1.01
Diesel Maintenance Cost	1	1	1	1	1	1	1	1	1	1	1	1	1
Health Cost Indices													
CO2 $/kg	1	1.02	1.0404	1.061208	1.08243216	1.1040808	1.12616242	1.14868567	1.17165938	1.19509257	1.21899442	1.24337431	1.26824179
NOx $/kg	1	1.02	1.0404	1.061208	1.08243216	1.1040808	1.12616242	1.14868567	1.17165938	1.19509257	1.21899442	1.24337431	1.26824179
PM $/kg	1	1.02	1.0404	1.061208	1.08243216	1.1040808	1.12616242	1.14868567	1.17165938	1.19509257	1.21899442	1.24337431	1.26824179

Year	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
Infrastructure upgrades													
Infrastructure annual escalation	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%
Infrastructure index	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Battery Price Indices													
Battery New Cost	0.59	0.58	0.58	0.57	0.56	0.55	0.54	0.54	0.53	0.52	0.51	0.50	0.50
Battery Second Life Value	0.59	0.58	0.58	0.57	0.56	0.55	0.54	0.54	0.53	0.52	0.51	0.50	0.50
Electric Bus	0.86	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.83	0.83
Electric Bus maintenance cost	0.6828	0.6584	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634
Electricity Indices													
Peak	0.94649335	0.94	0.94	0.93	0.93	0.93	0.92	0.92	0.92	0.91	0.91	0.90	0.90
Shoulder (time Weighted)	0.94649335	0.94	0.94	0.93	0.93	0.93	0.92	0.92	0.92	0.91	0.91	0.90	0.90
Off Peak	0.94649335	0.94	0.94	0.93	0.93	0.93	0.92	0.92	0.92	0.91	0.91	0.90	0.90
Green Power Surcharge	1	1	1	1	1	1	1	1	1	1	1	1	1
Demand Charges - Peak	0.94649335	0.94	0.94	0.93	0.93	0.93	0.92	0.92	0.92	0.91	0.91	0.90	0.90
Demand Charges - OffPeak	0.94649335	0.94	0.94	0.93	0.93	0.93	0.92	0.92	0.92	0.91	0.91	0.90	0.90
Fuel Cell Price Indices													
Fuel Cell Cost	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Hydrogen Cost	0.606408457	0.5835	0.5615	0.5403	0.5199	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
H2 Maintenance Cost	0.6828	0.6584	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634	0.634
ICE Price Indices													
Diesel Engine Cost	1	1	1	1	1	1	1	1	1	1	1	1	1
Diesel Cost	1.01012231	1.01433994	1.02	1.03	1.04	1.04	1.05	1.05	1.05	1.06	1.08	1.08	1.09
Diesel Maintenance Cost	1	1	1	1	1	1	1	1	1	1	1	1	1
Health Cost Indices													
CO2 $/kg	1.29360663	1.31947876	1.34586834	1.37278571	1.40024142	1.42824625	1.45681117	1.4859474	1.51566634	1.54597967	1.57689926	1.60843725	1.64060599
NOx $/kg	1.29360663	1.31947876	1.34586834	1.37278571	1.40024142	1.42824625	1.45681117	1.4859474	1.51566634	1.54597967	1.57689926	1.60843725	1.64060599
PM $/kg	1.29360663	1.31947876	1.34586834	1.37278571	1.40024142	1.42824625	1.45681117	1.4859474	1.51566634	1.54597967	1.57689926	1.60843725	1.64060599

Note: These are multipliers on the base (current year) assumed unit costs for the 25-year horizon.

APPENDIX C WORKFORCE DEVELOPMENT

Because the ZEB transition and implementation is an agencywide endeavor that also includes the need to actively consider utilities as a stakeholder and partner, an agencywide approach to a ZEB rollout is required. Additionally, the union(s) representing the bus operators and maintainers should also be included due to the large role they will play in the success of the ZEB transition and implementation.

Thus, it is prudent for transit agencies looking to implement ZEBs to form an advisory committee or task force composed of staff from each major functional department and union representation to help ensure the impact of ZEBs are considered for each. The task force should also name a leader who acts as a champion for the ZEB conversion within the agency and to external stakeholders. Communication will be critical during the transition to ensure customers are made aware of potential disruptions and changes to bus operations.

Additional resources and examples of key partnerships are presented below to exemplify the approach to the workforce engagement.

ZEBRA

The Zero Emission Bus Resource Alliance (ZEBRA) is a national professional association for transit agencies to share lessons learned about zero emission buses (ZEB). Founders envisioned ZEBRA as a group of transit leaders exchanging information without the involvement of manufacturers or outside groups[113].

ZEBRA provides a safe space for operators to support each other during their clean fleet transitions. While is a membership is required, participants get access to research, resources and best practices, and demonstrations of SMART (System Maintenance Automated Repair and Test) software, which is a program used for troubleshooting and generating best-practice repair procedures for unscheduled maintenance of ZEBs.

SunLine Transit Agency West Coast Center of Excellence in Zero Emission Technology[114]

The West Coast Center of Excellence in Zero Emission Technology (CoEZET) is hosted by SunLine Transit Agency and focuses on workforce investments, outreach, knowledge capture, workshops, and staffing support for ZEB-related initiatives. CoEZET is a collaboration between public and private organizations, including transit agencies, colleges, private industry, and government agencies, that ensures the development of excellence in the maintenance of zero emission buses. Currently, SunLine Transit Agency has partnered with College of the Desert, Rio Hondo College, California Community College-Doing What Matters, BAE Systems, Ballard Power Systems, BYD Coach and Bus, Hydrogenics, and Proterra to develop the Center of Excellence in Zero Emission Technology.

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113 http://www.cte.tv/wp-content/uploads/2018/06/What-is-ZEBRA.pdf

114 https://www.sunline.org/alternative-fuels/west-coast-center-of-excellence-in-zero-emission-technology

Funded by the FTA, this center serves to bring education to transit agencies looking deploy ZE fleets. Many of the courses offered cover topics that address in-service management of ZE technologies, such as fueling systems and fleet operations.

The center also assists with the reduction of unscheduled maintenance by demonstration of a shared resource software called SMART. CoEZET provides a place for focused training and instruction in conjunction with educational institutions and equipment manufacturers. The Center has been funded for a dedicated ZE maintenance facility which will be used to demonstrate many of the diagnostic tools necessary to maintain ZE fleets.

APPENDIX D SCHEDULE AND IMPORT DATA ASSUMPTIONS

Block ID
Modeled as a physical bus and all trips corresponding to one block number represent a full day's duty for each bus

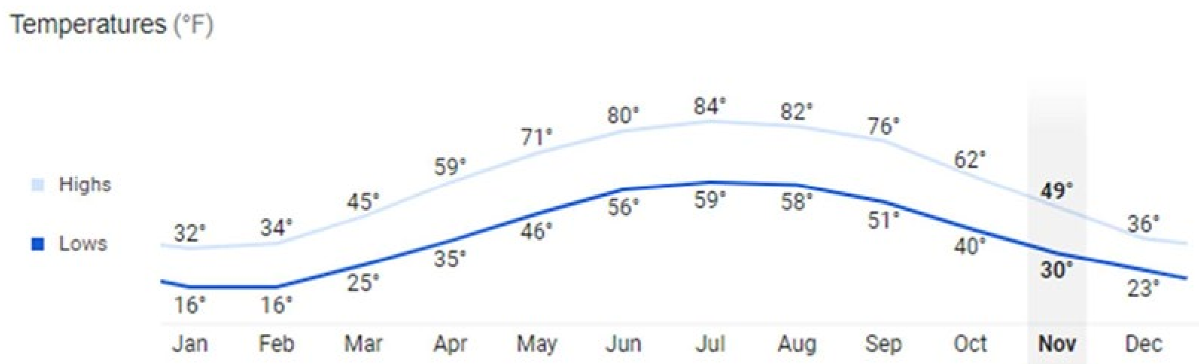
Trip ID
Correlated with GTFS data to obtain shape files which are used to determine where each vehicle travels. Each set of trips is considered a route.

Day type
Weekday schedule modeled, assumed to be the heaviest duty.

Run_id	Block_i	Block_r	Passing	Day_m	Time_p	Trip_id	Trip_nc	Route	Var	Trip_di	Shedul	Trip_ty	Trip_pa	work_i	work_i	Garrage	Garrade	Origina	Origina	Public_	Origina	Origina	Origina	Descrip	custom	Short_c	Long_d	Origina	Orig_sh
1128	230923	1002	55860	1.11E+62	2700g	404343	4.04E+08				Schedule-	PULL-OUT		1128		2700g	AATA Main Garage		404343		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	56700	1.11E+62	BTC	404343	4.04E+08				Schedule-	PULL-OUT		1128		2700g	AATA Main Garage		404343		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	56700	1.11E+62	BTC	404343	4.04E+08	34		to Miller F	Schedule-	REVENUE	34 OB	1128		2700g	AATA Main Garage		404343		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	57360	1.11E+62	D/MP	404343	4.04E+08	34		to Miller F	Schedule-	REVENUE	34 OB	1128		2700g	AATA Main Garage		404343		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	57600	1.11E+62	MRPR	404343	4.04E+08	34		to Miller F	Schedule-	REVENUE	34 OB	1128		2700g	AATA Main Garage		404343		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	57600	1.11E+62	MRPR	404354	4.04E+08	34		to BTC	Schedule-	REVENUE	34 IB	1128		2700g	AATA Main Garage		404354		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	57900	1.11E+62	D/MP	404354	4.04E+08	34		to BTC	Schedule-	REVENUE	34 IB	1128		2700g	AATA Main Garage		404354		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	58320	1.11E+62	BTC	404354	4.04E+08	34		to BTC	Schedule-	REVENUE	34 IB	1128		2700g	AATA Main Garage		404354		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	58500	1.11E+62	BTC	404263	4.04E+08	23		to Plym/G	Schedule-	REVENUE	23 OB Day	1128		2700g	AATA Main Garage		404263		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	58920	1.11E+62	CCTC	404263	4.04E+08	23		to Plym/G	Schedule-	REVENUE	23 OB Day	1128		2700g	AATA Main Garage		404263		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	59340	1.11E+62	UH	404263	4.04E+08	23		to Plym/G	Schedule-	REVENUE	23 OB Day	1128		2700g	AATA Main Garage		404263		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	59820	1.11E+62	PLBR	404263	4.04E+08	23		to Plym/G	Schedule-	REVENUE	23 OB Day	1128		2700g	AATA Main Garage		404263		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	60240	1.11E+62	PM	404263	4.04E+08	23		to Plym/G	Schedule-	REVENUE	23 OB Day	1128		2700g	AATA Main Garage		404263		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	60540	1.11E+62	G/NX	404263	4.04E+08	23		to Plym/G	Schedule-	REVENUE	23 OB Day	1128		2700g	AATA Main Garage		404263		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	61020	1.11E+62	PP&R	404263	4.04E+08	23		to Plym/G	Schedule-	REVENUE	23 OB Day	1128		2700g	AATA Main Garage		404263		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	61200	1.11E+62	PP&R	404301	4.04E+08	23		to BTC	Schedule-	REVENUE	23 IB Day	1128		2700g	AATA Main Garage		404301		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	61620	1.11E+62	G/NX	404301	4.04E+08	23		to BTC	Schedule-	REVENUE	23 IB Day	1128		2700g	AATA Main Garage		404301		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	61980	1.11E+62	PM	404301	4.04E+08	23		to BTC	Schedule-	REVENUE	23 IB Day	1128		2700g	AATA Main Garage		404301		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	62400	1.11E+62	PLBR	404301	4.04E+08	23		to BTC	Schedule-	REVENUE	23 IB Day	1128		2700g	AATA Main Garage		404301		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	62820	1.11E+62	UH	404301	4.04E+08	23		to BTC	Schedule-	REVENUE	23 IB Day	1128		2700g	AATA Main Garage		404301		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	63240	1.11E+62	CCTC	404301	4.04E+08	23		to BTC	Schedule-	REVENUE	23 IB Day	1128		2700g	AATA Main Garage		404301		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	63720	1.11E+62	BTC	404301	4.04E+08	23		to BTC	Schedule-	REVENUE	23 IB Day	1128		2700g	AATA Main Garage		404301		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	63900	1.11E+62	BTC	404347	4.04E+08	34		to Miller F	Schedule-	REVENUE	34 OB	1128		2700g	AATA Main Garage		404347		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	64560	1.11E+62	D/MP	404347	4.04E+08	34		to Miller F	Schedule-	REVENUE	34 OB	1128		2700g	AATA Main Garage		404347		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	64800	1.11E+62	MRPR	404347	4.04E+08	34		to Miller F	Schedule-	REVENUE	34 OB	1128		2700g	AATA Main Garage		404347		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	64800	1.11E+62	MRPR	404358	4.04E+08	34		to BTC	Schedule-	REVENUE	34 IB	1128		2700g	AATA Main Garage		404358		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	65100	1.11E+62	D/MP	404358	4.04E+08	34		to BTC	Schedule-	REVENUE	34 IB	1128		2700g	AATA Main Garage		404358		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	65520	1.11E+62	BTC	404358	4.04E+08	34		to BTC	Schedule-	REVENUE	34 IB	1128		2700g	AATA Main Garage		404358		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	65520	1.11E+62	BTC	404358	4.04E+08				Schedule-	PULL-IN		1128		2700g	AATA Main Garage		404358		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1128	230923	1002	66000	1.11E+62	2700g	404358	4.04E+08				Schedule-	PULL-IN		1128		2700g	AATA Main Garage		404358		WKD	1128	2309		10	AATA	Ann Arbor Transit Authority		
1013	240124	1102	21600	1.11E+62	2700g	405738	4.06E+08				Schedule-	PULL-OUT		1013		2700g	AATA Main Garage		405738		WKD	1013	2401		11	AATA	Ann Arbor Transit Authority		
1013	240124	1102	22500	1.11E+62	STJ	405738	4.06E+08				Schedule-	PULL-OUT		1013		2700g	AATA Main Garage		405738		WKD	1013	2401		11	AATA	Ann Arbor Transit Authority		
1013	240124	1102	22500	1.11E+62	STJ	405738	4.06E+08	24		to BTC	Schedule-	REVENUE	24-ib	1013		2700g	AATA Main Garage		405738		WKD	1013	2401		11	AATA	Ann Arbor Transit Authority		
1013	240124	1102	23220	1.11E+62	WCC	405738	4.06E+08	24		to BTC	Schedule-	REVENUE	24-ib	1013		2700g	AATA Main Garage		405738		WKD	1013	2401		11	AATA	Ann Arbor Transit Authority		
1013	240124	1102	24120	1.11E+62	W/PIT	405738	4.06E+08	24		to BTC	Schedule-	REVENUE	24-ib	1013		2700g	AATA Main Garage		405738		WKD	1013	2401		11	AATA	Ann Arbor Transit Authority		
1013	240124	1102	24780	1.11E+62	SS/E	405738	4.06E+08	24		to BTC	Schedule-	REVENUE	24-ib	1013		2700g	AATA Main Garage		405738		WKD	1013	2401		11	AATA	Ann Arbor Transit Authority		

APPENDIX E WEATHER DATA ASSESSMENT FOR AMBIENT TEMPERATURE ESTIMATION

10-year average temperatures (2010-2019)



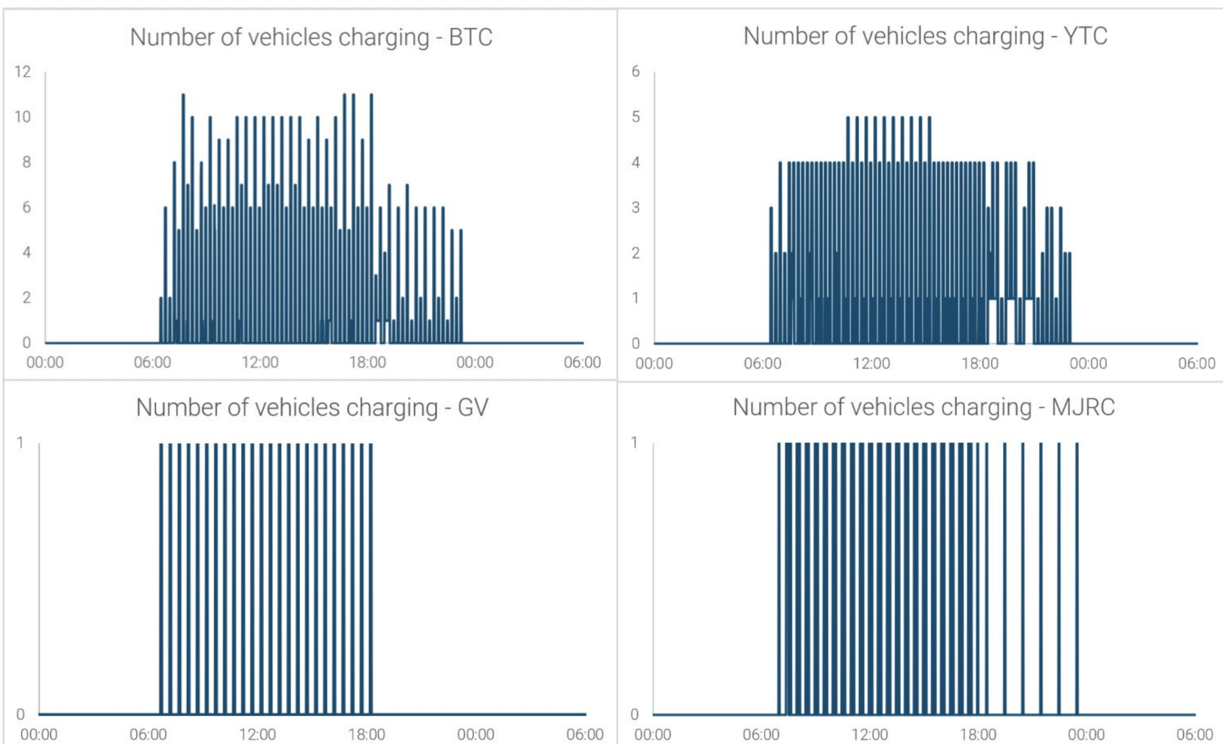
Days per month on average in Ann Arbor when the minimum temperature reaches 10˚F, 20˚F and 32˚F

	10 ºF -12 ºC	20 ºF -8 ºC	32 ºF 0 ºC
January	8	17	28
February	5	13	25
March	1	7	22
April	0	0	8
May	0	0	1
June	0	0	0
July	0	0	0
August	0	0	0
September	0	0	0
October	0	0	3
November	0	2	14
December	3	11	26
Year	18	49	127

Source: https://www.ncei.noaa.gov/access

APPENDIX F BATTERY-ELECTRIC BUS – PANTOGRAPH ON-ROUTE CHARGING SCENARIO

Time of day distribution of number of buses charging at pantograph charging locations on-route

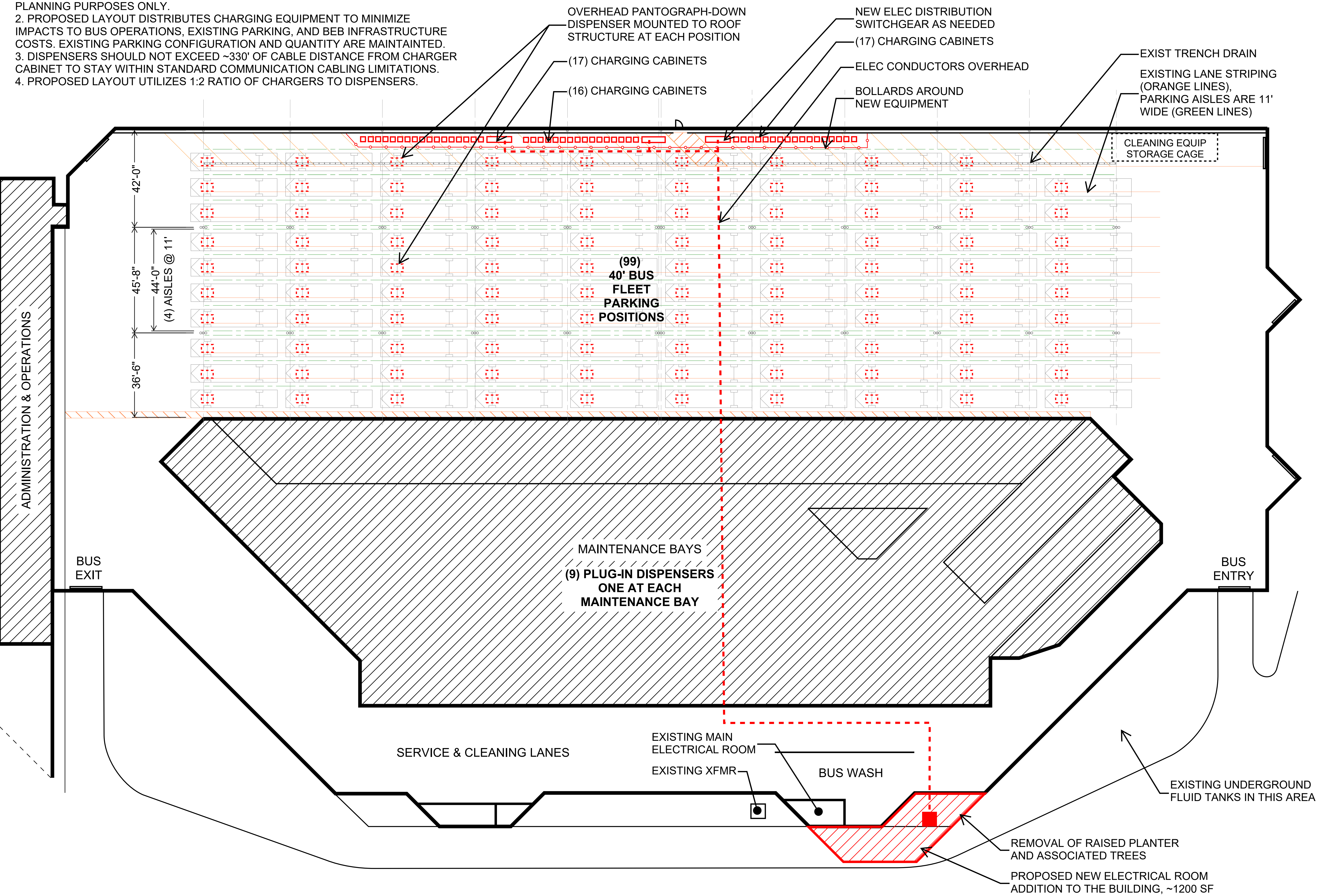


APPENDIX G SITE CONCEPT PLANS

Attached as a PDF.

NOTES:

1. CHARGING AND EQUIPMENT LAYOUT SHOWN IS CONCEPTUAL AND FOR PLANNING PURPOSES ONLY.
2. PROPOSED LAYOUT DISTRIBUTES CHARGING EQUIPMENT TO MINIMIZE IMPACTS TO BUS OPERATIONS, EXISTING PARKING, AND BEB INFRASTRUCTURE COSTS. EXISTING PARKING CONFIGURATION AND QUANTITY ARE MAINTAINTED.
3. DISPENSERS SHOULD NOT EXCEED ~330' OF CABLE DISTANCE FROM CHARGER CABINET TO STAY WITHIN STANDARD COMMUNICATION CABLING LIMITATIONS.
4. PROPOSED LAYOUT UTILIZES 1:2 RATIO OF CHARGERS TO DISPENSERS.



Stantec

Stantec Proj No.
2073016330

AATA BUS PROPULSION STUDY
2700 SOUTH INDUSTRIAL HIGHWAY, ANN ARBOR, MI 48104

SCENARIO 3 : BATTERY ELECTRIC BUS FLEET
CONCEPTUAL BUILDING PLAN

DATE:
04/08/22

DWG:

1.3

NOTES:

1. HYDROGEN FUELING EQUIPMENT LAYOUT SHOWN IS CONCEPTUAL AND FOR PLANNING PURPOSES ONLY.
2. FOR IMPLEMENTATION OF FCEB'S A NEW CODE COMPLIANT GAS DETECTION SYSTEM WILL BE REQUIRED THROUGHOUT THE MAINTENANCE AND BUS STORAGE AREAS. EXHAUST SYSTEM MODIFICATIONS WILL ALSO BE REQUIRED TO EXHAUST LIGHTER THAN AIR GASES FROM INSIDE THE BUILDING.
3. LAYOUT ASSUMES A VERTICAL 12,000 GALLON MINIMUM LIQUID HYDROGEN STORAGE TANK.
4. OPTION 2 UTILIZES A FIRE BARRIER WALL AROUND THE HYDROGEN YARD TO MINIMIZE CLEARANCES TO THE BUILDING.

EQUIPMENT LEGEND:

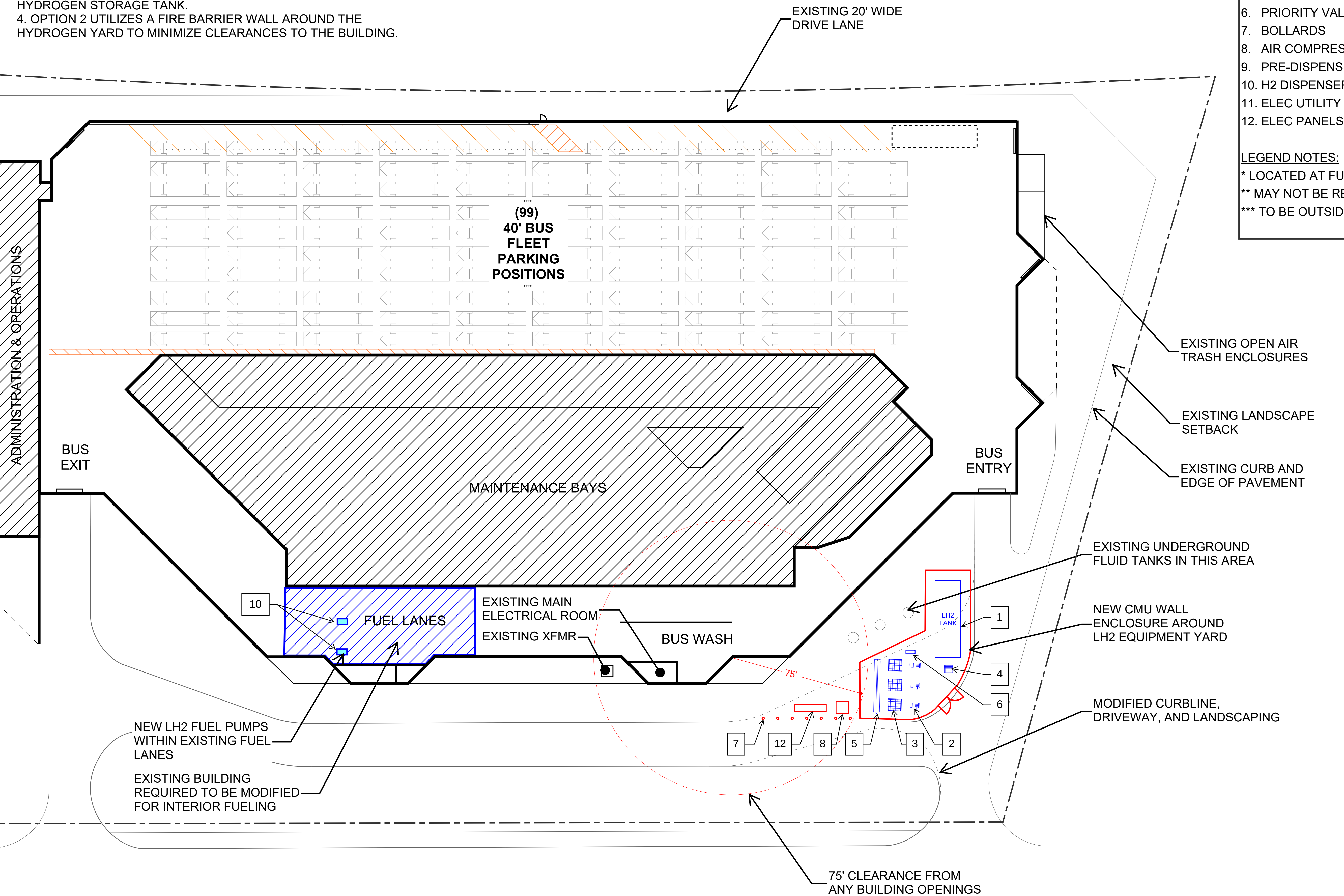
1. 18,000 GALLON LH2 TANK (QTY 1)
2. HIGH-PRESSURE LH2 PUMPS (QTY 3)
3. H2 VAPORIZER TOWERS (QTY 3)
4. H2 SUPER-HEATER (QTY 1)
5. GH2 STORAGE VESSELS (QTY 6)
6. PRIORITY VALVE PANEL (QTY 1)
7. BOLLARDS
8. AIR COMPRESSOR SYSTEM (QTY 1)
9. PRE-DISPENSING CHILLER (QTY 2)*
10. H2 DISPENSERS (QTY 2)*
11. ELEC UTILITY TRANSFORMER **
12. ELEC PANELS AND CONTROLS ***

LEGEND NOTES:

* LOCATED AT FUELING AREA

** MAY NOT BE REQUIRED, TBD

*** TO BE OUTSIDE OF HAZARDOUS AREA



Stantec

Stantec Proj No. 2073016330

AATA BUS PROPULSION STUDY
2700 SOUTH INDUSTRIAL HIGHWAY, ANN ARBOR, MI 48104

SCENARIO 2 : HYDROGEN FUEL CELL BUS FLEET
CONCEPTUAL SITE PLAN

DATE:
04/04/22

DWG:

2.2

APPENDIX H INDEPENDENT COST ESTIMATES

Attached as a PDF.

AAATA BUS PROPULSION STUDY

ANN ARBOR, MI

ROUGH-ORDER-OF-MAGNITUDE OPINION OF PROBABLE COST

JYI #: C2605A-R2

April 28, 2022
Revised: May 16, 2022

PREPARED FOR:

STANTEC

BY:

JACOBUS & YUANG, INC.
355 North Lantana Street, #220
Camarillo, CA 93010
Tel (213) 688-1341 or (805) 339-9434

PROJECT: AAATA BUS PROPULSION STUDY							**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI							**DATE:**	**28-Apr-22**
CLIENT: STANTEC							**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE CAPTIAL COST - SUMMARY	**BEB**		**EX. BUILDING AREA**	**148,045**	**FCEB**		**EX. BUILDING AREA**	**148,045**

ITEM NO.	DESCRIPTION	YEAR 2023 COST				YEAR 2023 COST			
		EST QTY	UNIT	UNIT COST	TOTAL COST	EST QTY	UNIT	UNIT COST	TOTAL COST
	SUMMARY OF CAPITAL COST ESTIMATE				**$**				**$**
	UPFRONT INFRASTRUCTURE W/O ESCALATION	148,045	SF	26.16	3,873,102	148,045	SF	113.12	16,746,827
	R.O.M. TOTAL OF OPINION OF PROBABLE CONSTRUCTION COST W/ PRORATES W/O ESCALATION	**148,045**	**SF**	**26.16**	**3,873,102**	**148,045**	**SF**	**113.12**	**16,746,827**

MIDPOINT OF CONSTRUCTION DATE [SEE END OF ESTIMATE FOR ESCALATION CALCS]

Jun-23	12.68%	**4,364,390**	**18,871,100**
Jun-24	22.26%	**4,735,100**	**20,474,000**
Jun-25	30.54%	**5,055,790**	**21,860,620**
Jun-26	40.97%	**5,459,960**	**23,608,230**
Jun-27	44.70%	**5,604,380**	**24,232,670**
Jun-28	54.82%	**5,996,410**	**25,927,760**
Jun-29	65.65%	**6,415,860**	**27,741,420**
Jun-30	77.24%	**6,864,650**	**29,681,940**
Jun-31	89.64%	**7,344,840**	**31,758,210**
Jun-32	102.90%	**7,858,620**	**33,979,710**
Jun-33	117.10%	**8,408,330**	**36,356,610**
Jun-34	132.28%	**8,996,500**	**38,899,770**
Jun-35	148.53%	**9,625,800**	**41,620,820**
Jun-36	165.91%	**10,299,130**	**44,532,220**
Jun-37	184.52%	**11,019,560**	**47,647,270**
Jun-38	204.42%	**11,790,390**	**50,980,220**
Jun-39	225.71%	**12,615,130**	**54,546,310**
Jun-40	248.49%	**13,497,560**	**58,361,840**

PROJECT: AAATA BUS PROPULSION STUDY						JYI #:	C2605A-R2
LOCATION: ANN ARBOR, MI						DATE:	28-Apr-22
CLIENT: STANTEC						REVISED:	16-May-22
DESCRIPTION: R.O.M. OPINION OF PROBABLE CAPTIAL COST - SUMMARY	BEB	EX. BUILDING AREA	148,045	FCEB		EX. BUILDING AREA	148,045

ITEM NO.	DESCRIPTION	YEAR 2023 COST				YEAR 2023 COST			
		EST QTY	UNIT	UNIT COST	TOTAL COST	EST QTY	UNIT	UNIT COST	TOTAL COST
	SUMMARY OF CAPITAL COST ESTIMATE				**$**				**$**
	BALANCE OF WORK BEYOND UPFRONT INFRASTRUCTURE	148,045	SF	125.31	18,552,201	148,045	SF	0.08	11,771
	R.O.M. TOTAL OF OPINION OF PROBABLE CONSTRUCTION COST W/ PRORATES W/O ESCALATION - BALANCE OF WORK BEYOND UPFRONT INFRASTRUCTURE	**148,045**	**SF**	**125.31**	**18,552,201**	**148,045**	**SF**	**0.08**	**11,771**

MIDPOINT OF CONSTRUCTION DATE [SEE END OF ESTIMATE FOR ESCALATION CALCS]

Jun-23	12.68%	**20,905,480**	**13,260**
Jun-24	22.26%	**22,681,180**	**14,390**
Jun-25	30.54%	**24,217,280**	**15,370**
Jun-26	40.97%	**26,153,290**	**16,590**
Jun-27	44.70%	**26,845,050**	**17,030**
Jun-28	54.82%	**28,722,880**	**18,220**
Jun-29	65.65%	**30,732,050**	**19,500**
Jun-30	77.24%	**32,881,780**	**20,860**
Jun-31	89.64%	**35,181,870**	**22,320**
Jun-32	102.90%	**37,642,860**	**23,880**
Jun-33	117.10%	**40,275,990**	**25,550**
Jun-34	132.28%	**43,093,320**	**27,340**
Jun-35	148.53%	**46,107,710**	**29,250**
Jun-36	165.91%	**49,332,970**	**31,300**
Jun-37	184.52%	**52,783,830**	**33,490**
Jun-38	204.42%	**56,476,080**	**35,830**
Jun-39	225.71%	**60,426,610**	**38,340**
Jun-40	248.49%	**64,653,480**	**41,020**

PROJECT: AAATA BUS PROPULSION STUDY					**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI					**DATE:**	**28-Apr-22**
CLIENT: STANTEC					**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE CAPTIAL COST - SUMMARY	**BEB**	**EX. BUILDING AREA**	**148,045**	**FCEB**	**EX. BUILDING AREA**	**148,045**

NOTES:

SPECIFIC INCLUSIONS

1 PREVAILING WAGE RATES IN THE AREA OF THE PROJECT
2 EQUIPMENT PADS
3 EQUIPMENT YARD
4 (2) 2,500KVA TRANSFORMERS [BEB]
5 2,500A MAIN SWITCHBOARD
6 (2) 2500KW GENERATOR SET WITH SEPARATE 800 GAL DIESEL FUEL STORAGE AND PIPINGS [BEB]
7 TOTAL (50) 180KW EV CHARGER CABINETS W/ (99) PANTOGRAPH DISPENSERS, OVERHEAD MOUNTED IN BUS STORAGE AREA [BEB]
8 TOTAL OF (10) 50KW EV CHARGER CABINETS W/ DUAL DISPENSERS IN MAINTENANCE BUILDING [BEB]
9 EQUIPMENT POWER
10 COMMUNICATIONS
11 PAVEMENT REPAIR PER TRENCHWORK
12 THE NINE REPAIR BAYS AND THE ONE PREVENTIVE MAINTENANCE BAY ARE OUTFITTED WITH CHARGING CAPABILITIES
13 GASEOUS CLEAN AGENT EXTINGUISHING SYSTEM TO ELECTRICAL ROOM

SPECIFIC EXCLUSIONS

1 ASBESTOS OR HAZARDOUS MATERIAL ABATEMENT
2 PROJECT SOFT COSTS & CONSTRUCTION CONTINGENCY
3 PRIMARY POWER SERVICE CONDUIT
4 CABLINGS AND CONNECTIONS FOR PRIMARY POWER SERVICE CONDUIT
5 ELECTRICAL UTILITY SERVICE FEES
6 CLEANING EQUIPMENT STORAGE CAGE
7 SIGNIFICANT CHANGES TO THE FACILITY ARE NOT ANTICIPATED FOR FIRE PROTECTION RELATED TO BEB SCOPE
8 ROUTING OF ETHERNET LINES OTHER THAN TO DATA SWITCH
9 NO MODIFICATIONS TO THE TELECOM SYSTEMS ARE ANTICIPATED AS A RESULT OF THE IMPLEMENTATION OF HYDROGEN FUELING.

GENERAL NOTES

1 ESTIMATE ASSUMES THAT ALL COMPONENTS WILL BE BID AS A SINGLE BID PACKAGE
2 ESTIMATE ASSUMES WORK TO BE DURING NORMAL WORKING HOURS
3 ESTIMATE ASSUMES BID COVERAGE FROM AT LEAST 4-5 RESPONSIVE BIDDERS
4 ESTIMATE IS BASED ON CONCEPTUAL DESIGN DRAWINGS AND REPORT PREPARED BY STANTEC AS FOLLOWS: DWNG. 1.3 - SCENARIO 3: BEB FLEET CONCEPTUAL BUILDING PLAN, DATED 4/8/22 + DWNG 2.2 - SCENARIO 2: HYDROGEN FUEL BUS FLEET CONCEPTUAL SITE PLAN, RECEIVED 4/8/2022
5 THE PRIMARY IMPACTS WILL BE TO THE MAINTENANCE EQUIPMENT AND TOOLING NEEDED TO SERVICE A BEB FLEET COMPARED TO AN ICE FLEET. THE ASSESSMENT OF THE ACTUAL EQUIPMENT NEEDED IS OUTSIDE OF THE SCOPE OF THIS REPORT BUT CAN BE ASSUMED TO BE RELATIVELY STRAIGHTFORWARD SINCE IT WILL NOT BE BUILT INTO THE FACILITY.
6 THE NEED FOR ENHANCED FIRE PROTECTION SYSTEMS HAS NOT BEEN DETERMINED AS A BASELINE REQUIREMENT FOR BEB IMPLEMENTATION AND WOULD BE LEFT UP TO THE DISCRETION OF THE LOCAL FIRE MARSHAL AND THE LOCAL BUILDING OFFICIALS
7 AAATA HAS ALREADY IMPLEMENTED FALL-ARREST SYSTEMS IN THE FACILITY, IT IS UNLIKELY THAT ADDITIONAL FALL PROTECTION SYSTEMS WOULD BE REQUIRED TO SAFELY ACCESS THE ROOFTOP OF BUSES FOR POTENTIAL BATTERY INSPECTION AND MAINTENANCE. IF CONSIDERABLE ROOFTOP ACCESS IS NECESSARY IN THE FUTURE, AAATA SHOULD CONSIDER ADDITIONAL FALL PROTECTION SYSTEMS THROUGHOUT THE SHOP.
8 UNIT COSTS FOR CHARGER AND PENTOGRAPH EQUIPMENT ARE BASED ON A BUDGETARY QUOTATION OBTAINED FROM HELIOX, DATED 5/9/2022 [BQ2202542-01CP], A COPY ATTACHED AT THE END OF THIS DOCUMENT. JYI ADDED 40% TO THESE COSTS FOR INSTALLATION, TAXES AND FREIGHT

PROJECT: AAATA BUS PROPULSION STUDY					**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI					**DATE:**	**28-Apr-22**
CLIENT: STANTEC					**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE CAPTIAL COST - SUMMARY	**BEB**	**EX. BUILDING AREA**	**148,045**	**FCEB**	**EX. BUILDING AREA**	**148,045**

DEFINITIONS

OPINION OF COST

An Opinion of Cost is prepared from a survey of the quantities of work-items prepared from written or drawn information provided at the Conceptual stage of design.

Historical costs, information provided by contractors and suppliers, plus judgmental evaluation by the Estimator are used as appropriate as the basis for pricing.

Allowances as appropriate will be included for items of work which are not indicated on the design documents, provided that the Estimator is made aware of them, or which in the judgement of the Estimator are required for completion of the work.

JYI cannot, however, be responsible for inclusion of items or work of which we have not been informed.

BID

An offer to enter a contract to perform work for a fixed sum, to be completed within a limited period of time.

SPECIAL NOTE - MARKET CONDITIONS

In the current market conditions for construction, our experience shows the following results on competitive bids, as a differential from JYI final estimates:

Number of bids	Percentage Differential
1...........	+ 25 to 50%
2-3..........	+ 10 to 25%
4-5..........	+ 0 to 10%
6-7..........	+ 0 to - 5%
8 or more....	+ 0 to -10%

Accordingly, it is extremely important to ensure that a minimum of 4-5 valid bids are received

PROJECT: AAATA BUS PROPULSION STUDY								**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI								**DATE:**	**28-Apr-22**
CLIENT: STANTEC								**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION**		**EX. BUILDING AREA**	**148,045**	**FCEB OPTION**			**EX. BUILDING AREA**	**148,045**

ITEM NO.	DESCRIPTION	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST
	SUMMARY OF ESTIMATE				**$**				**$**
1	GENERAL REQUIREMENTS								
2	DEMOLITION	0.44%		0.09	13,656	0.32%		0.29	42,456
3	SITE IMPROVEMENTS	2.69%		0.56	82,817	0.76%		0.69	101,700
4	BUILDING MODIFICATIONS & ADDITIONS				298,478				13,171,090
5	FURNITURE, FIXTURES AND EQUIPMENT				N.I.C.				N.I.C.
6	ELECTRICAL, INCLUDING BEB EQUIPMENT	87.17%		18.13	2,684,516				
7	COMMUNICATIONS								
	SUBTOTAL	**90.31%**		**20.80**	**3,079,467**	**1.08%**		**89.94**	**13,315,246**
	GENERAL CONDITIONS/ GENERAL REQUIREMENTS	12.50%		2.60	384,933	12.50%		11.24	1,664,406
	ESTIMATE/ DESIGN CONTINGENCY	20.00%		4.68	692,880	20.00%		20.24	2,995,930
	GEOGRAPHICAL FACTOR	-14.13%		(3.97)	(587,601)	-14.13%		(17.16)	(2,540,718)
	MARKET FACTOR **(ASSUME NOT APPLICABLE)**								
	SUBTOTAL			**24.11**	**3,569,679**			**104.26**	**15,434,864**
	BONDS & INSURANCE	2.00%		0.48	71,394	2.00%		2.09	308,697
	CONTRACTOR'S FEE	6.50%		1.57	232,029	6.50%		6.78	1,003,266
	R.O.M. OPINION OF PROBABLE COST EXCLUDING ESCALATION			**26.16**	**3,873,102**			**113.12**	**16,746,827**

ESCALATION (TO MIDPOINT) - See COST SUMMARY FOR ESCALATION CALCS

PROJECT: AAATA BUS PROPULSION STUDY						**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI						**DATE:**	**28-Apr-22**
CLIENT: STANTEC						**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION**	**EX. BUILDING AREA**	**148,045**	**FCEB OPTION**		**EX. BUILDING AREA**	**148,045**

ITEM NO.	DESCRIPTION	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST
1	**GENERAL REQUIREMENTS**				**$**				**$**
	SEE PERCENTAGE ALLOWANCE								
	SUBTOTAL								
2	**DEMOLITION**				**$**				**$**
	SITE DEMOLITION (HAULING INCLUDED)								
	REMOVE RAISED PLANTER & TREES	450	SF	8.00	3,600				
	REMOVE TAILPIPE EXHAUST & CAP AT MAINTENANCE BAYS	9	EA	864.00	7,776				
	DEMOLISH LANDSCAPE ISLAND AT ENTRY					1438	SF	5.00	7,190
	DEMOLISH DRIVE PAVING AT EQ. YARD					4146	SF	6.00	24,876
	DEMOLISH EX. CURB					331	LF	10.00	3,310
	MISC. SITE DEMO & PROTECTION WORK	1	LS	2,280.00	2,280	1	LS	7,080.00	7,080
	SUBTOTAL				**13,656**				**42,456**
3	**SITE IMPROVEMENTS**				**$**				**$**
	HARDSCAPE								
	NEW DRIVE PAVING AT DEMOLISHED LANDSCAPE ISLAND					1438	SF	10.00	14,380
	NEW CURB					121	LF	33.31	4,030
	PATCH SURFACE AT ELECTRICAL TRENCH	508	LF	28.50	14,478				
	CONCRETE PAVING + BASE + GRADING - GENERATOR YARD	450	SF	20.00	8,999				
	EQUIPMENT PAD S & THE LIKE								
	TRANSFORMER PAD/ SLAB BOX	3	EA	10,000.00	30,000				
	CONCRETE PAD - GENSET	2	EA	6,000.00	12,000				
	CONCRETE PAD - ATS	2	EA	400.00	800				
	MISC. HYDROGEN YARD PADS					1	LS	20,000.00	20,000
	EQUIPMENT ANCHORAGE								
	EQUIPMENT ANCHORAGE - TRANSFORMER	3	EA	750.00	2,250				
	EQUIPMENT ANCHORAGE - SWITCHBOARD	3	EA	500.00	1,500				
	EQUIPMENT ANCHORAGE - ATS	1	EA	350.00	350				
	EQUIPMENT ANCHORAGE - COMM. CABINET	1	EA	350.00	350				
	SITE MISCELLANEOUS								
	ALLOWANCE FOR REPLANTING OF TREES REMOVED FROM RAISED PLANTER, INCLUDING TREE IRRIGATION	1	LS	3,150.00	3,150	1	LS	7,350.00	7,350
	DOUBLE GATE TO CMU WALL AROUND LH2 EQUIPMENT YARD					1	PR	7,000.00	7,000

PROJECT: AAATA BUS PROPULSION STUDY		**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI		**DATE:**	**28-Apr-22**
CLIENT: STANTEC		**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION EX. BUILDING AREA 148,045**	**FCEB OPTION EX. BUILDING AREA**	**148,045**

ITEM NO.	DESCRIPTION	BEB YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST	FCEB YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST
	PIPE BOLLARD AT ELECTRICAL ROOM	4	EA	1,250.00	5,000				
	PARTIAL CHAIN LINK FENCE AT HYDROGEN YARD					135	LF	60.00	8,100
	ADDITIONAL SECURITY CAMERAS TIED TO EX. CONTROL ROOM					8	EA	4,500.00	36,000
	MISC. SITE IMPROVEMENTS ALLOWANCE	1	LS	3,940.00	3,940	1	LS	4,840.00	4,840
	SUBTOTAL				**82,817**				**101,700**
4	**BUILDING MODIFICATIONS & ADDITIONS**				**$**				**$**
	BEB OPTION								
	ELECTRICAL ROOM	$ 245.48	/SF						
	FOUNDATIONS & S.O.G.	1,200	SF	26.81	32,178				
	MASONRY WALLS	2,160	SF	40.00	86,400				
	DOUBLE DOOR	1	EA	8,000.00	8,000				
	ROOF STRUCTURE, ROOFING & ROOF DRAINS	1,200	SF	66.00	79,200				
	SPECIALTIES	1,200	SF	2.00	2,400				
	GASEOUS CLEAN AGENT EXTINGUISHING SYSTEM	1,200	SF	25.00	30,000				
	VENTILATION	1,200	SF	9.00	10,800				
	LIGHTING & BRANCH POWER	1,200	SF	18.50	22,200				
	ELECTRICAL EQUIPMENT - misc. circuitry only See Electrical for balance)	1,200	SF	10.00	12,000				
	COMMUNICATIONS & FIRE ALARM	1,200	SF	9.50	11,400				
	EXISTING BUILDING MODIFICATIONS								
	WALL PENETRATION AT NEW FEEDER LOCATION	6	EA	150.00	900				
	EQUIPMENT PADS TO CHARGERS, 10' L X 4' W	3	EA	1,000.00	3,000				
	REMOVE TAILPIPE EXHAUST & CAP AT MAINTENANCE BAYS	9	EA		SEE DEMOLITION				
	NEW FULL HEIGHT WALL & FOOTING BEWTWEEN CHARGING & MAINTENCE BAYS - ASSUME 18' H + FOUNDATION & C & P				N/A PER ARCH				
	FCEB OPTION								
	HYDROGEN FUEL FACILITY								
	NEW CMU WALL ENCLOSURE AROUND LH2 EQUIPMENT YARD, 9' H - INCLUDING FOUNDATION					243	LF	463.15	112,545
	NEW FULL HT. BLOCK WALLS TO CREATE FUEL BUILDING, 18' H INCLUDING FOUNDATION & C + P					230	LF	853.15	196,224
	FUEL BUILDING WITHIN EX. MAINTENANCE BUILDING + MODIFY					4431	SF	25.00	110,775
	HYDROGEN FUEL EQUIPMENT & RELATED								
	18.000 GALLON LH2 TANK					1	EA	875,000	875,000

PROJECT: AAATA BUS PROPULSION STUDY		**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI		**DATE:**	**28-Apr-22**
CLIENT: STANTEC		**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION EX. BUILDING AREA 148,045**	**FCEB OPTION EX. BUILDING AREA**	**148,045**

ITEM NO.	DESCRIPTION	BEB: EST QTY	BEB: UNIT	BEB: UNIT COST	BEB: TOTAL COST	FCEB: EST QTY	FCEB: UNIT	FCEB: UNIT COST	FCEB: TOTAL COST
		YEAR 2023 COST				**YEAR 2023 COST**			
	HIGH-PRESSURE LH2 PUMPS. 75 HP					3	EA	175,000	525,000
	H2 DISPENSER VAPORIZERS					3	EA	85,000	255,000
	H2 OFFLOAD VAPORIZER					1	EA	85,000	85,000
	GH2 STORAGE VESSELS					6	EA	38,000	228,000
	PRIORITY VALVE PANEL					1	EA	90,000	90,000
	BOLLARDS					15	EA	1,250	18,750
	AIR COMPRESSOR SYSTEM					1	EA	9,000	9,000
	PRE-DISPENSING CHILLER					2	EA	25,000	50,000
	H2 DISPENSERS					2	EA	85,000	170,000
	ALLOWANCE FOR FREIGHT, TAXES & INSTALLATION OF HYDROGEN FUELING EQUIPMENT					50%		2,305,750	1,152,875
	ELEC UTILITY TRANSFORMER, ALLOWANCE					1	LS	345,900.00	345,900
	ELEC PANELS AND CONTROLS, ALLOWANCE					1	LS	760,900.00	760,900
	INTRA HYDROGEN EQUIPMENT PIPING & POWER - ALLOWANCE					1	LS	684,800.00	684,800
	FUEL PIPING FROM HYDROGEN YARD TO BUILDING HYDROGEN DISPENSERS - ALLOWANCE					380	LF	112.50	42,750
	CUT & PATCH EX PAVING/FLOORING FOR PIPE TRENCH					380	LF	62.50	23,750
	BUILDING SYSTEM UPGRADES FOR FCEB								
	GAS/HYDROGEN DETECTION SYSTEM INCLUDING AUDIBLE & VISIBLE ALARMS					148,045	SF	11.22	1,661,065
	ENHANCED MECHANICAL VENTILATION - REMOVE & REPLACE EXISTING VENTILATION SYSTEM - The HVAC for this building is currently inadequate because it's just through-roof ventilators with heat recovery. additional units and ductwork will likely also be required to exhaust from the floor level for the current diesel vehicles in the facility to make it code compliant during transition to BEBs					148,045	SF	18.75	2,775,844
	ALLOWANCE FOR STRUCTURAL MODIFICATIONS NECESSITATED BY MODIFIED HVAC					148,045	SF	6.00	888,270
	ALLOWANCE FOR ELECTRICAL UPGRADES NECESSITATED BY ENHANCED SYSTEMS					148,045	SF	7.50	1,110,338
	ALLOWANCE FOR EXPLOSION PROOF M & E UPGRADES NECESSITATED BY HYDROGEN ENVIRONMENT					148,045	SF	6.75	999,304
	SUBTOTAL				**298,478**				**13,171,090**

PROJECT: AAATA BUS PROPULSION STUDY								**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI								**DATE:**	**28-Apr-22**
CLIENT: STANTEC								**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION**	**EX. BUILDING AREA**		**148,045**	**FCEB OPTION**	**EX. BUILDING AREA**			**148,045**

ITEM NO.	DESCRIPTION	**YEAR 2023 COST** EST QTY	UNIT	UNIT COST	TOTAL COST	**YEAR 2023 COST** EST QTY	UNIT	UNIT COST	TOTAL COST
5	**FURNITURE, FIXTURES AND EQUIPMENT**				**$**				**$**
	MAINTENANCE								
	F, F & E CHANGE FOR BEB FLEET - N.I.C.				N.I.C.				N.I.C.
	SUBTOTAL								
6	**ELECTRICAL, INCLUDING BEB EQUIPMENT**				**$**				**$**
	PRIMARY POWER SERVICE								
	NOT INCLUDED								
	MAIN POWER SYSTEM - NORMAL								
	TRANSFORMER, **2500 KVA**	3	EA	190,480.00	571,440				
	SWITCHBOARD, **2500A**, NEMA 3R	3	EA	151,650.00	454,950				
	EQUIPMENT GROUNDING SYSTEM	1	LS	2,500.00	2,500				
	POWER FEEDER RISERS, APPROX 25' L AT CHARGERS	3	EA	9,830.00	29,490				
	POWER FEEDER RISERS, APPROX 25' L BUILDING WALL TOWARDS ELECTRICAL ROOM	3	EA	9,830.00	29,490				
	U/G DUCT BANKED POWER FEEDERS (ELECTRICAL ROOM SWITCHGEAR TO OUTSIDE BUILDING WALL)	408	LF	355.81	145,172				
	EMERGENCY POWER								
	2.5 MW DIESEL GENERATOR INCL DAYTANK, MUFFLER & BATTERY CHARGER	2	EA	528,260.00	1,056,520				
	2.5 MW ATS & CONTROLS	2	EA	124,780.00	249,560				
	GENSET FEEDER, 2500A (FROM ELECTRICAL ROOM SWITCHBOARD)	200	LF	355.81	71,163				
	ATS FEEDER	200	LF	52.40	10,480				
	TRENCH/ DUCTBANK	100	LF	111.11	11,111				
	MISCELLANEOUS								
	MISC./ TESTING/COMMISSIONING	1	LS	52,640.00	52,640				
	SUBTOTAL				**2,684,516**				
7	**COMMUNICATIONS**				**$**				**$**
	PLEASE SEE BALANCE OF WORK								
	SUBTOTAL								

PROJECT: AAATA BUS PROPULSION STUDY						**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI						**DATE:**	**28-Apr-22**
CLIENT: STANTEC						**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION**	**EX. BUILDING AREA**	**148,045**	**FCEB OPTION**	**EX. BUILDING AREA**		**148,045**

ITEM NO.	DESCRIPTION	**YEAR 2023 COST** EST QTY	UNIT	UNIT COST	TOTAL COST	**YEAR 2023 COST** EST QTY	UNIT	UNIT COST	TOTAL COST
	SUMMARY OF ESTIMATE				**$**				**$**
1	GENERAL REQUIREMENTS								
2	DEMOLITION								
3	SITE IMPROVEMENTS	0.13%		0.13	19,815				
4	BUILDING MODIFICATIONS & ADDITIONS				494,141				
5	FURNITURE, FIXTURES AND EQUIPMENT				N.I.C.				N.I.C.
6	ELECTRICAL, INCLUDING BEB EQUIPMENT	94.62%		94.28	13,957,505				
7	COMMUNICATIONS	1.89%		1.89	279,221	100.00%		0.06	9,359
	SUBTOTAL	**96.65%**		**99.64**	**14,750,682**	**100.00%**		**0.06**	**9,359**
	GENERAL CONDITIONS/ GENERAL REQUIREMENTS	12.50%		12.45	1,843,835	12.50%		0.01	1,170
	ESTIMATE/ DESIGN CONTINGENCY	20.00%		22.42	3,318,903	20.00%		0.01	2,106
	GEOGRAPHICAL FACTOR	-14.13%		(19.01)	(2,814,618)	-14.13%		(0.01)	(1,786)
	MARKET FACTOR **(ASSUME NOT APPLICABLE)**								
	SUBTOTAL			**115.50**	**17,098,803**			**0.07**	**10,849**
	BONDS & INSURANCE	2.00%		2.31	341,976	2.00%		0.00	217
	CONTRACTOR'S FEE	6.50%		7.51	1,111,422	6.50%		0.00	705
	R.O.M. OPINION OF PROBABLE COST EXCLUDING ESCALATION			**125.31**	**18,552,201**			**0.08**	**11,771**

ESCALATION (TO MIDPOINT) - See COST SUMMARY FOR ESCALATION CALCS

PROJECT: AAATA BUS PROPULSION STUDY								**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI								**DATE:**	**28-Apr-22**
CLIENT: STANTEC								**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION**	**EX. BUILDING AREA**		**148,045**	**FCEB OPTION**	**EX. BUILDING AREA**			**148,045**

ITEM NO.	DESCRIPTION	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST
1	**GENERAL REQUIREMENTS**				**$**				**$**
	SEE PERCENTAGE ALLOWANCE								
	SUBTOTAL								
2	**DEMOLITION**				**$**				**$**
	SITE DEMOLITION (HAULING INCLUDED)								
	PLEASE SEE UP-FRONT INFRASTRUCTURE								
	SUBTOTAL								
3	**SITE IMPROVEMENTS**				**$**				**$**
						PLEASE SEE UP-FRONT INFRASTRUCTURE			
	EQUIPMENT ANCHORAGE								
	EQUIPMENT ANCHORAGE - 150KW CABINETS	50	EA	350.00	17,500				
	EQUIPMENT ANCHORAGE -25KW CABINETS	5	EA	275.00	1,375				
	MISC. SITE IMPROVEMENTS ALLOWANCE	1	LS	940.00	940				
	SUBTOTAL				**19,815**				
4	**BUILDING MODIFICATIONS & ADDITIONS**				**$**				**$**
	EXISTING BUILDING MODIFICATIONS								
	BOLLARDS TO CHARGER LOCATION	34	EA	1,250.00	42,500				
	MPE & F/P MODIFICATIONS TO BUS CHARGING AREA								
	MODIFICATIONS TO FIRE PROTECTION FOR PANTOGRAPHS	47,058	SF	1.73	81,175				
	MODIFICATIONS TO HVAC DUCTWORK FOR PANTOGRAPHS, MINIMAL	47,058	SF	0.98	45,882				
	MODIFICATIONS TO LIGHTING, ETC. FOR PANTOGRAPHS	47,058	SF	3.00	141,174				
	STRUCTURAL REINFORCING AT OVERHEAD VEHICLE PANTOGRAPH DISPENSER LOCATIONS	99	EA	1,200.00	118,800				
	MPE & F/P MODIFICATIONS TO MAINTENANCA AREA								
	MODIFICATIONS TO FIRE PROTECTION, M P & E SYSTEMS - MINIMAL ALLOWANCE	45,340	SF	1.43	64,610				

PROJECT: AAATA BUS PROPULSION STUDY		**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI		**DATE:**	**28-Apr-22**
CLIENT: STANTEC		**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION EX. BUILDING AREA 148,045**	**FCEB OPTION EX. BUILDING AREA**	**148,045**

ITEM NO.	DESCRIPTION	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST
	FCEB OPTION					PLEASE SEE UP-FRONT INFRASTRUCTURE			
	SUBTOTAL				**494,141**				
5	**FURNITURE, FIXTURES AND EQUIPMENT**				**$**				**$**
	PLEASE SEE UP-FRONT INFRASTRUCTURE								
	SUBTOTAL								
6	**ELECTRICAL, INCLUDING BEB EQUIPMENT**				**$**				**$**
	MAIN POWER SYSTEM - NORMAL								
	OVERHEAD MOUNTED POWER FEEDERS (CHARGERS TO OUTSIDE MAINTENANCE BUILDING WALL)	3042	LF	393.37	1,196,632				
	FLEET PARKING CHARGERS & DISPENSERS								
	DISCONNECT SWITCH, 250A/ 3P, NEMA 3R	50	EA	3,018.75	150,938				
	FAST DC/OC 180kW/60kW/60kW UL - MULTIPORT, INCLUDING 40% INSTALLATION & TAXES	50	EA	89,264.00	4,463,200				
	INVERTED PANTOGRAPH (600A UL) - HE2121089-01 - SCHUNK SL 301.102 INCLUDING 40% INSTALLATION & TAXES	99	EA	69,055.00	6,836,445				
	U/G FEEDER, 500A - SWITCHBOARD TO 180KW CABINETS	1,500	LF	315.85	473,775				
	TRENCH/ DUCTBANK - SWITCHBOARD TO CHARGERS	180	LF	83.33	15,000				
	MAINTENANCE BUILDING CHARGERS & DISPENSERS								
	FAST DC 50 kW MOBILE UL, INCLUDING 40% INSTALLATION & TAXES	5	EA	54,117.00	270,585				
	DISPENSERS AT EACH MAINTENANCE BAY - BASED ON HELIOX INVERTED PANTOGRAPH (250A UL) - HE2121089-01 - SCHUNK SL301.102, INCLUDING 40 INSATALLATION + TAXES	10	EA	43,701.00	437,010				
	STRUCTURE MOUNTED FEEDER,100A - SWITCHBOARD TO 50kW CHARGERS	175	LF	32.27	5,647				
	FEEDER FROM CHARGER TO DISPENSERS - STRUCTURE MOUNTED	810	LF	40.33	32,670				
	U/G FEEDER (SWITCHBOARD IN BUILDING AWAY FROM MAIN BUILDING) ,100A - SWITCHBOARD TO 50 kW CHARGERS	125	LF	50.64	6,330				
	TRENCH/ DUCTBANK - (2) to (6) CONDUITS	125	LF	46.18	5,773				
	TRENCH/ DUCTBANK - (8) to (12) CONDUITS								

PROJECT: AAATA BUS PROPULSION STUDY						**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI						**DATE:**	**28-Apr-22**
CLIENT: STANTEC						**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE COST	**BEB OPTION**	**EX. BUILDING AREA**	**148,045**	**FCEB OPTION**	**EX. BUILDING AREA**		**148,045**

ITEM NO.	DESCRIPTION	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST	YEAR 2023 COST EST QTY	UNIT	UNIT COST	TOTAL COST
	TRENCH/ DUCTBANK - (14) to (18) CONDUITS								
	MISCELLANEOUS								
	SITE ACCEPTANCE TEST - SAT & COMMISSIONING, DEPOT CHARGERS	50	EA	1,270.00	63,500				
	SUBTOTAL				**13,957,505**				
7	**COMMUNICATIONS**				**$**				**$**
	COMMUNICATIONS SYSTEM								
	IP ETHERNET WIRING FROM EACH CHARGER TO LOCAL DATA SWITCH - INCLUDES P.O.C.	11500	LF	10.38	119,425				
	POC TO LOCAL EXISTING DATA SWITCH	1	EA	1,000.00	1,000				
	IP ETHERNET WIRING FROM EACH 150 KW CHARGER TO ASSOCIATED DISPENSER - INCLUDES P,.O.C.	10890	LF	9.27	101,002				
	COMM. FEEDER - FROM COMMUNICATIONS CABINET TO 25KW CHARGER CABINETS - INCLUDES P.O.C.	2,850	LF	10.30	29,358				
	IP ETHERNET WIRING FROM EACH 25 KW CHARGER TO ASSOCIATED DISPENSER - INCLUDES P.O.C.	900	LF	9.95	8,956				
	IP ETHERNET WIRING FROM LOCAL DATA SWITCH TO HYDROGEN YARD INCLUDED WITH POWER DUCTBANK- INCLUDES P.O.C.					380	LF	9.95	3,781
	IP ETHERNET WIRING FROM LOCAL DATA SWITCH TO HYDROGEN YARD , STRUCTURE MOUNTED- INCLUDES P.O.C.					395	LF	10.17	4,018
	MISC./ TESTING	1	LS	19,480.00	19,480	1	LS	1,560.00	1,560
	SUBTOTAL				**279,221**				**9,359**

PROJECT: AAATA BUS PROPULSION STUDY		**JYI #:**	**C2605A-R2**
LOCATION: ANN ARBOR, MI		**DATE:**	**28-Apr-22**
CLIENT: STANTEC		**REVISED:**	**16-May-22**
DESCRIPTION: R.O.M. OPINION OF PROBABLE CAPTIAL COST - ESCALATION PARAMETERS			

ESCALATION CALCULATION PARAMETERS

BASE MONTH	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22	Apr-22
CONSTRUCTION START MONTH	**Jun-23**	**Jun-24**	**Jun-25**	**Jun-26**	**Jun-27**	**Jun-28**	**Jun-29**	**Jun-30**	**Jun-31**	**Jun-32**	**Jun-33**	**Jun-34**	**Jun-35**	**Jun-36**	**Jun-37**	**Jun-38**	**Jun-39**	**Jun-40**
CONSTRUCTION DURATION (MONTHS)	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
MID POINT OF CONSTRUCTION	Oct-23	Oct-24	Oct-25	Oct-26	Oct-27	Oct-28	Oct-29	Oct-30	Oct-31	Oct-32	Oct-33	Oct-34	Oct-35	Oct-36	Oct-37	Oct-38	Oct-39	Oct-40
% ANNUAL ESCALATION	8.50%	8.50%	8.00%	8.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%
ALLOWANCE FOR ESCALATION (TO MIDPOINT OF	12.68%	22.26%	30.54%	40.97%	44.70%	54.82%	65.65%	77.24%	89.64%	102.90%	117.10%	132.28%	148.53%	165.91%	184.52%	204.42%	225.71%	248.49%