



Zero Emission Bus Feasibility Study

Submitted by:
Center for Transportation and the Environment



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DASH
Zero Emission Bus Feasibility Study
Alexandria Transit Company

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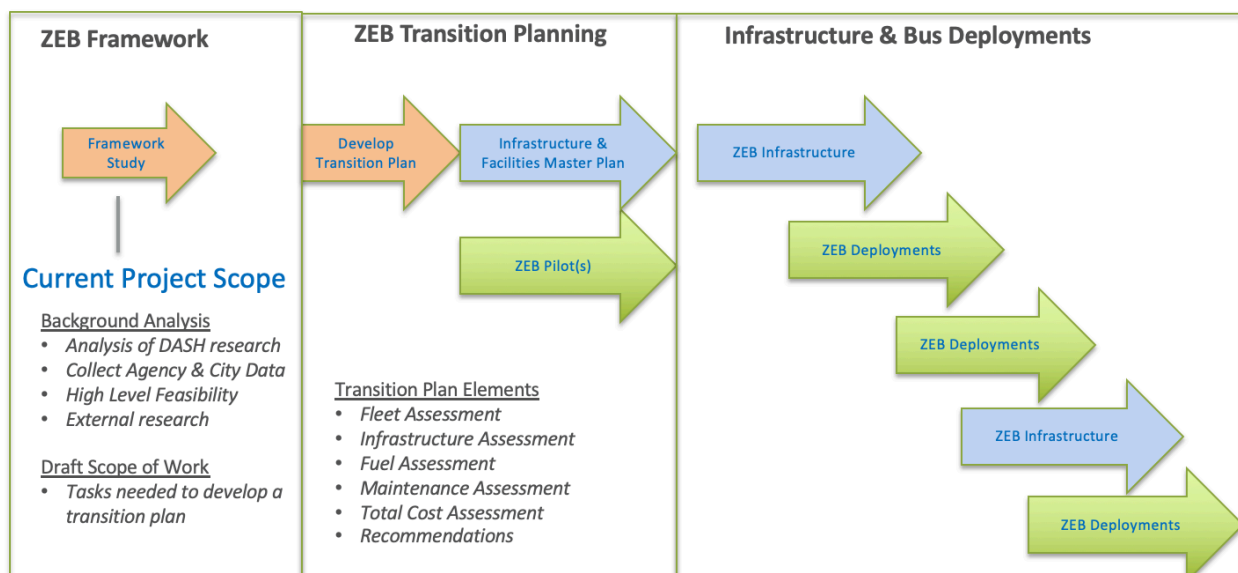
1 Introduction

DASH is the city bus system for Alexandria, Virginia. It is operated by the Alexandria Transit Company, a non-profit service corporation wholly owned by the City of Alexandria. DASH provides service to nearly four million passengers annually within portions of the City of Alexandria and between the City and the Pentagon Metrorail station. As part of its key role in providing safe, reliable service while supporting key city goals to provide environmentally friendly alternatives to the single occupant vehicle, DASH has undertaken several initiatives to understand zero emission bus technologies and their implementation. As part of their overall long-term fleet policy planning, DASH has engaged the Center for Transportation and the Environment (CTE) to perform a zero-emission bus fleet feasibility and planning study.

The study was conducted in two parts:

- **Part 1 - Background Analysis & Feasibility Study:** This body of work helps DASH understand the feasibility of transitioning to a zero-emission bus fleet based on: 1) evaluating the internal efforts taken to date, 2) collecting information on DASH's fleet, facilities, routes (including current and future block schedules) as well as governmental support and environmental conditions in the city, 3) performing a high level feasibility assessment based on this information, and 4) including supplemental best practices and external research.
- **Part 2- Implementation Plan Scope:** Based on the information from Part 1, CTE developed a draft scope of work that identifies tasks that are needed to develop a plan to transition the fleet to 100% zero emission.

This document describes Part 1– Background Analysis & Feasibility Study, shown in the first panel in the figure below.



2 Background Analysis

The goal of the background analysis is twofold: 1) to better understand the overall environment and support structure in which DASH will establish a new zero emissions fleet, and 2) analyze existing DASH research and internal efforts taken to date in evaluating the potential transition to zero emission buses (ZEB's). In support of these goals we elaborate on the following aspects:

- **Local Support and Initiatives:** this includes information on the political environment and local programs driving the motivation and goal-setting to establish a zero-emission fleet
- **Funding Sources:** this includes existing funding sources that DASH utilizes to purchase vehicles and infrastructure, whether this funding is primarily local, regional or federal, and suggestions for additional funding paths
- **DASH research on ZEB's:** this includes efforts taken by DASH to better understand ZEB technologies and their implementation
- **Strategic Planning:** a look at existing frameworks and plans that drive the future transition of the fleet and the future operations that the fleet will be required to support.

The following sections address these items.

2.1 Local Support & Initiatives

The City of Alexandria has clearly established numerous goals and initiatives related to environmental sustainability that directly impact and guide DASH's future planning. Over a decade ago the city established the **Eco-City Alexandria** initiative as a long-term strategic effort to become a sustainable community. In support of this overall initiative, The **Eco-City Charter** was adopted in 2008 and an **Environmental Action Plan** (EAP) in 2009. The EAP is considered to be the blueprint that will allow the city to achieve the goals of the Eco-City Charter. The **Alexandria Environmental Policy Commission** (which is part of the Alexandria Transportation Commission) serves as a key connection point between DASH and the city's environmental efforts.

As a result of the original EAP and the subsequent **Climate Change Action Plan** in 2011, an action item was established to develop a DASH policy that requires all new buses purchased to be low emission, hybrid or CNG vehicles in order to accelerate the goal of reducing fossil fuel use and the associated greenhouse gas and particulate matter emissions as well as noise pollution. This action item has guided bus procurement activities at DASH over the last decade and resulted in a transformation of the fleet toward hybrid electric, and more recently, clean diesel buses. Clean diesels were established as a path to achieve higher vehicle reliability than the hybrids have been able to achieve at a lower capital cost while supporting a state of good repair and lower vehicle emissions by continuing to take older diesel vehicles out of the fleet.

However, the city views electrification as the way forward to ultimately achieve its long-term goals in the area of transportation and in July 2019 established a revision to the EAP called **Environmental Action Plan 2040**. This revision includes a specific goal to replace 25% of the municipal fleet with electric vehicles by 2027, and 100% by 2040

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(https://www.alexandriava.gov/news_display.aspx?id=110544). Together with other key goals and actions (including the adoption of a new Green Building Policy in June 2019), the new initiative supports an overarching goal of reducing community greenhouse gas emissions 50% by 2030 and 100% by 2050. Clearly the city is committed to sustainability, and transportation is a key part of the effort. DASH's leadership and board has also recommended that DASH eventually convert to fully electric vehicles to meet its fleet replacement needs (TDP FY'19-FY'24) and stated its support to gradually transition the fleet to electric powered buses as soon as it is technically and financially possible. In 2018 DASH also established a Zero-Emission Fleet Working Group to guide transition planning.

Finally, the City of Alexandria also supports the Paris Agreement and complementary initiatives in neighboring Washington, DC. The nation's capital currently participates in the Mayors National Climate Action Plan Agreement (MNCAA) and has its own goal of buying all zero emission buses from 2025 forward.

2.2 Funding Sources

DASH's funding currently comes from primarily local and regional sources. Capital funding for bus replacements and facility improvements comes primarily from the city's Capital Improvement Program funds, as well as funds from the Northern Virginia Transportation Authority (NVTA) and the Virginia Department of Rail and Public Transportation (DRPT). Additional funding for electric buses is being provided by the VW Settlement Fund which is being managed by the Virginia Department of Environmental Quality (DEQ). \$14 million of the nearly \$94 million total VW Settlement for Virginia is being allotted to electric bus transit systems across the state. Primary examples of DASH capital funding are in Table 1 below.

Table 1. DASH Funding Sources

Source	Amount	Example Projects Funded
CIP (FY'19-FY-28)	\$51 million	Bus & battery replacements, facility expansion, technology
DRPT Smart Scale	\$11.3 million	Bus facility expansion from 90 to 130 bus capacity, 6 buses
NVTA (FY'18-FY'23 Six Year Plan)	\$11.9 million	8 ZEBs and facility upgrades for electric buses
VW Mitigation	Cost differential between clean diesel and electric	6 battery electric buses (funded in 2020)

Operating costs for DASH are primarily covered by a subsidy from the City of Alexandria's General Fund each year. The city also provides operational funding from the Transportation Improvement Program (TIP) and Capital Improvement Program (CIP). Fare revenues cover

approximately 20-25% of operating costs.

DASH does not generally receive federal funds for its capital improvement projects. In lieu of applying for its own federal funding, DASH provides information to the National Transit Database (NTD) which supports additional funding to the City of Alexandria, a designated recipient, who in turn uses the funds to subsidize WMATA. As mentioned above, the City of Alexandria also subsidizes DASH. A few years ago, DASH did get federal funds through the Congestion Mitigation and Air Quality (CMAQ) program and Regional Surface Transportation Program (RSTP) when those programs were managed through the Federal Highway Administration (FHWA), but DASH discontinued these grant requests after these programs were put under the Federal Transit Authority (FTA). DASH does not currently abide by the requirements to be a recipient of FTA funds but has recently started re-evaluating the effort and cost to do so in the future relative to the potential funds that could be obtained.

Obviously, any additional funding source can be of benefit in assisting and budgeting for individual deployment projects as part of a larger fleet transition effort. However, DASH should also consider the requirements of various federal programs when deciding whether to pursue such funding. Application criteria (available at the appropriate federal websites) should be evaluated to make sure the appropriate data and supporting documents are available that would result in competitive entries. Furthermore, DASH should assess the impacts of any post-award reporting requirements, such as Federal Financial Reports and Milestone Reports that would require ongoing monitoring during any deployment project. Regardless of funding source, CTE recommends that once DASH starts operating their first battery electric buses, they should put a priority on tracking vehicle performance and emissions reductions through a validation reporting/KPI process. This not only strengthens the case for future funding but also helps the agency and city understand if the project is meeting the emissions and financial goals of the program.

2.3 DASH ZEB Research & Demonstrations

DASH has taken a number of steps to better understand ZEB technologies and the requirements for implementation and operation. This has included the following:

- Interacting with other transit agencies that have done bus pilots/deployments to share information and learn from their experience
- Interacting with electric bus manufacturers to learn about their offerings, the technologies they employ and present/future product lines
- Participating in workshops and plant trips to OEM facilities as available
- Meeting with the local utility (Dominion Energy) to discuss applicability of current rate plans and potential future rate plans specific to ZEB's
- Organized both battery electric and fuel cell electric bus demonstrations on DASH's actual routes in order to collect real-world data on potential vehicle performance and the sensitivities relative to DASH's route structure and conditions.

A specific example of interacting with OEM's is a trip that DASH personnel took to visit the New Flyer Vehicle Innovation Center in Anniston, AL, where they participated in a workshop and

learned about the vehicle manufacturing process. This will help DASH in the future as they determine vehicle specifications that are most relevant and beneficial to their operation. Meeting with the local utility is an important step that many agencies do not think of during early planning- one which can have a future impact as the fleet expands and charging becomes a larger percentage of overall operating expenses. Available rate plans and charging schedule can dramatically impact overall cost to charge the buses, and many utilities have not yet developed rate schedules that are optimized for electric bus charging. Furthermore, DASH has had numerous discussions with Dominion Energy about Dominion's mandate in establishing a future electric vehicle rate plan, and they have also discussed plans for the creation of Time of Day/Time of Use rates that could benefit the agency if they could take advantage of off-peak hours to charge the fleet.

It is certainly important for an agency to obtain some real-world experience with ZEB's before and after they make the decision to select one or more OEM's and issue purchase orders. One way to do this is to take advantage of bus demonstrations on their local routes. The other way recommended by CTE is to plan one or more pilot programs using relatively small bus deployments to gain experience in operating these buses and setting expectations for performance and maintenance. This includes the realization and documentation of any operational limitations (e.g. battery capacity/range) that must be accounted for in the agency's process & route planning. This recommendation is already being implemented, as DASH has been awarded Volkswagen settlement funds enabling the purchase and deployment of six battery electric buses. The agency decided to award three buses to New Flyer and three to Proterra for the purposes of this project.

Regarding bus demonstrations, DASH has completed one program with bus OEM New Flyer and one with Proterra. The first one was done with a New Flyer 40-foot Xcelsior Charge in February 2018. The bus was run on a number of different routes at varying times of day and varying temperatures. This was an effective time to test a battery electric bus (BEB) and get a sense for the potential impact of the use of HVAC on overall efficiency, especially with regard to electric heat. The second demonstration was in May 2018 with a Proterra 40-foot Catalyst E2 model. Due to the moderate spring weather there were no extreme effects of HVAC, but the test provided the team additional data from a different OEM's product for comparison purposes. CTE finds it useful to compare and contrast between different OEM's in different conditions, especially since it allows DASH to get a sense for the design priorities each OEM has and how each company interacts and coordinates with its potential customers. A summary of the demonstrations is in Table 2 below.

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Table 2. BEB Demonstration Summary

Date	OEM / Model	Measured Efficiency *	Observations
February 2018	New Flyer 40' Excelsior Charge	2.26 – 2.93 kWh/mi (Average 2.55)	HVAC energy usage significant due to cold weather, no significant impacts from grade/hills
May 2018	Proterra 40' Catalyst E2	2.0 – 2.6 kWh/mi (Average 2.3)	Moderate spring weather, no extreme HVAC impacts

** Note: the term “efficiency” with regard to battery electric buses refers to the amount of energy consumed per mile of travel. Therefore, lower numbers represent better efficiency.*

Finally, CTE recommends that, in addition to demonstrations and pilot deployments, another good way to incorporate real-world data into the planning process is through route and vehicle modeling and simulation. In this process, actual route data is collected to derive speed and elevation/grade across representative routes from the agency. Then this information is fed into a computer simulation that runs these routes using vehicle system data based on actual specifications from the manufacturer. In this way, energy usage and potential charging schedules can be estimated relatively early in the process, the ideal time being after a bus model is selected and before a purchase order is placed with the OEM.

2.4 DASH Strategic Planning

DASH has been engaged in significant strategic planning in recent months due to the fleet replacement initiatives driven by the local plans and commitments discussed earlier in this report. There are two key strategic planning documents DASH uses to communicate long range plans for its fleet, infrastructure, and service/route structure. The first is the annual **Transit Development Plan (TDP)**, which contains sections that talk about current and future fleet structure and size, funding sources, and details of projects that will accomplish the fleet replacement schedule and associated facility improvements. The second document is the **Alexandria Transit Vision (ATV)**, the result of a process by which DASH evaluates its overall service and route structure looking into the future to best support the needs of a growing and changing community.

Through review of the TDP and additional information shared by the DASH team on this project, CTE has compiled a view of the current fleet structure and planned replacement dates. See Table 3 below.

Table 3. Active Fleet Current Composition

Bus Type (Qty)	Size	Replacement
Diesel (6)	35'	2019-2021
Hybrids (52)	35x35', 12x40', 5x29'	2021-2029
Clean Diesel (27)	35'	2030-2031

As is evident by this summary, there is opportunity in the current replacement schedule to make significant strides in transitioning the fleet to electric buses within the next 10-15 years, with the intent to meet the EAP 2040 goal of a 100% electric municipal fleet by 2040. To support this goal, CTE detailed the recommended steps and requirements to complete a transition plan in accompanying study entitled “Zero Emission Bus Implementation Plan Scope”. The current active fleet of 85 buses is serving 11 fixed routes and the one King Street Trolley route in the downtown area. The route structure itself will be going through significant changes over the next decade, which is reflected in the ATV process that is currently underway. As a result of a thorough process to assess the community’s needs as it grows over the next decade, the DASH team is currently designing a future vision for a new route structure planned to be fully in place by 2030. The new structure includes a movement towards increased ridership/frequency as opposed to adding or maintaining coverage-oriented service in low-density, low-ridership residential areas. It is expected that route consolidation, the adding of new strategic routes, and the extension of service on other routes will result in a system that is much less structured to support peak/off-peak (AM/PM) runs and more structured to support full-day service and higher overall utilization. This will provide more useful transit service with higher frequencies and longer spans of service.





DASH is currently evaluating the best strategy to incorporate electric buses into this changing environment and has established a section of the TDP to specifically address ongoing plans to begin to introduce ZEB vehicles and infrastructure into the system. DASH has been effective in kickstarting the transition through these initial plans by making them an integral part of the strategic planning documents. This study and the work to follow are aimed at adding definition to the future state needs and to the transition process that emerges. Please see Section 3 (Feasibility Assessment) for more information on the future state route structure vision and the implications of electric bus service.

3 High Level Feasibility Analysis

The purpose of the high-level feasibility analysis is to assess current and projected route structures and estimate the capability of an electric fleet to meet those requirements given the current technology capabilities in the industry. Specifically, we incorporate CTE's knowledge and experience regarding two leading technologies: the battery electric bus (BEB) and the fuel cell electric bus (FCEB). For BEB's we utilize generic, average efficiencies expressed in kWh/mi to estimate the energy requirements per block and the capability of BEB's to complete those blocks on one charge. In cases where BEB's cannot complete an existing block on one charge, we provide options for DASH to consider that will allow a fully electric fleet to meet all block service requirements.

To summarize, the results of this section will include the requirements to replace the current DASH fleet with the equivalent number of battery electric buses or fuel cell electric buses to meet service needs of the current route structure and the estimated route structure based on DASH's 2030 Vision. This vision is described by the current draft of the ATV, which was under development as of the date this analysis was performed. Please see Table 4 for a summary of these scenarios.

Table 4. Feasibility Study Scenarios

	Battery Electric	Fuel Cell Electric
Current Route Structure		
2030 Vision		

3.1 Assumptions

Because this level of analysis is meant to be for initial screening and scoping, there are a number of basic assumptions that apply to the whole study and are important to understand before the results are interpreted. First, we have some basic assumptions about characteristics of the current fleet and route structure:

- **We utilize a 20% industry-standard spare ratio** to reflect DASH's current goal.
- **We use the weekday schedule as a basis to calculate the number of buses required**, since the weekday schedule is the most demanding in terms of the number of buses (i.e. the most blocks)

Second, there are basic assumptions with regard to technology and performance:

- **We assume that the technology level (e.g. battery capacity) remains constant over time**
- **Battery capacity for BEB's is 450 kWh nameplate / 360 kWh useable service energy (when battery is new).** This is based on current battery technology for buses of similar size to what DASH currently has and has planned for the fleet. There is more explanation of battery capacity in the next section of this report.
- **The BEB energy required for the blocks is based on an overall efficiency of 2.7 kWh/mi.** This includes the energy required for moving the bus as well as for HVAC/accessory usage. This is a generic average based on CTE's experience with bus planning and deployments across the country. At this level of analysis, this number is not customized for DASH's operational environment but does reflect relatively strenuous energy usage which CTE considers conservative and prudent for high-level planning purposes. We considered both climate in the Alexandria, VA area as well as data reviewed from the bus demonstrations to help validate this assumption. We also provide a sensitivity analysis so that DASH can understand the impact of an even less favorable efficiency of 3.0 kWh/mi for further use in planning. Route & vehicle modeling, if chosen by DASH at a later date, would provide more customized and accurate results relative to the actual DASH operation.
- **For FCEB's we assume that based on current technology and range, buses can be replaced on a 1:1 basis (one FCEB to replace one diesel).** This is based on FCEB capabilities relative to DASH's current overall block duration and mileage requirements.

3.1.1 Typical Battery Capacity

Battery capacity is most often presented by the OEM's to potential customers as a "nameplate" number. This is an identifier given by the OEM to help customers better understand the overall, generalized capacity of the battery and to distinguish the capabilities of various battery/vehicle combinations. It does not represent the actual service capacity (total energy that can be stored and used) in a particular battery. In reality, there are regions of the total battery cell capacity that cannot be used without damaging and/or otherwise shortening the life of the cells. These zones are deemed "unusable" by the battery OEM and are not reflected in total battery State of Charge (SOC) indicators- therefore they are invisible and inaccessible to the customer during actual use.

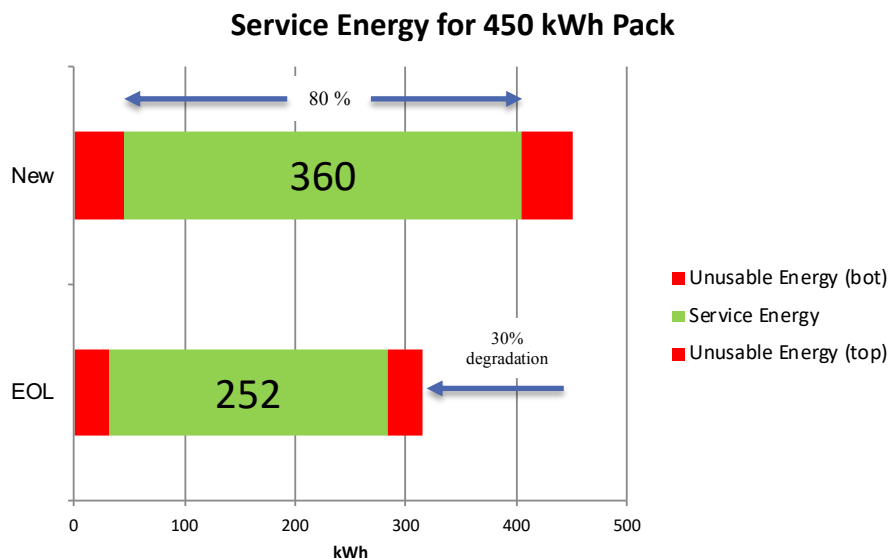
By way of explanation, please refer to the top bar of Figure 1. In this example, the nameplate or marketed capacity of the battery is 450 kWh when the battery is new. Note that, there are two zones marked in red, one at the bottom of the charging range and one at the top. These zones are the unusable zones and can represent up to 20% of the battery nameplate capacity. Therefore, the actual usable battery capacity (denoted as Service Energy in green) is 360 kWh. That means that the actual energy available for use by the bus is 360 kWh when the battery is fully charged. Note that there are additional zones (not shown here) that are part of the total

charging capacity that the operator may wish to avoid for the purposes of avoiding de-rated operation or to reserve as a contingency for unusual circumstances or emergencies. These are not considered specifically in this high-level scoping analysis but would be included in a more detailed route and charge modeling exercise.

Another concept to make note of is that as the battery ages, its overall charging capacity decreases. The bottom bar in Figure 1 shows the same battery that is near the end of its serviceable life (denoted “EOL”). This generally corresponds to the End of Life definition in most battery warranties and often represents about 70% of the original capacity of the battery when new. Note that the same unusable zones apply, so that the service energy of a battery at the end of its life is only 252 kWh in this example.

As mentioned in the discussion of assumptions earlier, we used a battery capacity (practical service energy available when fully charged) of 360 kWh for this assessment.

Figure 1. Typical Battery Capacity



3.1.2 Local Climate Conditions

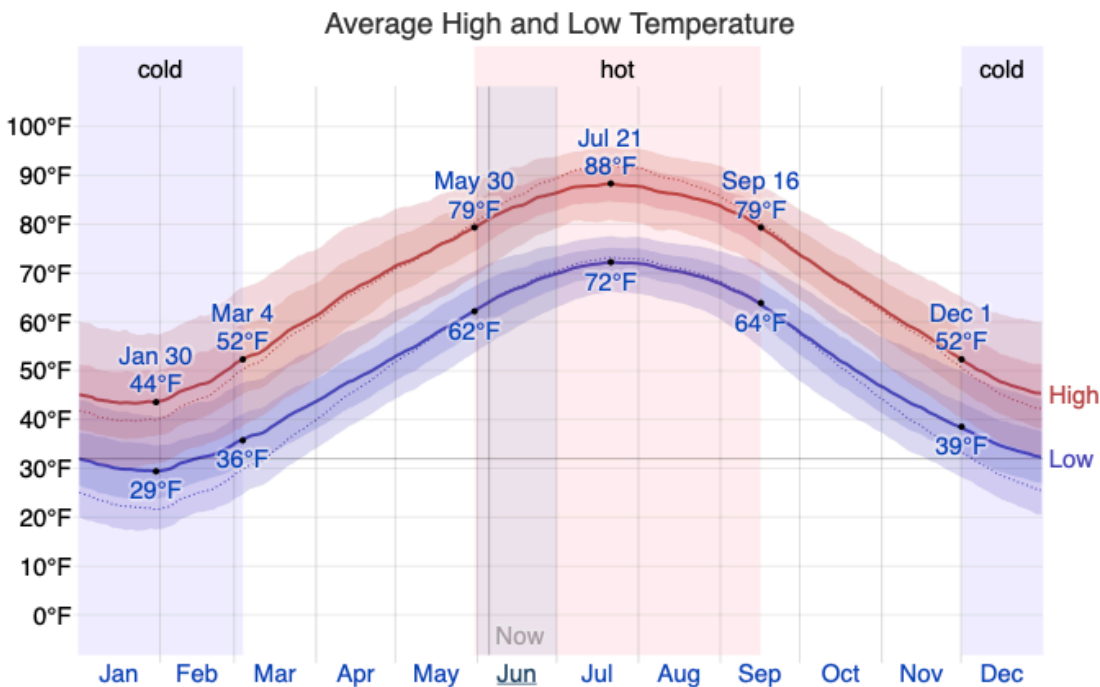
There are many aspects of electric bus operation that can affect its performance, and therefore electricity consumption. These include characteristics such as terrain/grade, the overall speed of the route (e.g. high-speed commuter route vs. low-speed circulator route), and driver behavior (e.g. severity of acceleration/deceleration, speed changes, use of accessories) among other influencers.

One of the primary drivers is HVAC use, especially in parts of the country that have more extreme/less moderate temperatures during specific times of the year. The standard HVAC

systems included in BEB's are driven by the same energy source that the motor is, namely the battery.

Both high temperatures and humidity in the summer and low temperatures in the winter can cause higher than normal HVAC usage, causing a significant amount of energy drain from the battery. The temperature profile for Alexandria is shown in Figure 2 below.

Figure 2. Annual Temperature Profile for Alexandria



Alexandria's average temperatures are relatively moderate most times of the year in comparison to other parts of the country. However, certain periods of lower than average temperatures in the winter or even average temperatures in the coldest months can cause noticeable additional energy usage that needs to be considered when estimating vehicle range. DASH saw this first hand during the New Flyer demonstration where buses operated part of the time during very cold mornings and the resulting energy usage per mile was higher. Route and Charge Modeling exercises account for these more variable conditions to help agencies understand the sensitivity on days where the passenger loads are particularly high and the temperatures particularly extreme. In the analysis in this study, the baseline average efficiency utilized (2.7 kWh) assumes a typical temperature profile such as the one above and was cross checked against the numbers achieved during the demonstrations. It is also important to note that although there are some routes in the demonstrations that resulted in efficiencies worse than 2.7 kWh, these are readings that cover a small window of time and temperature relative

to the entire operation, and there can be other factors contributing to higher energy usage during any one run. The efficiencies used in this study (2.7 kWh baseline and 3.0 kWh for the sensitivity analysis) are at a much less granular level and are averaged over a longer period of time.

Some operators in colder, more extreme climates than Alexandria's (such as in the Upper Midwest) have opted to utilize diesel heaters to take some HVAC energy burden off of the battery and extend the range of the bus. It should be noted that the need for a diesel heater is also dependent on a number of additional factors including how strenuous the routes are (e.g. topography, speed, length, passenger loads) as well as whether any on-route charging is available. These factors can be better assessed once detailed route modeling takes place. Based on the basic information gathered to date, CTE recommends that DASH pursue a possible option with the OEM's to outfit some of the six buses expected in FY 2020 with diesel heaters to get some initial experience with them and to assess their impact on energy usage in DASH's operational environment. Furthermore, since diesel heaters do produce some emissions, the agency should consider potential impacts on emission reduction targets and milestones. As battery technology continues to improve, the need for diesel heaters, and therefore the associated environmental impacts, should diminish over time.

3.2 Current & Future DASH Block Structures

The material in this section contains summaries of DASH's current block structure, the assumptions that are part of the draft 2030 Vision being developed as part of the ATV, and finally a picture of the block structure anticipated when the 2030 Vision assumptions are incorporated.

3.2.1 Current DASH Block Structure

The current DASH service supports a total of 11 different distinct routes plus the King Street Trolley service downtown. Service varies according to the day of the week, with weekday service containing a large number of shorter peak service runs, while the weekends have a smaller number of longer, full-day runs. Bus quantities below assume the current fleet composition (no electric).

Figure 3. Current Blocks

For **weekday service** there are generally 74 buses operating on a given day, plus another 11 buses as spares (this is not including the contingency fleet). There is a total of 113 blocks with more than half of these running as peak service, that is, separate AM and PM runs. The rest of the buses are running full day routes as well as the King Street Trolley. A summary is as follows:

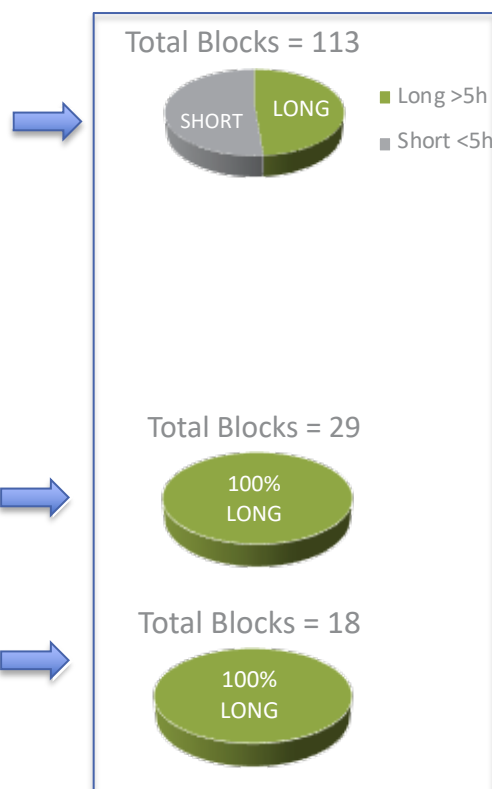
- 40 buses running peak AM/PM
- 29 buses running full day routes
- 5 additional running King Street Trolley

On **Saturday**, there are 29 buses running long blocks.

- 23 buses running full day routes
- 6 additional running King Street Trolley

On **Sunday**, there are 18 buses running long blocks.

- 12 buses running full day routes
- 6 additional running King Street Trolley



3.2.2 Assumptions for 2030 Vision

As of the writing of this report, the assumptions for DASH's 2030 Vision, as defined by the current draft structure in the ATV, are quite different than the current state. In general, there will be a large increase in the percentage of blocks that are over 5 hours in length. The overall number of blocks during the weekdays will not increase, however, because a number of the short, peak service blocks will be combined into a smaller number of longer blocks. Table 5 below shows the assumptions that are included in the analysis of electric bus deployments serving the future state (2030 Vision) route structure.

Table 5. Assumptions for 2030 Vision (Changes from Current)

Days	Apply To:	# Blocks	Duration/Miles
Weekday	Long Blocks (>5hr)	15% increase	10% increase
	Short Blocks (<5hr)	50% of blocks stay as is, remainder combined	Increase combined blocks by 5 hours
Saturday	All Blocks	40% increase	20% increase
Sunday	All Blocks	10% less than Saturday	10% less than Saturday
All	King St Trolley	2 additional blocks	Increase by 1-7 hours

3.2.3 Future DASH Block Structure

The new DASH service again varies according to the day of the week, except with a much larger percentage of longer blocks during the weekdays and more overall blocks on the weekend (and of longer duration and length) relative to the current structure. The bus quantities below assume the current fleet composition (no electrics).

For **weekday service** there would be 94 buses operating on a given day, plus another 24 buses as spares (this is not including the contingency fleet). There is a total of 108 blocks, with only 15% running as peak service, and only 23% of the blocks are over five hours. The rest of the buses are running longer routes, including the King Street Trolley. A summary is as follows:

- 14 buses running peak AM/PM
- 73 buses running full day routes
- 7 additional running King Street Trolley

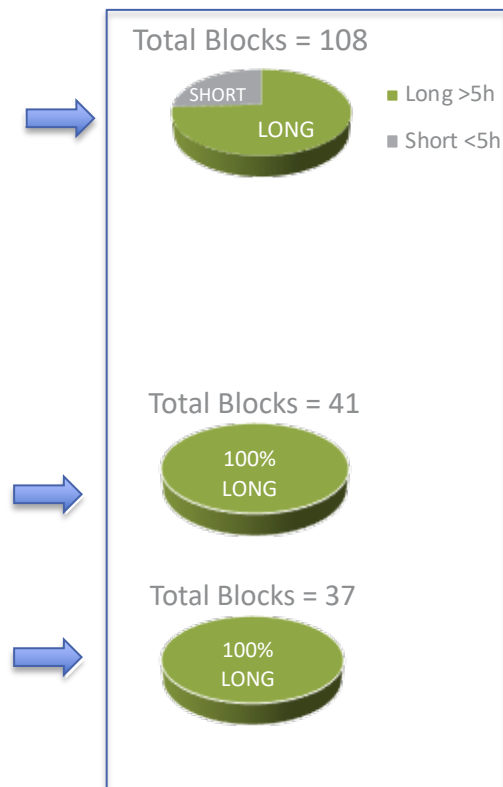
On **Saturday**, there are 41 buses running long blocks.

- 33 buses running full day routes
- 8 additional running King Street Trolley

On **Sunday**, there are 37 buses running long blocks.

- 30 buses running full day routes
- 7 additional running King Street Trolley

Figure 4. Future Blocks



3.3 Estimated Zero Emission Buses Required

After the data collection and detailed blocking structures were generated, CTE estimated the number of battery electric buses and fuel cell electric buses that would be required to support both the current and future state systems. During the data collection phase of this project, CTE obtained detailed mileage and duration information from DASH describing each of their current blocks. For battery electric buses, we applied the kWh/mi efficiency baseline to those mileages to estimate the total energy required for each block for an average weekday as well as for Saturday and Sunday. Weekdays contain the most demanding schedule (requiring the most buses, both in the baseline and future state), therefore we used the weekday results to guide our recommendation regarding the number of buses required.

We include fuel cell electric buses (FCEB's) in this analysis because fuel cell technology is rapidly developing and expected to play a potentially important role as agencies transition their fleets to 100% zero emissions. One benefit of FCEB's is that their current range is comparable to that of diesel buses, so an FCEB is capable of completing any of the individual DASH blocks analyzed in this study. The downside of current FCEB's is that the vehicle and infrastructure buildout costs as well as the cost of hydrogen remain high due to the relative infancy of the market. However, this is changing in a positive direction as the technology and markets continue to develop. Even though the number of current deployments of FCEB's is relatively low, CTE considers the technology an important one to consider for a role during the timeframe required for full fleet transitions. Therefore, this analysis as well as our transition planning studies include scenarios with FCEB's as an option for consideration.

Current battery electric bus technology does not provide the range to complete all of blocks that their diesel counterparts do, at least not on one full charge. So, our BEB results are based on analyzing the block energy requirements and counting the cases where electric buses can replace current buses on a 1:1 basis versus cases where it would take more than one electric bus to operate a block currently covered by one conventional bus. We start with the initial assumption that buses are charged overnight and are expected to run as long as they can the following day on that one charge. This is partially based on initial conversations with DASH personnel regarding the hub & spoke route structure. The center of the "hub" is generally the King Street area where buses do not spend much time and therefore would not be able to achieve significant charging. Outlier locations have somewhat more layover time but would have barriers to consider regarding permitting and an evaluation of whether a significant part of the fleet would benefit from charging at any one location. This is beyond the scope of this study.

Based on these initial conditions, we determine that any block that requires an amount of energy that is less than the service energy available for a new battery (360 kWh) would be able to be served by one battery electric bus (BEB). Any block that requires more than (360 kWh) would require more than one bus under the assumption of one overnight charge per day. As

discussed earlier, the capacity of batteries does degrade as the battery gets older. It is assumed here that there will be a relatively steady replacement schedule over time such that as an older BEB becomes less capable of completing a longer, more strenuous route it could be moved to an easier route on the schedule and substituted with a newer BEB. In the case of fuel cell electric buses, current technology and range is such that each DASH block would be served by one FCEB. Therefore, replacements can be made on a 1:1 basis. This is reflected in each set of results below. Please refer to the Appendix for detailed lists of block-level energy calculation results for different types of routes.

Finally, note that these results do not capture variations in efficiencies across different routes and distinct conditions. Therefore, this data should be used for high level scoping only. For more accurate and detailed planning, CTE recommends route modeling to capture a better cross-section of DASH's operating conditions and associated vehicle system performance.

3.3.1 Current System

As mentioned previously, under the current route & block structure, DASH operates 74 buses on a typical weekday and has an additional 11 buses as operational spares, reflecting a spare ratio of just over 12%. However, DASH's current goal is to reach the industry standard of 20%, so we calculate a total current fleet size of 93 (19 spares) to reflect that spare ratio. Out of the 74 operating buses, 64 of them can be replaced with BEB's on a 1:1 basis based on the energy required to complete each of those blocks. The other 10 buses cannot complete their blocks on one charge. Therefore, under the scenario of operating a full day on one charge, those 10 blocks would require twice as many buses (20). This means that 84 BEB's would be required to operate the blocks that 74 buses are able to complete today. Including spares (at a spare ratio of 20%) means that DASH should plan for a total of 105 BEB's (versus 93 buses today). Using all FCEB's, the fleet size would remain the same as today. Results are summarized in Table 6.

Table 6. Zero Emission Buses Required Under Current Route Structure

For: Current Route Structure	Current Fleet	BEB 1:1	BEB 2:1	BEB Total	FCEB Total
# buses operating	74	64	20	84	74
# buses w/20% spare goal	93			105	93

3.3.2 Future System (2030 Vision)

Under the future block structure described in Section 3.2.3, CTE estimates that with the current (non-electric) fleet composition, DASH would require 94 buses plus 24 additional buses as operational spares. Out of the 94 operating buses, 70 of them can be replaced on a 1:1 basis

DASH
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with BEB's based on the energy required to complete each of those blocks. The other 24 buses cannot complete their blocks on one charge. Therefore, under the scenario of operating a full day on one charge, those 24 blocks would require twice as many buses (48). This means that 118 BEB's would be required to operate the blocks that 94 non-electric buses would be able to complete. Including spares (at a spare ratio of 20%) means that DASH should plan for a total of 148 BEB's (versus 118 non-electric buses). Using all FCEB's, the fleet size would be the same as with the current fleet at 118 buses. Results are summarized in Table 7.

Table 7. Zero Emission Buses Required Under Future Route Structure

For: 2030 Vision	Current Fleet	BEB 1:1	BEB 2:1	BEB Total	FCEB Total
# buses operating	94	70	48	118	94
# buses w/20% spare goal	118			148	118

It should be noted that in both the current system and future system scenarios the number of additional BEB's could potentially be reduced by restructuring the blocks that require more than one BEB in order to optimize vehicle utilization. This exercise was not part of this study but could be done in future transition planning. Furthermore, if it is determined that on-route charging is feasible at some point at certain locations, some buses could stay in revenue service longer before returning to the depot and avoid having to be replaced with an additional bus in the middle of a block.

3.4 Deployment Options

In the context of this study, deployment options are discussed relevant to an end state of a 100% zero emissions fleet. There are three primary ways an agency can handle the additional requirements of an electric fleet caused by battery/range limitations. **The first option is to add BEB's** to accommodate the portions of blocks that cannot be completed on one charge. This is accomplished by the BEB calculations in the previous sections. As mentioned previously, the above results are based on a 2.7 kWh/mi average efficiency across all routes, which does not account for variation in environmental or load conditions or differences in operational conditions such as speed or grade between specific routes. To provide additional insight in this study, CTE performed a sensitivity analysis by running the same calculations using an efficiency of 3.0 kWh/mi. DASH can use this variant if they require more conservative numbers for certain planning activities or as a way to set expectations in advance regarding the fleet requirements under different sets of conditions. Using the more pessimistic average efficiency of 3.0 kWh/mi results in a requirement for roughly **10 additional buses** (including spares) beyond the numbers shown in the previous sections for the current route structure and **11 additional buses** (including spares) for the future route structure.

Transitioning a fleet to all BEB's has a few advantages. First it allows for a consistent and less complex charging/fueling infrastructure and process since there would presumably be one set of depot-style chargers in one location where all buses would be charged overnight. This eliminates the need to have different types of chargers in the field (such as overhead chargers) as well as eliminating the need to tightly control the logistics of buses charging remotely where there is limited layover time and the potential for multiple buses competing for the same charger while in revenue service. The disadvantage of this option is the higher costs associated with owning and maintaining a larger fleet. As described in section 3.3.2, block restructuring can help in reducing the number of extra buses required. Also offsetting this extra cost is the fact that BEB's upfront per unit purchase cost (~\$750,000 not including add-ons/option) is somewhat lower than other technologies, such as FCEB's (~\$1,200,000 not including add-ons/options).

The second option is to purchase fuel cell electric buses (FCEB's) instead of battery electric buses (BEB's). This would allow a one-to-one replacement due to the longer range of FCEB's. However, as mentioned above, the upfront unit cost is higher, and another disadvantage is that it requires additional investment in hydrogen fueling infrastructure and logistics to either get the hydrogen delivered or manufactured on-site. It follows that another variant of these first two options is to have a mixed fleet incorporating both technologies, which can take advantage of each technology's strengths but also adds more complexity to the fleet and to the transition.

Finally, a **third option is to utilize on-route charging with a BEB fleet**. The advantage of this option is that it would allow for a longer range away from the depot and achieve more revenue hours in a given day. Another advantage is that electricity demand would be spread across the

day and in different locations to possibly help minimize demand charges that could otherwise be incurred by buses charging concurrently for longer periods in the evening. The disadvantages include the additional up-front cost for charging infrastructure, potential permitting and location restrictions, and adding buses may still be required depending on the amount of block restructuring that could be done.

3.4 Feasibility Analysis Conclusions

There are three summary conclusions as a result of this analysis:

1. **The DASH route structure, both current and future, generally supports the transition to an all-electric fleet.** The centralized system, covering a relatively small area with routes of reasonable duration and mileage, is beneficial in effectively managing a gradual and phased transition to electric technology. This is enhanced by local support and initiatives as well as the amount of research and effort that DASH is putting into understanding the benefits and implementation requirements of the technology.
2. **Utilizing battery electric buses will most likely require a somewhat larger fleet assuming today's level of technology.** However, as technology advances (which CTE firmly expects that it will continue to do), this requirement will be reduced. Furthermore, the options of incorporating fuel cell electric buses, block restructuring, and possible focused use of on-route charging can also compensate for current BEB range limitations.
3. **Modeling and full transition planning can further clarify the expected impacts and optimize deployments relative to DASH's current and future operations.** CTE recommends that this next level of planning be pursued by DASH so that a more complete picture of benefits, impacts and lifecycle costs can be generated. Furthermore, master planning will enable an effective set of phased projects to gradually introduce both vehicles and infrastructure in a controlled fashion to maximize performance and minimize service disruptions through the transition period.

4 Best Practices

As a result of CTE's involvement in a large number of electric bus deployments over a long period of time and across a diverse set of transit agencies, we have had the opportunity to collect a large database of best practices and lessons learned. This knowledge base is becoming increasingly important as more agencies are preparing for a long-term commitment to these beneficial technologies via full fleet transition.

The Appendix includes a selection of these lessons learned that we feel would be of particular interest to DASH at this time in their evaluation activities based on the work we have done together on this project. Below is a summary of the topics covered in the Appendix. CTE is also happy to provide more complete access to additional topics or topic categories upon request.

Battery Electric Buses

- Impact of HVAC on range
- Mid-day charging
- Maximizing utilization
- Understanding manufacturer's claims
- Operating ZEB's during emergencies / back up power

Charging Battery Electric Buses

- Managing demand
- Charging technology selection
- Charge and rate modeling
- Considering charging time in block planning

Fuel Cell Buses

- Spare parts and downtime
- Modeling fuel costs
- Hydrogen safety training

Hydrogen Fueling

- Fueling station technology selection
- Fueling station operation
- Redundancy – hydrogen delivery
- Scaling up fueling infrastructure

Appendices

1. Block Level Energy Requirements (Current System)
2. Selection of Lessons Learned

Appendix 1: Current Block Energy Assessment

AM/PM Blocks: Optimized Pairing of Long & Short Blocks to Maximize Utilization on One Charge

AM BLOCKS			PM BLOCKS			FULL DAY		AM BLOCKS			PM BLOCKS			FULL DAY	
Block #	Miles	Energy Req'd	Block #	Miles	Energy Req'd	Total Miles	TOTAL ENERGY	Block #	Miles	Energy Req'd	Block #	Miles	Energy Req'd	Total Miles	TOTAL ENERGY
24	76	204	97	18	47	93	252	60	36	96	69	46	125	82	221
10	66	177	104	19	52	85	229	54	35	93	82	46	125	81	218
38	65	176	90	25	67	90	243	1330	33	90	84	48	130	81	220
11	56	152	1323	25	67	81	219	50	33	89	89	49	133	82	222
15	54	145	1327	25	67	79	213	49	31	84	101	50	135	81	219
31	51	136	105	26	71	77	208	56	31	83	77	53	142	83	225
4	49	132	88	27	72	76	204	9901	29	79	93	53	143	82	222
25	46	125	80	30	82	77	207	62	29	78	81	54	146	83	223
2	45	122	96	31	83	76	205	1326	28	75	86	54	147	82	222
8	44	118	102	32	87	76	205	1334	28	75	68	56	150	84	226
29	43	116	72	33	88	76	205	9904	27	72	9906	57	154	84	225
48	43	115	73	33	89	76	204	27	26	71	83	58	157	84	228
19	42	115	95	33	89	75	203	42	26	69	74	58	157	84	226
44	41	111	1335	33	89	74	200	1322	25	68	76	61	163	86	231
30	40	108	78	35	93	75	201	32	24	66	67	67	181	91	246
34	40	108	1331	35	95	75	203	9903	24	65	91	69	186	93	251
23	39	106	87	36	98	76	204	63	21	58	103	72	193	93	251
6	39	105	85	38	103	77	207	9902	19	52	75	83	224	102	276
45	37	99	94	38	103	75	202	64	17	46	71	85	229	102	275
9905	36	97	100	43	115	79	213				70	85	230	85	230

Battery Service Energy Capacity (New) = 360 kWh

Appendix 1 (Continued)

First In / First Out Block Pairing

AM BLOCKS			PM BLOCKS			FULL DAY		AM BLOCKS			PM BLOCKS			FULL DAY	
Block #	Miles	Energy Req'd	Block #	Miles	Energy Req'd	Total Miles	TOTAL ENERGY	Block #	Miles	Energy Req'd	Block #	Miles	Energy Req'd	Total Miles	TOTAL ENERGY
27	26	71	67	67	181	93	252	19	42	115	86	54	147	97	261
32	24	66	68	56	150	80	216	30	40	108	87	36	98	76	206
9904	27	72	69	46	125	73	197	50	33	89	88	27	72	60	162
9901	29	79	70	85	230	114	309	4	49	132	89	49	133	98	264
42	26	69	71	85	229	110	298	25	46	125	90	25	67	71	192
56	31	83	72	33	88	64	172	60	36	96	91	69	186	104	282
1326	28	75	1335	33	89	61	165	44	41	111	102	32	87	74	199
6	39	105	74	58	157	97	262	45	37	99	93	53	143	90	242
2	45	122	75	83	224	128	346	9903	24	65	94	38	103	62	168
64	17	46	1331	35	95	52	141	8	44	118	95	33	89	77	207
9902	19	52	76	61	163	80	215	11	56	152	1323	25	67	81	219
1330	33	90	80	30	82	64	172	62	29	78	96	31	83	60	161
1334	28	75	78	35	93	62	169	31	51	136	9906	57	154	108	290
9905	36	97	77	53	142	89	239	15	54	145	100	43	115	97	261
49	31	84	81	54	146	85	230	29	43	116	73	33	89	76	205
1322	25	68	82	46	125	72	193	48	43	115	101	50	135	93	250
63	21	58	83	58	157	80	215	10	66	177	103	72	193	137	370
23	39	106	84	48	130	87	236	38	65	176	97	18	47	83	223
34	40	108	85	38	103	78	210	24	76	204	104	19	52	95	256
54	35	93	1327	25	67	59	161				105	26	71	26	71

Battery Service Energy Capacity (New) = 360 kWh

Appendix 1 (Continued)

Full Day Blocks - Assessment

Achievable on One Charge

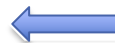
Block #	St Time	End Time	Miles	Energy Req'd	Achievable?
17	1055A	737P	72	196	YES
55	642A	617P	93	251	YES
14	524A	541P	102	274	YES
36	601A	722P	107	288	YES
21	542A	747P	110	296	YES
66	755A	740P	110	298	YES
40	611A	734P	112	303	YES
9	518A	700P	113	305	YES
43	615A	742P	113	306	YES
1	447A	739P	117	315	YES
33	600A	1046P	123	333	YES
26	553A	923P	124	336	YES
39	608A	835P	126	339	YES
18	535A	730P	127	342	YES
12	520A	715P	128	346	YES
57	645A	1008P	129	348	YES
53	637A	1005P	130	352	YES
37	603A	828P	131	353	YES
59	653A	1020P	131	355	YES
7	515A	943P	132	356	YES

Not Achievable on One Charge

Block #	St Time	End Time	Miles	Energy Req'd	Achievable?
16	531A	829P	138	374	NO
22	545A	843P	142	383	NO
28	556A	940P	143	387	NO
58	649A	1040P	146	393	NO
46	620A	1047P	157	424	NO
5	458A	1236X	159	428	NO
52	637A	1115P	162	436	NO
13	520A	1136P	170	458	NO
3	450A	1057P	170	459	NO

Options:

- Run additional buses
- Re-block with on-route charging



Appendix 2: Lessons Learned

Battery Electric Buses

Plan for utilizing ZEBs during emergencies	In the event of a power outage, you may want to consider implementing a backup power or other power storage solution to ensure uninterrupted operation of the ZEB fleet. Your agency may provide assistance for community critical functions, such as evacuations. A backup power source will allow your ZEB fleet to continue to support these functions as needed.
Impact of HVAC systems on range	High air conditioning or heating requirements can impact the range of a BEB in extreme climates. Identify if changes must be made to the ZEB deployment plan seasonally to allow for more charging time, or to deploy BEBs on shorter pieces of work.
Consider incorporating a mid-day charge to increase bus usage	If appropriate for your agency's service plan and fuel costs, pairing blocks with a mid-day charge can maximize the utilization of the buses, while accommodating range limitations.
Service planning to maximize bus use throughout its service life	Ensure that you complete sufficient planning to maximize bus use when the battery is new and towards the end of its service life. Identify blocks that will optimize usage of the electric bus, to fully utilize the available battery capacity. Consider the costs and benefits of designing new blocks specifically for the capabilities of your electric buses. For initial deployment projects, this may not be cost effective. Changes to your service may be required as ZEBs compose a larger percentage of your fleet.
Understanding manufacturer's claims	A large transit agency ordered several Battery Electric Buses (BEBs) to deploy in their service area for a specific route based on manufacturer claims for expected range. After buses were delivered, the agency found that the buses did not meet the range and performance required to be deployed on the planned routes.

Appendix 2 (Continued)

Battery Electric Bus Charging

Managing demand charges	A transit agency installing five depot chargers found that by locating the chargers on the same meter servicing the maintenance facility, the increase in demand created by the depot chargers overnight was offset by the facility demand during the day.
Select charging technology	<p>Three options exist for charging BEBs: plug-in charging, overhead conductive charging, and wireless inductive charging.</p> <p>When selecting charging infrastructure, agencies must consider their route demands (speeds, grades, stops, lengths, layovers), bus service or blocking demands (deadheads, duration, and frequency), seasonal temperatures, passenger loads, available garage space and power, layover or transit center locations and space, and utility rate schedules and costs.</p>
Charge modeling as a complement to electricity rate modeling	<p>Ensure that estimates of how long it will take to charge your buses, as well as any proposed charge management procedures are incorporated into your electricity rate modeling. For example, you may be able to charge buses sequentially, instead of simultaneously, to lower demand charges.</p> <p>For on-route charging, consider that the charger will only be available at certain times of the day. Therefore, you will need to determine when, where, and for what duration the bus will be charged.</p>
Incorporating charging time into block planning	Adjust route schedules to accommodate BEB charging time; this is part of the transition from conventional technology buses to electric buses. An agency may need to add deadhead miles prior to the start of the route depending on the location of the on-route charging station and availability of an in-depot charger.

Appendix 2 (Continued)

Fuel Cell Buses

Limited spare part availability causing downtime and increased operational costs	<p>One transit agency has experienced issues with the availability of bus components that have a long lead time for delivery. One reason for the lead time is the need to order foreign supplied parts through a distributor.</p> <p>The transit agency found that their distributor only offered some components as kits. This added unnecessary cost for cases where only one part out of the kit was needed for repair. Working directly with the component manufacturer also helps address this issue.</p>
Model fuel costs for planned operation	<p>For FCEBs, estimate the total costs of obtaining hydrogen, either by purchasing directly, or producing on-site. If your transit agency is producing hydrogen on-site, include costs for raw materials and electricity to power the equipment.</p>
Safety training - hydrogen	<p>Hydrogen, by itself, burns invisibly and does not produce any smoke. Large hydrogen fires can only be extinguished by shutting of the fuel supply of the fire. Small hydrogen fires can be extinguished with dry power retardant, carbon dioxide, a halon extinguisher, or a fire blanket.</p> <p>It is recommended that the fuel supply of a hydrogen fire is shut off before extinguishment due to the risk of reignition. If the fuel source cannot be shut off, the fire should be contained and actions to be taken to prevent the fire from spreading.</p>

Appendix 2 (Continued)

Hydrogen Fueling

Hydrogen fueling station technology selection	<p>Consider the following criteria for deploying hydrogen fueling infrastructure:</p> <ul style="list-style-type: none">• Type of structure: temporary, semi-permanent, or permanent• Location (will impact permitting requirements)• Fueling medium (liquid or gaseous hydrogen; most transit applications utilize liquid hydrogen)• Hydrogen delivery or on-site production
Scaling up fueling infrastructure	<p>Consider the end goals for fleet electrification when planning fueling infrastructure needs.</p> <p>In general, scaling up hydrogen fueling infrastructure may be less costly and less land-intensive than scaling up battery charging infrastructure. Additional vaporizers and dispensers would need to be added to the station, but a separate facility will most likely not be necessary.</p>
Redundancy - hydrogen delivery	<p>There are limited hydrogen suppliers in the U.S., therefore you may want to establish a redundancy plan to receive hydrogen if your usual supplier is unable to meet the demand due to a natural disaster or other event.</p>
Model fuel costs for planned operation	<p>For FCEBs, estimate the total costs of obtaining hydrogen, either by purchasing directly, or producing on-site. If your transit agency is producing hydrogen on-site, include costs for raw materials and electricity to power the equipment.</p>
Hydrogen fueling station - operation	<p>One of the benefits of hydrogen fueling infrastructure is that the operation is similar to diesel fueling stations that transit agencies are familiar with. Transit agencies should plan for additional fueling time required to vaporize liquid hydrogen (if using). This may contribute to additional labor or operational costs.</p>