SEPTA FORWARD >>>

Zero-Emission Bus PLAYBOOK

Version 2
September 2022
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Contents

Contents

1 Executive Summary

SEPTA is committed to transitioning away from diesel powered buses to ensure a clean, sustainable, and resilient future. The agency is planning for a full transition to all zero-emission buses (ZEBs), which could include a combination of battery-electric buses (BEBs) and fuel cell electric buses (FCEBs). This playbook outlines the planning and analysis to support a full transition by the year 2040, provided that funding is available for the necessary infrastructure investments.

SEPTA's plan for a transition to all ZEBs is presented here as a "playbook" in order to convey that it will be a planning process, and implementation decisions will continue to be refined over time. The 15- to 20-year transition period will include significant facility upgrades that need to be planned years in advance, while also monitoring constant improvements in zero-emission bus technology improvements. Navigating this dynamic will require a flexible approach within the context of a longer-term vision that can continue to be refined over time. The analysis presented in this playbook provides direction for how SEPTA can transition to all zero-emission buses by the year 2040, including where to prioritize initial investments and next steps for piloting concepts and beginning the implementation process. Future iterations of this playbook can incorporate lessons learned from piloting implementation concepts, additional analysis on key topics such as the likely need for a new garage and additional technology monitoring over time.

This playbook focuses on maximizing the use of ZEBs within the SEPTA fleet. To the extent that BEBs are used, SEPTA may need to overcome range limitations by installing some on-route charging and making schedule changes that add to operating costs and the total fleet requirement. SEPTA has identified overhead drop-down pantographs as its preferred BEB charging technology for charging at depots and on-route locations, consistent with many peer agencies in the United States. To the extent that FCEBs are used, SEPTA will need to overcome challenges related to siting hydrogen fueling infrastructure and fuel costs.

Service Compatibility and Fleet Replacement Plan

Different types of ZEB technologies have different performance characteristics and thus different levels of compatibility to operate SEPTA's existing bus schedules. Schedule compatibility is one of many factors to consider when evaluating potential ZEB technologies. FCEBs have an operating range on the order of 300 miles, which can accommodate all of SEPTA's existing bus schedules. Trackless trolleys have an unlimited range as they are powered via overhead wire. BEBs have a more limited range based on battery capacity, so careful study of BEB service compatibility is necessary.

Overall, 55% of SEPTA's weekday bus service was found to already be compatible with current BEB technology and an assumed network of 32 on-route chargers at SEPTA-owned layover locations, based on conservative assumptions reflecting reasonably worst-case performance for battery range and energy consumption. While electric bus range and schedule compatibility will be higher under ideal conditions, our analysis seeks to plan for adverse conditions, including battery degradation, imperfect charging operations, and reduced efficiency during cold weather. Weekday and Sunday service have relatively high compatibility with BEBs, while Saturday service has relatively low compatibility with BEBs because of longer scheduled distances for service on those days. City districts are more compatible with BEB technology, and the two suburban bus districts, Victory and Frontier, have rather low compatibility. Buses at the suburban districts operate an average of 123 miles per weekday block, while buses at the city districts operate 58 miles on average per weekday block, which explains the disparity in compatibility results. However, the higher-compatibility city districts account for the vast majority (86%) of SEPTA's bus service. Note that this evaluation is based on SEPTA's Fall 2019 bus schedules, and the network changes being developed through the Bus Revolution initiative may require similar modeling to understand their impacts on BEB compatibility.

For the remaining 45% of SEPTA's service that is difficult to electrify, a combination of schedule changes, additional on-route chargers, and improvements in BEB technologies over time will be needed to fully electrify the fleet. For example, sensitivity tests indicated that deploying diesel heaters

in the winter could increase schedule compatibility by 16 to 20 percentage points; while this option is used by peer agencies, SEPTA has sought to avoid it so far because it would produce a small amount of tailpipe emissions.[1]

Based on existing procurement contracts, if optional purchases are executed, the earliest that SEPTA could be able to begin receiving delivery of only ZEBs would be 2026. Based on SEPTA's 15-year bus lifetime, under this scenario the last fossil fuel buses would be replaced in 2040, achieving a fully ZEB fleet. A timeline for achieving a fully zero-emission fleet by 2040 aligns well with commitments made by peer agencies such as New York City MTA, NJ Transit and CTA.

Facility Upgrade Plan

Transitioning to a ZEB fleet requires planning to coordinate the delivery of ZEBs with the supportive facilities needed for charging/fueling and storage. With eight main bus districts and a fleet of over 1,400 buses, the ZEB transition will be a major undertaking lasting 15 years or more. A facility planning effort was completed to understand the nature of facility upgrades needed to support a ZEB fleet and to develop an appropriate conversion timeline.

For BEBs, the project team selected a strategy in which each garage would have two fast chargers placed in fueling lanes,[2] in addition to as many slow chargers as can be accommodated within each facility. Facility upgrade plans also include switchgear, transformers, utility requirements, maintenance bay upgrades, and backup power generation for resiliency. Without resiliency solutions such as backup power generation and battery storage, SEPTA could find itself unable to maintain reliable bus service in the event of a power outage. A network of on-route charger locations would also be needed to extend the range of BEBs.

For FCEBs, the project team developed estimates of the necessary fuel tanks, pumps, vaporizers, maintenance bay upgrades, and fueling stations and dispensers required at each bus district. The layout of each facility was also reviewed to confirm whether there may be suitable space for hydrogen fuel storage in compliance with safety requirements. Our research found that some districts cannot store hydrogen fuel due to space constraints, and others are questionable based on the information available at this time;[3] these issues will be addressed further in ***Chapter 7***.

The review of SEPTA's bus facilities also revealed three factors that could impact storage capacity with a ZEB fleet. First, there are a significant number of buses currently stored in non-standard or overflow areas, where they would not be able to use a slow charger overnight. In addition, the installation of charger equipment is expected to reduce storage capacity due to space and tolerances required, and hydrogen fueling infrastructure will similarly displace existing parking and storage.

1 The CTA Charging Forward study estimated that fuel usage by electric buses would be up to 2.2% of the volume currently used. Similarly, TransLink reported that using diesel heaters only reduced their greenhouse gas savings slightly, from 95% to 93%.

2 These chargers would be used by buses during their regular servicing process and would prioritize buses that only need a modest amount of charging. See Chapter 7 for more detail.

3 However, bus storage and maintenance would be possible in all cases.

Finally, schedule compatibility analysis indicated that many vehicle schedules will require modifications to become compatible with BEBs, producing a fleet increase of at least 25 buses in total to ensure schedule compatibility.[4] The fleet increase to accommodate BEBs is smaller if the fleet uses more FCEBS and fewer BEBs. In total, this analysis shows that SEPTA will likely require a new bus garage or expansion of existing districts as part of its fleet conversion process. More discussion and study will be needed to develop SEPTA's preferred solution to this issue and understand its financial implications.

The projected sequencing of bus district upgrades to accommodate the anticipated growth of the ZEB fleet over time took into account a number of factors shown in ***Tables 1 and 2*** below.

4 Note that this may require additional analysis as SEPTA's bus schedules change; if schedules become less peak-focused per the 'Lifestyle Network' vision this could create longer vehicle assignments that are more difficult to operate using BEBs.

Table 1 *– Prioritization order for BEB district upgrade sequencing, including factors that were used to inform the sequence*

Notes: Berridge is a maintenance facility that would only need modest upgrades. A new garage or expansion of existing districts should be considered as an addition to this sequence. Southern and Midvale routes are often paired to gain pull-in/pull-out efficiency.

Garage/ District	Indoor or Outdoor?	Equity Prioritization	Where are On-route Chargers Shared?	Schedule Compatibility (Weekdays)	Storage Impacts	Structural/ Civil Modifications	Capital Upgrade Costs
Midvale	Indoor	High	Allegheny	Medium	Low	Low	$52.0M
Berridge	Indoor	—	—	—	—	Low	$0.38M
Allegheny	Indoor	High	Midvale	High	Medium	Low	$25.1M
Callowhill	Indoor	High	Comly/Southern	High	Low	Low	$27.9M
Frankford	Mixed	High	Frontier	High	High	Medium	$21.5M
Comly	Mixed	High	Callowhill/Frankford	Medium	Medium	High	$30.0M
Southern	Mixed	Medium	Midvale	Medium	High	High	$34.5M
Victory	Outdoor	Medium	Callowhill/Southern	Low	High	High	$27.7M
Frontier	Outdoor	Low	Frankford	Low	Medium	Low	$31.5M

Table 2 *– Prioritization order for hydrogen FCEB district upgrade sequencing, including factors that were used to inform the sequence*

Notes: Berridge is a maintenance facility that would only need modest upgrades. A new garage or expansion of existing districts should be considered as an addition to this sequence.

Garage/ District	Indoor or Outdoor?	Equity Prioritization	FCEB Schedule Compatibility	Feasible for Hydrogen Fuel Storage	Feasible for Bus Storage/ Maintenance	Capital Upgrade Costs
Midvale	Indoor	High	High	Yes	Yes	$22.8M-$45M
Berridge	Indoor	—	—	—	—	—
Allegheny	Indoor	High	High	No	Yes	$10.9M-$21M
Callowhill	Indoor	High	High	No	Yes	$12.6M-$25.8M
Frankford	Mixed	High	High	Maybe	Yes	$11.4M-$22.5M
Comly	Mixed	High	High	Maybe	Yes	$12.6M-$25.8M
Southern	Mixed	Medium	High	Maybe	Yes	$13.6M-$25.8M
Victory	Outdoor	Medium	High	Maybe	Yes	$11.9M-$31.1M
Frontier	Outdoor	Low	High	Yes	Yes	$10.3M-$19.4M

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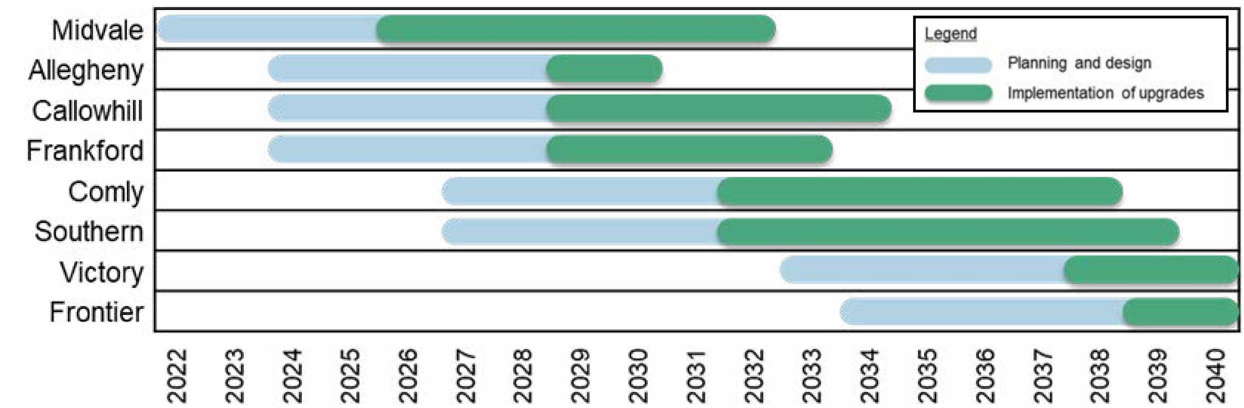

Figure 1 *– Potential timeline of facility improvements. Planning and design should begin approximately 5 years before a district needs to begin receiving zero-emission buses.*

The upgrades at a given district would not necessarily occur in a single year. It is anticipated that these upgrades could be completed in incremental pieces that roughly align with the growth of the ZEB fleet that needs to be accommodated. ***Figure 1*** shows a potential conversion timeline in which upgrades at several garages are completed over the course of six or seven years. The blue color indicates the planning and design before each garage upgrade, while the green color indicates the period over which upgrades are implemented.

Next Steps and Further Analysis

According to the implementation timeline, Midvale will need to begin receiving ZEBs in 2026, and Allegheny, Callowhill and Frankford will need to begin receiving ZEBs in 2028-2029. Detailed design, environmental review and construction may take up to five years, and so more detailed planning and design for these districts should begin in 2022-2023. Detailed design will help refine the preferred ZEB types for these districts: Thus far, Midvale is rated as feasible for hydrogen fuel storage, Allegheny and Callowhill are rated as not feasible, and Frankford is rated as maybe feasible. The design process should consider potential remote fueling solutions in cases where garages are located near each other. To the extent that BEBs are needed, a more detailed plan for phasing and design of on-route charging locations should also be undertaken.

In the near term, SEPTA may also want to conduct the following pilots and analyses:

- A pilot of fast-charging BEBs and storing them outdoors, unconnected to chargers, overnight in the winter. This would be valuable to vet whether a fast-charging strategy is viable for buses stored in overflow and non-traditional parking spaces where slow charging would not be feasible.
- A pilot of 60' BEBs ahead of anticipated procurements that would begin delivery in 2028. Performance data from such a pilot could be used to do more detailed schedule compatibility analysis on 60' buses with local conditions.
- Continuing to evaluate different types of bus heaters that could decrease battery consumption rates and increase schedule compatibility with minimal emissions.

In addition, the following next steps are recommended as areas where SEPTA can conduct further strategic analysis and correct course as needed:

- → Develop a strategy to incorporate a new bus garage or expansion of existing storage
- → Evaluate how the Bus Revolution, SEPTA's comprehensive redesign of its entire bus network impacts schedule compatibility and charging strategies
- → Continue evaluating FCEB technologies as well as feasibility of accessing large quantities of hydrogen fuel
- → Analyze the potential impacts of FCEB remote fueling operations.

ZEB Cost Modeling

The overall results of our cost modeling for the fleet transition period of 2022-2040 are shown in ***Table 3*** below. This shows that modeled operating costs would be lower for the ZEB fleet scenarios compared with the hybrid fleet baseline over the 2022-2040 transition period: 6% lower for the BEB scenario or 4% lower for the 80% FCEB scenario. However, modeled capital costs for the ZEB scenarios would be higher compared with the hybrid fleet baseline: 12% higher for the BEB scenario or 3% to 19% for the 80% FCEB scenario. In total, we anticipate that the BEB fleet scenario adds a cost of $46m over the transition period, while the FCEB fleet scenario could range from a net savings of $58m to a net cost of $262m.

There are several reasons that the ZEB scenarios could be more costly than shown. Our estimates do not consider the cost of a new garage, which will likely be needed to address existing capacity issues that would be exacerbated with the addition of new

Table 3 *– Total costs for each scenario and each cost category over the period 2022-2040, in millions of year of expenditure (YOE) dollars*

Operating Costs	Hybrid Scenario ($M)	Electric 100% BEB Scenario ($M)	Fuel Cell 80% FCEB Scenario ($M)	Capital Costs	Hybrid Scenario ($M)	Electric 100% BEB Scenario ($M)	Fuel Cell 80% FCEB Scenario ($M)
Diesel Fuel	$716	$392	$392	**Vehicle Purchases**	$2,021	$2,175	$2,155 to $2,250
Hydrogen Fuel	$0	$0	$218	**Charger Infrastructure**	$0	$90	$23
Electricity	$0	$114	$41	**Facility Upgrades**	$0	$252	$156 to $253
Maintenance	$2,337	$2,288	$2,266	**Anticipated Subsidy**	$0	-$252	-$248 to -$262
Schedule Changes	$0	$62	$13				
Operating Costs Total	$3,054	$2,856	$2,930	**Capital Costs Total**	$2,021	$2,265	$2,087 to $2,407
				Total Operating & Capital Costs	$5,075	$5,121	$5,017 to $5,337

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fueling equipment or charging equipment at districts and which could significantly increase the capital investment. The ZEB scenarios also do not address any existing state of good repair needs or structural upgrades that may need to be addressed in conjunction with upgrades to accommodate ZEBs at each district. For BEBs, there will also be costs associated with bringing additional PECO service to districts and on-route charging locations and further coordination with PECO will be needed to identify these costs. There is also a risk that the anticipated subsidies do not continue at the level assumed.

However, there are also reasons that the ZEB scenarios may be more attractive than shown. The transition period includes the continued operation of hybrid buses until 2040, so full operational savings from transitioning will not be experienced until the end of the period. In addition, the transition period includes capital investments to support the new fleet that would not be part of the ongoing financial picture. An overview of potential funding options to help offset transition costs and potential project delivery options are described in the ***Funding and Project Delivery*** section of this report.

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2 Introduction

Across the country, many transit agencies are beginning a transition away from fossil fuels and toward ZEBs. While transit is already a sustainable form of transportation compared to single-occupancy vehicles, transit agencies have an opportunity to further contribute to regional and national greenhouse gas reduction goals and improve local air quality by transitioning away from diesel-powered buses. SEPTA is planning for a full transition to all ZEBs, which could include a combination of BEBs and FCEBs, and this playbook outlines the planning and analysis to support a full transition by the year 2040, if funding is made available for the investments that will be necessary to charge and fuel these new buses.

SEPTA's transition to zero-emission buses supports Governor Wolf's Executive Order in January 2019, which stated that Pennsylvania will strive to reduce net greenhouse gas emissions 26% from 2005 levels by 2025, and 80% from 2005 levels by 2050.[5] Locally, the shift to ZEBs aligns with the City of Philadelphia's 2021 Transit Plan: A Vision for 2045. And nationally, it aligns with the Federal Transit Administration's Sustainable Transit for a Healthy Planet Challenge to support President Biden's greenhouse gas reduction goal of achieving a more than 50% reduction in greenhouse gas emissions from 2005 levels by 2030.

Benefits of ZEBs

The clean propulsion system of ZEBs provides many benefits including zero tailpipe emissions, potentially lower operating and maintenance costs, and better experiences for drivers, riders, and the local communities where the buses operate.

→ **Zero Tailpipe Emissions:** ZEBs have zero tailpipe emissions as a result of the all-electric propulsion systems, thereby eliminating direct, local air pollution. Vehicle exhaust generated by burning diesel contains many substances that contribute to poor health and disease. By eliminating vehicle exhaust, ZEBs help to achieve better air quality and protect the health of the local communities where they operate.[6]

5 Sustainable Transportation. Pennsylvania Department of Environmental Protection. Source URL: https://www.dep.pa.gov/Citizens/climate/SustainableTransport/Pages/default.aspx

6 "Transforming Transit, Realizing Opportunity", 2020.

Table 4 *– Emissions rates for buses (grams per miles)*

Sources: EPA (BEB emissions rates for nitrogen oxides and CO_2-E equivalents); Transit Cooperative Research Program Guidebook (nitrogen oxides and non-methane hydrocarbons emissions).

Emissions	Clean Diesel (B2)	Hybrid-Electric	Battery Electric
Ozone (Nitrogen Oxides)	0.65	0.49	0.49
Non-Methane Hydrocarbons (VOCs)	0.010	0.008	0.006
Greenhouse Gasses (CO_2-E)	3,407	2,597	622

- **Low Greenhouse Gas Emissions:** Although ZEBs produce zero tailpipe emissions, there are indirect emissions associated with the source of electricity or hydrogen used. In this region, indirect emissions from electricity are still lower for most pollutants than direct emissions associated with diesel bus combustion and are likely to improve over time. ***Table 4*** provides a comparison of emissions from clean diesel, hybrid electric, and BEBs.
- **Lower Noise Pollution:** Decreased noise pollution is an additional benefit affecting riders, drivers, and surrounding residents. As they do not possess traditional combustion engines, ZEBs produce less noise than diesel powered buses. ***Table 5*** provides a comparison of noise levels produced by various modes of transit.
- **Potentially Lower Maintenance Costs:** Given the lack of a combustion engine, ZEBs are expected to require less maintenance over the lifetime of the bus when compared to conventionally fueled buses.[7] The propulsions systems are expected to need less frequent maintenance repairs since they have fewer moving components. ZEBs do not require oil and oil filter changes. Regenerative breaking is also expected to contribute to reduced maintenance costs, because brakes experience less wear over time.
- **Potentially Lower Operating Costs:** ZEB operating costs are projected to be lower than conventionally fueled buses due to the increased fuel economy, although actual cost impacts will depend on the charging strategy and resulting electricity rates incurred.[8] Lower operating costs are also closely tied to operator driving habits. Driving habits significantly influence BEB efficiency and performance.

Table 5 *– Transit mode noise relative to EV buses*

Source: SEPTA BEB Readiness Report (2018)

Noise (dB) per Mode	
EV Transit Bus (Proterra)	52
Diesel Transit Bus	80
Trolley Bus	70
Commuter Rail	73
Light Rail	78
Subway	100

7 TCRP Guidebook for Deploying Zero-Emission Transit Buses (2021), p. 117.

8 TCRP Battery Electric Buses – State of the Practice (2018), p. 2.

Playbook Concept

SEPTA's plan for a transition to all ZEBs is presented here as a "playbook" in order to convey that it will be a planning process, and implementation decisions will continue to be refined over time. The 15- to 20-year transition period will include significant facility upgrades that need to be planned years in advance, while also monitoring constant improvements in ZEB technology. The analysis presented in this playbook provides direction for how SEPTA can transition to all zero-emission buses by the year 2040, including where to prioritize initial investments and next steps for piloting concepts and beginning the implementation process.

Future iterations of this playbook can incorporate lessons learned from piloting implementation concepts, additional analysis on key topics such as the likely need for a new garage and consideration of additional technology that comes to market during the implementation period.

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3 Project Background and Context

SEPTA at a Glance

The Southeastern Pennsylvania Transportation Authority (SEPTA) is the primary mass transit provider in the Philadelphia region, serving Bucks, Chester, Delaware, and Montgomery Counties, and the City of Philadelphia. SEPTA's service territory covers 4 million people across 2,200 square miles. SEPTA is the sixth largest mass transit system in the U.S., and the largest in Pennsylvania, providing service to over 1 million weekday riders.

SEPTA employs four main types of buses: conventional diesel powered buses, hybrid-electric diesel powered buses, electric trackless trolley buses, and BEBs. The average lifespan of a SEPTA bus is approximately 15 years, and SEPTA replaces approximately 100 buses each year.

SEPTA has phased out nearly all conventional, combustion diesel buses through the purchase of hybrid-electric diesel buses (***Figure 2***). SEPTA purchased the first of many diesel-powered hybrid-electric vehicles in 2002 and now has over 1,200 hybrid-electric vehicles, representing close to 90% of the entire fleet. Delivery of additional hybrid-electric buses will continue through 2024, by which time hybrids and BEBs will comprise nearly 100 percent of SEPTA's fleet. BEBs account for the smallest portion of SEPTA's bus fleet. SEPTA currently has 25 BEBs as part of a pilot program that began in June 2019 at Southern Bus District.

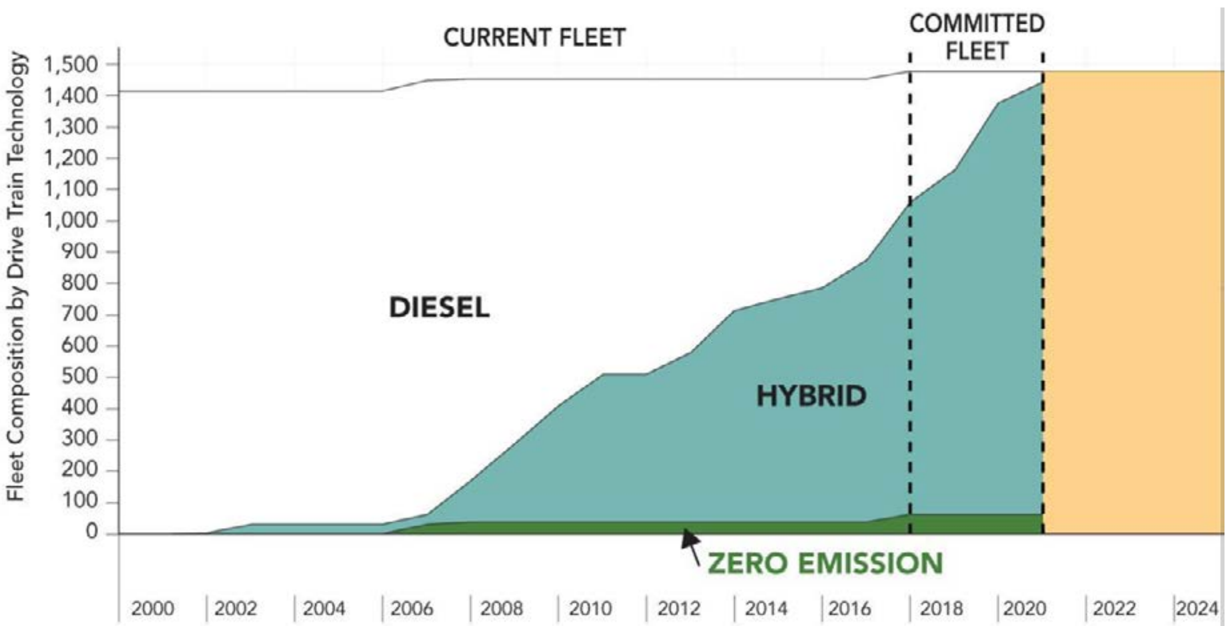

Figure 2– *Current Bus Fleet Timeline Assuming Consistent Fleet Size*

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History of SEPTA BEB Deployment To-Date

Recognizing the multi-faceted benefits of electrification, SEPTA began evaluating the feasibility of introducing BEBs into its fleet in 2014. SEPTA participated in vehicle demonstrations and conducted a full assessment of the opportunities and challenges associated with operations and maintenance before moving forward with a pilot program at Southern Bus District. The pilot placed 25 BEBs in revenue operation in 2019. This section provides additional information about the Southern Bus District BEB deployment and discusses the preparations for a deployment of FCEBs at Midvale Bus District.

25 Buses – Southern (2016 Low-No Grant)

In 2015, SEPTA and several regional partners conducted a comprehensive engineering and planning effort to evaluate the introduction of BEB technology at Southern Bus District. SEPTA performed the engineering analysis and collaborated with Delaware Valley Regional Planning Commission (DVRPC) to produce a vehicle technology analysis for Routes 29 and 79 originating out of Southern Bus District. The report compared the costs and benefits of trackless trolley service restoration, continued diesel-electric hybrid bus service with removal of trackless trolley infrastructure, and a BEB pilot program. The DVRPC report concluded BEBs are a viable option for the two routes.[9]

In 2016, SEPTA was awarded a $2.6 million Federal Transit Administration (FTA) grant under the Low or No Emission Vehicle Program (Low-No) for the purchase of 25 all-electric zero-emission 40-foot Proterra Catalyst buses, with 440 kWh batteries, and associated charging equipment at Southern Bus District. The $2.6 million grant represented the price differential between diesel-electric hybrid buses and BEBs. SEPTA matched the FTA grant with internal capital funds to cover the remaining cost of deploying the 25 BEBs.

During the planning period, the rapid emergence of battery-electric technology resulted in a change of course with respect to SEPTA's charging infrastructure strategy. Initially, SEPTA planned to charge buses on-route with technology capable of rapidly charging a battery during a layover. With this option, a full battery charge could be achieved in less than 10 minutes. However, new extended-range battery technology was introduced during the planning stage that would enable SEPTA to charge buses overnight rather than periodically throughout the day. The ability to centralize charging operations at Southern Bus District and perform all charging activities overnight was considered the preferred option for SEPTA. A change order was approved by the SEPTA Board in March 2017 to transition to the new battery technology.

9 Vehicle Technology Analysis for SEPTA Routes 29 and 79. Delaware Valley Regional Planning Commission, July 2015. Source URL: http://www.dvrpc.org/reports/13028.pdf

At the project onset, Southern Bus District had existing power capacity to charge no more than five BEBs simultaneously. To meet the new power demands, SEPTA installed a 2 MW portable substation at the northwest corner of the property to provide the additional capacity to charge all 25 BEBs simultaneously overnight. The portable substation is connected to 25 Tritium Inc. 55 kW charging stations. A SEPTA employee is responsible for plugging-in and cleaning the buses as part of daily operations.

In June 2019, the BEBs entered revenue operation on Routes 29 and 79. Due to warranty and reliability issues, the buses were removed from service in February 2020. The “Range Analysis” section of this report provides an overview of the performance of the 25 BEBs while in revenue service from June 2019 to February 2020.

10 Buses (Future) – Midvale (2018 Low-No Grant)

In 2018, SEPTA was again awarded FTA Low-No Program funding to purchase an additional 10 40-foot BEBs and associated charging equipment. The $1.5 million in grant funding was initially intended to be used to purchase BEBs for SEPTA’s Midvale Bus District, SEPTA’s largest bus facility.

In May 2020, Burns Engineering prepared a study evaluating the feasibility of installing BEB charging equipment at the Midvale Bus District in preparation for the fleet of 10 BEBs. The study reviewed various charging technologies available to SEPTA and the feasibility of utilizing those charging technologies at Midvale Bus District based on electrical, operational, and structural considerations. The study considered the charging equipment configurations needed to accommodate fleet sizes ranging from a pilot of 10 BEBs up to a full fleet of BEBs (320 buses). The study concluded that the existing 13.2kV electrical service could potentially accommodate the new loads associated with 10 40-foot BEBs to be procured for Midvale Bus District using the 2018 FTA Low-No Program funding. However, the existing service will not support a full-scale electric vehicle charging system, and an electrical service upgrade would be necessary. Should SEPTA decide to install roof-mounted charging equipment at Midvale, structural modifications are required to support the charging equipment for both a pilot and full fleet of BEBs.

In June 2020, SEPTA was selected to receive $4.3 million through the FTA Low-No Grant Program to support updates to Midvale’s electrical infrastructure. The project proposes to connect Midvale District to the Broad Street Line Subway traction power system via Butler Substation, leveraging existing power sources to establish a scalable source of energy for ZEBs.

In Spring 2022, SEPTA requested permission to repurpose the grant for the purchase of 10 FCEBs at Midvale in order to gather performance data to eventually compare with the previously purchased Proterra BEBs. The FTA granted authorization for this change in July 2022, so SEPTA will proceed with developing a FCEB specification and procurement.

In August of 2022, SEPTA was selected for a $23 million grant as part of the federal Low-No Grant Program Grants for Buses and Bus Facilities Competitive Program. These funds will support improvements including redundant power feeders, backup generators, and electrical substations, at three bus depots.

Peer Agency Context In North America

The number of agencies using ZEBs, specifically BEBs, has been growing in the United States over the last decade from just a small handful of agencies in the early 2010s to over 65 agencies in 2019. The number of BEBs in the US has also increased significantly from a little more than 50 BEBs in 2012, to over 500 in 2019. The number of FCEBs in the US is considerably lower, with about 87 deployed as of 2022.

The zero-emission bus industry is continuing to mature and agencies across the country are still determining the best path forward for transitioning their entire fleet to zero emission vehicles. Agencies are facing many of the same challenges and concerns about the transition from battery range performance, cold weather performance, hydrogen fuel supply and storage challenges, and the additional training and upfront costs to accommodate zero emission buses.

Peer agencies from across the country were looked at to understand their approach to transitioning their fleets to all ZEBs. The following provides an overview of several peer agencies, their approximate bus fleets and number of garages, and their timelines for full electrification. ***Appendix J*** includes notes from interviews with key peer agencies.

→ **NJ Transit, New Jersey**

- Electrification goal: 50% by 2030, 100% by 2040
- Garage and bus fleet: 16 bus garages with over 1,200 buses

→ **Massachusetts Bay Transportation Authority (MBTA), Boston**

- Electrification goal: current push to expedite fleet conversion to 2030 and statewide decarbonization by 2050.
- Garage and bus fleet: 9 bus garages with over 1,100 buses
- Forecasting as one bus garage upgrade every 2-3 years to support full electrification

→ **Metropolitan Transportation Authority (MTA), New York**

- Electrification goal: 100% by 2040, all new bus purchases after 2030 must be ZEB
- Garage and bus fleet: 28 bus garages with over 3,200 buses
- Forecasting two to three depot infrastructure projects to be completed each year in order to support full electrification

→ **Washington Metropolitan Area Transit Authority (WMATA), Washington D.C.**

- Electrification goal: 100% ZEB by 2045, all new bus purchases after 2030 must be ZEB
- Garage and bus fleet: 9 bus garages with over 1,600 buses

→ **Alameda-Contra Costa Transit District**

- Current ZEB fleet includes 28 BEBs and 39 FCEBs
- Planning for a fleet that is 70% FCEB and 30% BEB

→ **SunLine Transit Agency**

- Current ZEB fleet includes 4 BEBs and 21 FCEBs
- Planning to use mixed fleets at two operating divisions

→ **Stark Area Regional Transit Authority**

- Current ZEB fleet includes 12 FCEBs
- Fuel deliveries of gray hydrogen

→ **Champaign–Urbana Mass Transit District**

- Current ZEB fleet includes 2 FCEBs
- Fuel produced using on-site electrolyzer

4 Technology Selection

ZEBs use an electric-drive system powered by batteries, hydrogen fuel cells, or electric wires. Different configurations of BEBs and FCEBs are being evaluated by transit agencies with the goal of replacing conventionally fueled vehicles and thereby eliminating tailpipe emissions. Trackless trolleys can similarly be used as a form of ZEB technology. All three technologies are available today, although BEBs and trackless trolleys are at a more advanced stage of commercialization and deployment. ***Table 6*** summarizes some of the key trade-offs of these technologies.

Battery Electric Bus Technologies

BEBs are powered by on-board batteries that can be charged via a variety of different charging technologies, either on route or at the bus depot. BEBs may have lower operating and capital costs than FCEBs. However, BEBs do have range limitations and transit agencies often need to install on-route charging at layover locations and make schedule changes to accommodate battery ranges. There are a variety of different charging mechanisms that can be used to re-charge buses at the district or on-route. The following section provides an overview of the benefits and drawbacks of the different types of BEB charging systems.

Table 6– *Simple comparison of BEB and FCEB technology tradeoffs*

	Battery Electric Bus (BEB) with On-route Chargers	Fuel Cell Electric Bus (FCEB)	Trackless Trolley
Range	Medium	High	High
Reliability	Medium	High	High
Operating Costs	Medium	Medium	Medium
Infrastructure Requirements	High	Medium	Very High

Based on a literature review that included the TCRP Guidebook for Deploying Zero Emission Transit Buses, the Foothill Transit Battery Electric Bus Evaluation, and the AC Transit Zero Emission Transit Bus Technology Analysis.

Battery Electric Bus Charging Technologies

There are several ways in which charging mechanisms for BEBs can vary. Chargers can vary by location, power type, power level, and power transfer method. To successfully scale BEB technology, the selected charging solution(s) should maximize bus operating range, minimize facility impacts, and efficiently utilize staff time.

Location: Charging can happen either at the depot (district) or on-route. Many transit agencies prefer to maximize the amount of charging that happens at the depot and minimize the amount of charging that happens on-route. While maximizing charging at the depot does impact depot storage space, depot-based charging can maximize the usage of each charger and minimize the need for distributed maintenance activity. On route charging can also be problematic when bus layover locations are not owned by SEPTA which can complicate the prospects of installing charging equipment.

Power Type: Power type refers to the type of current used to charge the buses. The current from chargers can be either alternating current (AC) or direct current (DC). Most BEB models on the market utilize DC charging. The utility-provided AC power is typically converted to DC power by using a rectifier located within a DC charging cabinet that is installed with the charging unit. Some BEB manufacturers in the North American market also offer AC charging and perform the conversion to DC power onboard the bus using onboard converters, which adds cost and weight. However, the benefit of this method is that it eliminates the need for charging cabinets, which reduces the amount of space required at districts. Additionally, since the power delivered to the bus is AC, future migration to inductive charging using AC power is possible.

Power Level: Charger power levels can be categorized as fast charging or slow charging. Fast charging generally refers to charging power above 150 kW and slow charging generally refers to power levels below 150 kW. While fast charging can be used on-route or at depots, slow charging is generally only used at the depot.

Power Transfer: Power may be transferred to bus batteries using a plug-in, overhead conductive, or inductive solution.

Plug-In

→ Plug-in charging infrastructure consists of a charging cabinet and dispenser. From the dispenser, a cable with a charging connector connects to a charge port on the bus. Low power plug-in chargers consist of a single dispenser and charger cabinet. Higher-powered chargers, typically starting around 150 kW, can provide power to multiple dispensers, which can charge several buses sequentially, helping to limit peak demand.

  Plug-in chargers can be mounted on the ground or overhead. When mounted overhead, cords are pulled down from the ceiling thereby eliminating charging cables on the ground. However, there are limits to the length of the charging cables. In some instances, overhead installations may not be possible without modifications to existing roof structures.

Plug-in chargers are typically installed at the depot and are used to charge buses overnight. The benefits of plug-in charging include lower per unit cost and the ability to take advantage of lower off-peak electricity rates by charging overnight. Despite these benefits, it is important to note that plug-in chargers typically utilize slower charging rates, which results in longer charging times. Ground-mounted chargers may require more space than other charging solutions when utilized for large deployments, and plug-in charging is a hands-on process, as employees must manually plug and unplug the buses.

Overhead Conductive (Pantograph)

→ Overhead conductive charging utilizes a pantograph in one of two different configurations: pantograph-up (vehicle roof mounted) or pantograph-down (infrastructure mounted). Unlike plug-in charging, pantograph charging systems do not require an employee to manually connect the bus to the charging equipment. The pantograph-down system (most commonly seen in North America) involves a pantograph moving downward to connect to charge rails on the bus to initiate charging. In the pantograph-up configuration, (commonly seen in Europe) a moveable pantograph installed on the roof of each bus moves upward to connect with a fixed charging rail to initiate charging. Both configurations require a transformer, switchgear, and charging equipment to be installed nearby.

The benefit of using the pantograph-down system is that the moveable parts of the charger are not on the bus, reducing any added weight and maintenance requirements. The bus height is also lower, which enables the bus to pass under low-clearance bridges. A risk of the pantograph-down system is that is that the moveable parts that are more likely to malfunction are located on the charger, and a malfunctioning charging station can have an impact on service if buses are unable to use the charger. Regardless of the pantograph configuration, bus operators must be trained to properly align the bus with the overhead charging infrastructure to ensure an effective charging session.

Overhead conductive chargers may be installed on-route for fast charging during layovers or for fast or slow charging at the district. When considering on-route charging locations utilizing overhead chargers, it is important to consider that the charging infrastructure may interfere with road clearances or may require a dedicated pull-off lane.

Wireless Inductive

→ Wireless inductive charging relies on the principle of resonant magnetic induction to transfer power between pads embedded in the ground and receiver pads mounted on the underside of the bus. Operators position the bus to align with the charger using visual cues on the road and on the dashboard. When

the ground-mounted pads and bus-mounted pads align, charging begins automatically as power is transferred via the magnetic field created by the magnetic coils found within the pads. The charging process does not involve any moving parts.
When installed, the ground assembly does not obstruct roadways. Performance is not affected by standing water, rain, snow, ice, or road salt and is capable of being plowed over during snowy conditions. Maximum power levels for inductive charging are not as high as that of conductive charging and can range from 50-450 kW.

Wireless inductive charging can be utilized for both depot and on-route charging. Inductive charging is useful at on-route locations because the system has a smaller infrastructure footprint compared to other charging technologies, requires no manual connections to commence charging, and does not interfere with road clearances or sidewalks. Disadvantages of inductive charging include a less efficient charge if the bus is not properly aligned with the charging pads and potentially higher costs if the charger must be completely removed and repaired. Wireless chargers also require coolant systems for the charger receiver on the bus, which means a greater level of integration with other bus systems.

Inductive charging is still considered an emerging technology. There are a limited number of manufacturers and only a few BEB deployments in North America and Europe where it is in use. There is also no industry standard for the technology yet, leading to risks associated with owning proprietary technology.

Fuel Cell Electric Bus Technologies

Vehicles and Performance

A fuel cell electric bus (FCEB) is similar to a battery electric bus in that its motor is directly powered by a battery. However, the battery of a FCEB is much smaller and is continually being recharged by a hydrogen fuel cell. While a BEB stores all of its energy in a large battery, a FCEB stores most of its energy in pressurized hydrogen gas used to charge a small battery. The only direct emissions from a FCEB are heat and water vapor.

FCEBs have several operational differences from BEBs that may be attractive for transit agencies. In general, their operations are relatively similar to diesel or CNG buses. Fueling times are low, typically 7-10 minutes, and range is on the order of 300 miles. FCEBs do not experience significant additional energy usage in cold weather, which is not the case for BEBs. Unlike BEBs, there will be no need for on-route chargers to ensure operational compatibility, and changes to operator schedules should be unnecessary unless off-site fueling is utilized. Performance data from the Alameda-Contra Costa Transit District (AC Transit) shows that FCEBs have lower availability, or readiness to operate each day, than diesel buses but higher availability than BEBs. (However, AC Transit has less experience with BEBs than with FCEBs.) Their data also show similar costs per mile for ZEB energy and maintenance.

Within the zero-emission bus market, FCEBs are less common than BEBs. As of 2022, there are estimated to be approximately 87 FCEBs deployed in the US, or 6% of all ZEBs. However, these numbers are increasing rapidly. Currently, New Flyer offers 40’ and 60’ “Xcelsior Charge H2” FCEBs with 37.5 kg to 50 kg fuel capacity. El Dorado (ENC) offers 35’ and 40’ “Axess-FC” FCEBs with up to 50 kg fuel capacity. Both companies are Buy America compliant.

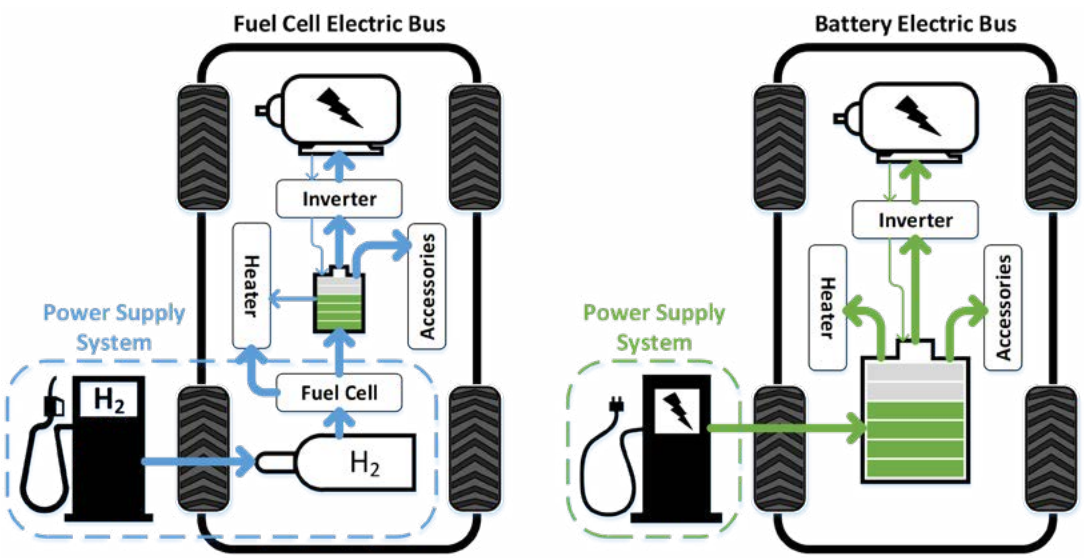

Figure 3 *– Diagram of BEB and FCEB power systems*

__Table 7__ – Summary of data from AC Transit operations of vehicles with different types of propulsion
Source: AC Transit Zero Emission Transit Bus Technology Analysis, Volume 2 (2021)

Fleet	Diesel (Baseline)	Diesel Hybrid	Fuel Cell Electric (FCEB)	Battery Electric (BEB)
Cost/Mile	$1.41	$1.80	$1.97	$2.02
Fleet Availability (readiness to operate each day)	96%	75%	69%	47%
Reliability (Miles Between Chargeable Road Calls)	12,075	4,091	6,314	3,618

Fuel Considerations

When transit agencies begin to procure hydrogen fuel, they can choose from several different types that have different levels of environmental sustainability and life cycle emissions. The different approaches to producing hydrogen also have cost implications, with more sustainable fuel being more expensive. In keeping with the broader goals of the Zero-Emissions Bus Playbook, SEPTA's choice of hydrogen fuel type will prioritize more sustainable options to the extent they are available. See Section 6, Sustainability and Equity Analysis, for emissions projections from different fueling scenarios.

Transit agencies using FCEBs may generate hydrogen fuel on-site or have it trucked in by a vendor. On-site generation is not considered a feasible option for SEPTA, based on a review of its technical requirements: On-site generation via electrolysis requires substantial space and electrical upgrades. An electrolyzer producing 4,000 kg daily for a bus district would require about 11 MW of electrical capacity and about 17,700 square feet of space, including liquefaction equipment and electrical equipment. On-site generation would also require a great deal of new staffing and expertise. Alternatively, if fuel is trucked in, storage tanks and dispensers for a bus district might require about 500

10 The process also produces some CO, though a secondary step seeks to process this with H2O into more CO_2 and hydrogen.

__Table 8__ – Summary of available types of hydrogen fuel

Name	Description	Emissions
Gray Hydrogen	Produced from fossil fuels via a process called steam methane reforming (SMR). During this process, high temperature steam is used to split methane gas at high pressures.	CO_2 is released into the atmosphere.[10]
Blue Hydrogen	The same as grey hydrogen (produced from fossil fuels via SMR), but instead of CO_2 being emitted to the atmosphere, a portion of it is captured and stored.	While CO_2 capture rates for blue hydrogen have not yet been standardized in the US, in the EU a 70% GHG reduction is required to be considered "low carbon hydrogen."
Electrolysis Hydrogen	Produced via electrolysis using electricity from the grid (including coal power and renewable energy sources)	There are CO_2 emissions associated with the production of this fuel but not its use.
Green Hydrogen	Produced via electrolysis using electricity generated from renewable energy sources (like wind or solar).	There are no CO_2 emissions associated with the production or use of green hydrogen.

kW of electrical capacity and about 870 square feet of space, including storage and electrical equipment. SEPTA does not plan to pursue on-site hydrogen generation at this time, but fuel delivery may be feasible.

Hydrogen can be stored and transported in either gaseous or liquid forms. Gaseous hydrogen is the form that is ultimately consumed by FCEBs, and it can be stored in vehicle fuel tanks under normal temperatures and high pressure. Liquid hydrogen tends to be the more attractive form for storage and transport because it has an eight-times greater density compared with gaseous hydrogen. This reduces the size of storage tanks and, if fuel is being delivered, requires fewer deliveries. Liquid hydrogen is stored at very low temperatures and normal ambient pressure. Liquid hydrogen can be converted to gaseous form for FCEBs using a pump and vaporizer prior to dispensing.

The figure below summarizes the most viable approach to hydrogen supply at SEPTA bus districts. Hydrogen would be delivered and stored in liquid form, and then it would be converted to gaseous form to fuel buses.

The current availability of hydrogen fuel from vendors is limited but growing. As part of the research for this study, our team identified ten supplier sites ranging from 350 miles away to over 2,000 miles away (though more local suppliers are expected in the future). Our team interviewed three of the companies, and two indicated that they have current capacity to support SEPTA's fleet with green hydrogen. They indicated that liquid hydrogen costs in the range of $7 to $9 per kilogram at delivery, which aligns with NREL reporting of $8.86 as the average cost per kilogram.

Trackless Trolley Technology

Trackless trolleys (also called trolleybuses) started operating in Philadelphia in 1923. These are rubber-tired vehicles with two poles on top that connect with overhead wires. One pole receives power from a live overhead wire (positive return), and the other pole connects to a different wire for grounding (negative return). SEPTA's vehicles require overhead wire for the entire length of each trackless trolley route, though they have the ability to travel off-wire for a limited time using diesel fuel. There are also vehicle types that can operate off-wire for a limited time using battery power. Trackless trolleys are electric vehicles with similar benefits to ZEBs in terms of emissions and energy efficiency. Trolleybuses were a popular form of transit in the early to

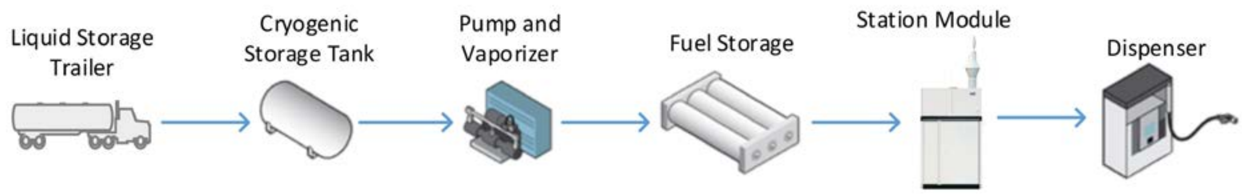

Figure 4 *– Diagram showing flow of hydrogen fuel, from delivery to fueling, under most viable approach*
Source: TCRP Guidebook for Deploying Zero-Emission Transit Buses (2020)

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mid-1900s, but today they are only used by a small number of US transit agencies. Seattle and San Francisco have continued using trolleybuses in part because they perform well on hilly topography. Boston is in the process of phasing out its trackless trolleys, leaving Dayton and Philadelphia with the last trackless trolley fleets in the eastern US.

One of the primary reasons for the national move away from this propulsion type is the associated infrastructure requirements. The overhead contact system, substations, poles, wires, and cross spans can cost approximately $5M to $7M per mile one-way. Facility maintenance costs for trackless trolley service is also consistently much higher than for other bus service, based on 2019 NTD data.

Based on the findings of the preliminary cost analysis shown in the call-out box, expanding the trackless trolley network is not considered a financially viable way for SEPTA to pursue a zero-emission fleet. This result is primarily driven by the high cost of overhead infrastructure to power trackless trolleys. Our team also studied variants in which the infrastructure mileage was reduced to reflect vehicles with off-wire capabilities, but this did not reduce costs sufficiently to make this mode viable. For these reasons, trackless trolleys have been excluded from further evaluation in this study.

Technology Fueling and Utility Needs and Partnerships

SEPTA may consider pursuing various partnerships that can support fueling or charging a FCEB or BEB fleet. There will likely be a need for electrical upgrades coordinated with PECO, the local utility serving SEPTA. The PECO rate structure could also be an area for coordination, as there may be opportunities for new rate classes that better support electric bus charging. Original equipment manufacturers (OEMs) offer such partnerships as turnkey services including planning, design, financing, operations, and energy optimization – though most larger transit agencies handle these functions in-house.

Several transit agencies deploying FCEBs were interviewed as part of the research for this plan; a common partnership they identified was outsourcing the operation and maintenance of specialized hydrogen generation, storage, and fueling infrastructure. Several hydrogen suppliers were also interviewed to inform this plan. The suppliers indicated that they offer additional services beyond delivering hydrogen fuel. They offer turnkey infrastructure solutions quoted in the range of $3.5M to $5.5M. Contracts also can include installation and operation of all equipment for a monthly fee.

Additional detail about potential partnerships is provided in the section "***Funding and Project Delivery Options***" in Chapter 7.

Preliminary Cost Analysis

A preliminary cost analysis was conducted to understand whether expanding SEPTA's trackless trolley system might be a viable alternative to other types of ZEB technology. This analysis considered the costs of vehicle purchases, on-route equipment, electricity, maintenance, and facility upgrades over a 15-year period. For simplicity, it did not consider the impact of inflation, discount rates, or implementation phasing. This preliminary analysis focused on Southern District, whose operating characteristics are relatively compatible with the potential types of propulsion.

The specific assumptions used in this analysis are identified in the table below. These come from a mix of sources identified below the table.

Table 9 *– Inputs used in the preliminary cost analysis of three propulsion types*

District	FCEBs	BEBs	Trackless Trolley
Vehicle cost	$1M–$1.2M	$900k	$1M–$1.35M
Fleet size increases	N/A	Add buses for 6.5% of incompatible blocks**	N/A
Supportive equipment at districts	$10.3M–$45M per district	$21.5M–$52M for upgrades plus $5.9M-$19.3M for chargers per district	$12.5M for new substation, overhead contact system, and overhead maintenance retrofit
Supportive equipment on-route	N/A	$1.6M - $4.1M for each of 32 locations, allocated by districts using them	$5M-$7M per unique one-way route mile, 87 unique route miles
Cost of fuel or electricity	$0.88-$1.13 per mile	$0.35 per mile*	$0.35 per mile
Cost of vehicle maintenance	$2.00 per mile	$2.00 per mile	$1.60 per mile
Cost of equipment maintenance	$230k annually per 100 buses	Annual cost of $2,500 per slow charger and $15,000 per fast charger	$7,800 annually per unique one-way route mile
Cost of schedule modifications	N/A	Daily operating cost increase of $27.56 to $34.24 per vehicle block that needs to be split to ensure compatibility	N/A

** Increases by 4% if diesel heaters are used to extend range*

*** Note that service schedules are expected to change in the future as a result of Bus Revolution.*

Sources:

- *SunLine Transit Agency American Fuel Cell Bus Progress Report - https://www.nrel.gov/docs/fy20osti/71312.pdf*
- *Zero Emission Transit Bus Technology Analysis - https://www.actransit.org/sites/default/files/2021-06/0604-20%20Report-ZEB%20Perf_FNL_062321.pdf*
- *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2020 - https://afdc.energy.gov/files/u/publication/fc_bus_status_2020.pdf*
- *SEPTA internal financial data, 2022.*

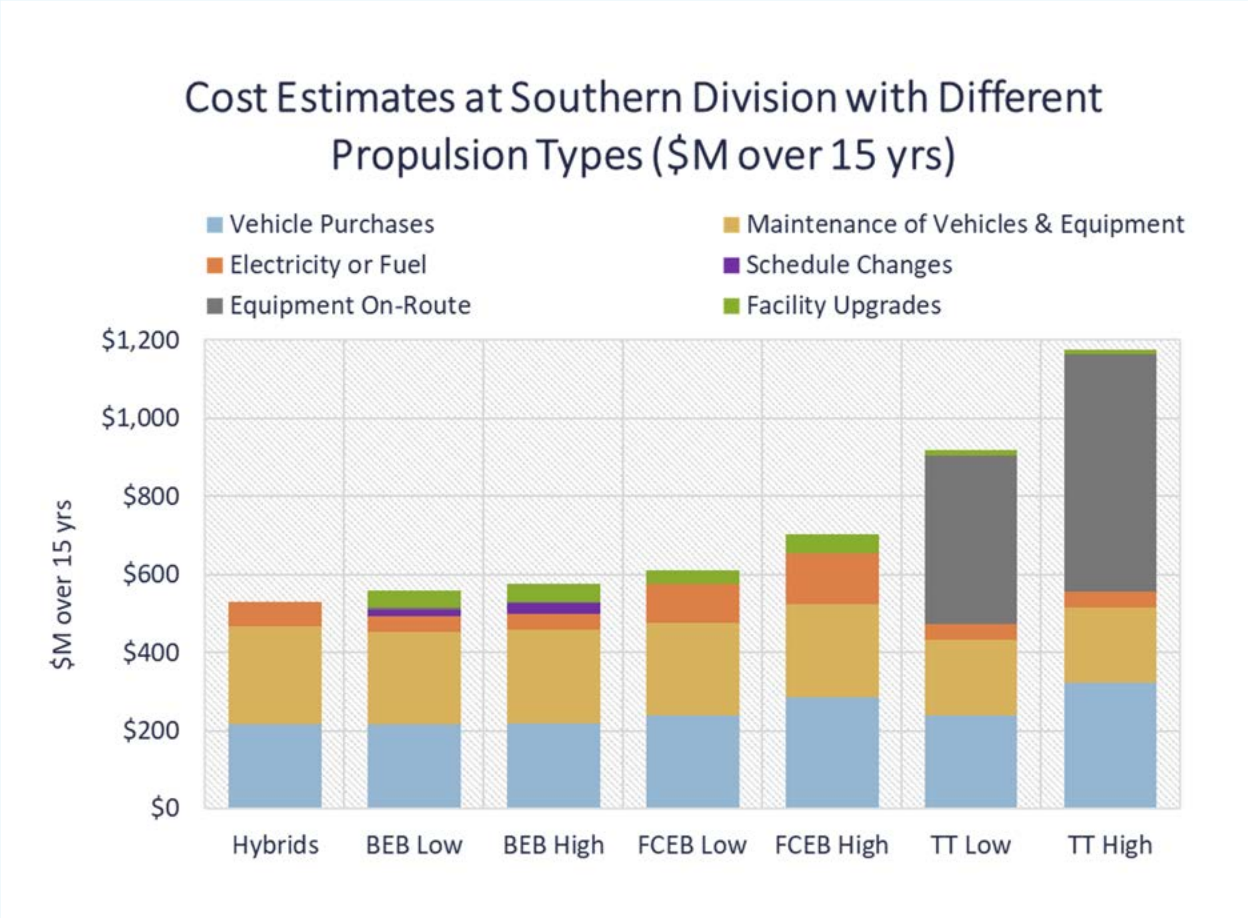

Figure 5 *– Preliminary cost estimates at Southern Division with Different Propulsion Types ($M over 15 years)*

The results of this analysis are illustrated in the graph above. This shows that the Trackless Trolley option could be 40% to 79% more expensive than the FCEB option and 62% to 107% more expensive than the BEB option. The cost of on-route power infrastructure would have to drop by 75% to bring trackless trolley costs in line with FCEB costs. (Note that this analysis follows a different methodology from the more detailed cost modeling included later in this study, and their results should not be compared directly.)

5 Schedule Compatibility

Battery Electric Bus Compatibility

This analysis seeks to determine where SEPTA bus service is most and least suitable for electrification, taking into consideration performance data gathered from the Proterra BEB pilot on Routes 29 and 79. As technologies continue to improve in the coming years, this work will also provide tools for SEPTA to evaluate various scenarios and make adjustments. The results will help inform a framework for SEPTA to work toward its goal of full bus fleet electrification, while also providing pragmatic information about planning for uncertainty.

A detailed simulation of BEB operations was undertaken to understand what portion of SEPTA bus service would be compatible to operate with BEBs under different scenarios. The model is designed to predict the state of charge (SOC) of BEBs as they travel through a day's worth of assigned trips. This daily assignment, called a vehicle block, is the main unit of analysis in our modeling.

To simulate the SOC of BEBs, the project team developed several assumptions and scenarios that address BEB battery performance, charging mechanics, and on-route charging networks. The full set of assumptions can be found in ***Appendix A***. These assumptions are conservative and represent reasonably worst-case performance.

Our analysis also compared several scenarios with different potential networks of on-route chargers. To develop these networks, SEPTA staff evaluated the feasibility of its layover locations to potentially accommodate on-route chargers. This evaluation considered factors such as whether the location was a transit center, a bus turnaround loop, or on-street, whether there was space to install necessary electrical infrastructure, and whether the location was owned by SEPTA, another government entity, or a private entity. This process concluded that the most realistic scenario was a network of on-route chargers at 32 SEPTA-owned locations; however, the specific locations included may be refined over time in later phases of planning and design.

Figure 6 *– Charger locations included in the scenario with on-route charging at 32 SEPTA-owned locations*

The model results estimated what percentage of vehicle blocks were suitable to operate with BEBs under our conservative modeling assumptions using the baseline on-route charger network of 32 SEPTA-owned locations. The table below shows these results broken down by bus district and by weekday, Saturday, and Sunday schedules. Note that the Frankford Trackless service is included only to test the potential for future BEB conversion.

Table 10 *– Percent of blocks suitable for electrification at each bus district on each service day, if on-route chargers are provided at 32 SEPTA-owned locations*

	District	Weekday	Saturday	Sunday
City	**Frankford** (Trackless)	100%	100%	100%
	Frankford (Bus)	73%	65%	78%
	Allegheny	72%	67%	80%
	Callowhill	67%	46%	50%
	Midvale	56%	37%	50%
	Southern	54%	28%	28%
	Comly	44%	20%	40%
Suburban	**Victory**	22%	29%	29%
	Frontier	19%	14%	17%

Several key takeaways can be observed from this table. First, weekday and Sunday service have relatively high compatibility with BEBs, while Saturday service has relatively low compatibility with BEBs. This is largely because on Saturdays, buses tend to be scheduled to operate longer total distances before returning to the garage. The table also shows significant differences between the compatibility of different bus districts, with the two suburban bus districts, Victory and Frontier, having rather low compatibility. Buses at the suburban districts operate an average of 123 miles per weekday block, while buses at the city districts operate 58 miles on average per weekday block, which explains the disparity in compatibility results. The higher-compatibility city districts account for the vast majority (86%) of SEPTA's bus service.

Strategies For Service That Is Difficult To Electrify

The schedule modeling results show that a substantial portion of SEPTA's bus service could be electrified with current technology and current schedules. However, to achieve full fleet electrification, some changes would need to be considered to address the service that is most difficult to electrify. We analyzed several types of strategies that could be used to increase compatibility with BEBs. Over the course of the transition to a BEB fleet, SEPTA could use a mixture of these strategies to eventually achieve 100% compatibility. The potential benefits of schedule changes and technology improvement as strategies for service that is difficult to electrify are further explained in the following sections.

- **Schedule changes,** such as splitting up longer blocks or increasing layover times. This is an effective strategy for increasing compatibility, but it has the downside of increasing operating costs. In limited cases where vehicle blocks need to be broken apart during peak times, this can also increase the bus fleet size.
- Implement additional **on-route charging** locations. For example, adding chargers at 16 high-usage locations that are owned by other public entities is estimated to increase schedule compatibility by 8 percentage points at the city districts.
- Adopt **improved BEB technologies** that are coming to market. For example, BEBs with a 660 kWh battery could significantly increase service compatibility. Similarly, technology improvements related to bus heating could have a major benefit in terms of expanding range, as this heating energy represents about a quarter of energy consumption during winter conditions.

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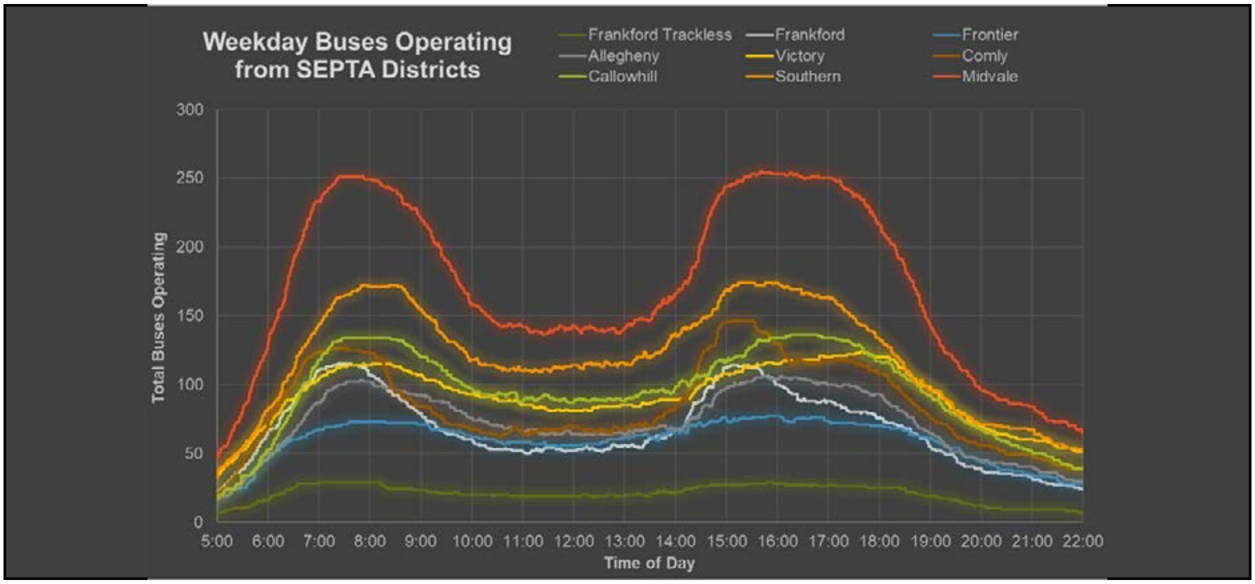

Figure 7 *– Graph of total buses in service by time of day for various SEPTA districts*

Schedule Changes

SEPTA could consider schedule changes that improve compatibility with BEBs. The simplest type of change would be to split up longer vehicle blocks that surpass the range of BEBs. This strategy would add operating time for the bus to pull into a garage and for a new bus to pull out from the garage. It also has the potential to increase the peak fleet requirement, but this can be minimized with careful scheduling. ***Figure 7*** shows the fleet usage at a typical SEPTA bus district; the total buses in use peak in the morning around 7 AM – 9 AM and in the afternoon around 4 PM – 5 PM. As long as schedulers split blocks apart outside of these peak times, the operation can use already-available buses and avoid adding to the overall peak fleet.

It should be noted that the bus network changes over time, and the Bus Revolution initiative could impact service compatibility for electrification. For example, it could increase compatibility if more routes serve terminals with on-route chargers, or it could reduce compatibility if vehicle blocks become longer due to reduced focus on peak service.

Other scheduling strategies can also be considered to enhance compatibility with BEBs. If on-route charging is available at one end of a route but not another, existing layover time might be shifted to the location that has charging available. Similarly, schedulers could increase layover times beyond the route's existing cycle time, though this will increase the number of vehicles on the route – this strategy should be avoided during peak pullout.

An array of other service changes will likely be considered as part of SEPTA's Bus Revolution initiative. This initiative is focused on improving the bus network from a customer perspective, but forward-compatibility with BEBs may be worth considering as route terminals and schedules are reevaluated.

Technology Improvement

Improved technology options could lead to broader compatibility with SEPTA bus service. For example, our modeling estimates that larger 660 kWh batteries could increase schedule compatibility significantly (18 percentage points). Battery consumption rates are also expected to decline over time as energy density improves. Within the next decade, this trend is likely to yield a modest benefit to schedule compatibility (4 percentage points). For the service that is most difficult to electrify, often due to long distances traveled in suburban areas, FCEBs are being considered. FCEBs have significantly longer ranges than BEBs, potentially up to 300 miles.

Fuel Cell Electric Bus Compatibility

As noted earlier, FCEBs have an operating range on the order of 300 miles. As a result, FCEBs would be compatible to operate all of SEPTA's existing bus schedules.

Table 11 *– Percent of blocks suitable for operation with FCEBs at each bus district*

	District	Weekday	Saturday	Sunday
City	**Frankford** (Trackless)	100%	100%	100%
	Frankford (Bus)	100%	100%	100%
	Allegheny	100%	100%	100%
	Callowhill	100%	100%	100%
	Midvale	100%	100%	100%
	Southern	100%	100%	100%
	Comly	100%	100%	100%
Suburban	**Victory**	100%	100%	100%
	Frontier	100%	100%	100%

6 Sustainability and Equity Analysis

Background

Deploying ZEBs will create many benefits for residents of the SEPTA service area by reducing greenhouse gas emissions, local air pollution, and traffic noise. Reduced air pollution can help address public health issues such as asthma and cardiovascular conditions. These issues disproportionately affect low-income and minority communities in the Philadelphia region. SEPTA already has analysis on how service decisions impact low-income and minority communities, in compliance with federal requirements, and a similar analysis was conducted to understand how the rollout of ZEBs could impact these communities.

This fleet transition could be an opportunity to prioritize benefits for disadvantaged communities:

- Reduced air pollution and associated health impacts
- Reduced traffic noise
- Reduced greenhouse gas emissions

This chapter will first examine the equity considerations in planning a ZEB transition, and it will then quantify the expected emissions reductions associated with a transition to ZEBs. While our analysis does not consider the visual impacts or community acceptance of bus fueling and charging technologies, these could be topics for future study.

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Methodology

The equity analysis seeks to help prioritize ZEB deployments among different operating districts by understanding the demographics of the areas served. Specifically, we calculated the percent low income and percent minority within a half-mile of each of the eight SEPTA bus garages and within a quarter mile of the routes operated by the same bus districts. Percent low income represents the share of population below 200% of the poverty level. Percent minority represents the non-white share of the population. The Equity Analysis utilized census tract level data from the American Community Survey (2015-2019) five-year estimates. The percentage results are found below in ***Table 12***.

Findings

The overall equity analysis values and priority ratings are shown in ***Table 12*** and ***Table 13*** below. "Low" ratings were given for low-income or minority values below 30%, "medium" ratings were given for values between 30% and 45%, and "high" ratings were given for values greater than 45%. Districts with high overall equity rating include Allegheny, Callowhill, Comly, Frankford, and Midvale. Districts with medium overall equity rating include Southern and Victory. The only district that had a low overall equity rating is Frontier.

Table 12*– Percent low-income and minority within a half and quarter mile of each bus district*

District	% Low Income (in area within ½ mile of depot)	% Low Income (in area within ¼ mile of depot's routes)	% Minority (in area within ½ mile of depot)	% Minority (in area within ¼ mile of depot's routes)
Allegheny	60.7%	44.0%	95.1%	62.1%
Callowhill	58.4%	42.7%	98.9%	62.2%
Comly	47.8%	39.0%	80.0%	52.7%
Frankford	54.3%	44.4%	85.6%	61.9%
Frontier	15.1%	20.1%	39.4%	27.6%
Midvale	51.2%	40.0%	87.1%	59.2%
Southern	21.1%	48.1%	10.2%	72.3%
Victory	41.6%	24.1%	80.6%	36.6%

Table 13*– Equity prioritization per bus district*

District	% Low Income (in area within ½ mile of depot)	% Low Income (in area within ¼ mile of depot's routes)	% Minority (in area within ½ mile of depot)	% Minority (in area within ¼ mile of depot's routes)	Overall Equity Rating
Allegheny	High	Medium	High	High	High
Callowhill	High	Medium	High	High	High
Comly	High	Medium	High	High	High
Frankford	High	Medium	High	High	High
Frontier	Low	Low	Medium	Low	Low
Midvale	High	Medium	High	High	High
Southern	Low	High	Low	High	Medium
Victory	Medium	Low	High	Medium	Medium

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We also mapped low-income and minority populations to understand their geographic distribution. As seen below in ***Figure 8***, the share of population below 200% the federal poverty level is mostly concentrated within Philadelphia County. Allegheny, Midvale, Comly, Frankford, Victory, and Callowhill Districts have a range between 42% to 61% in this low-income category. The Frontier and Southern Districts have 15% to 21% of population in this low-income category.

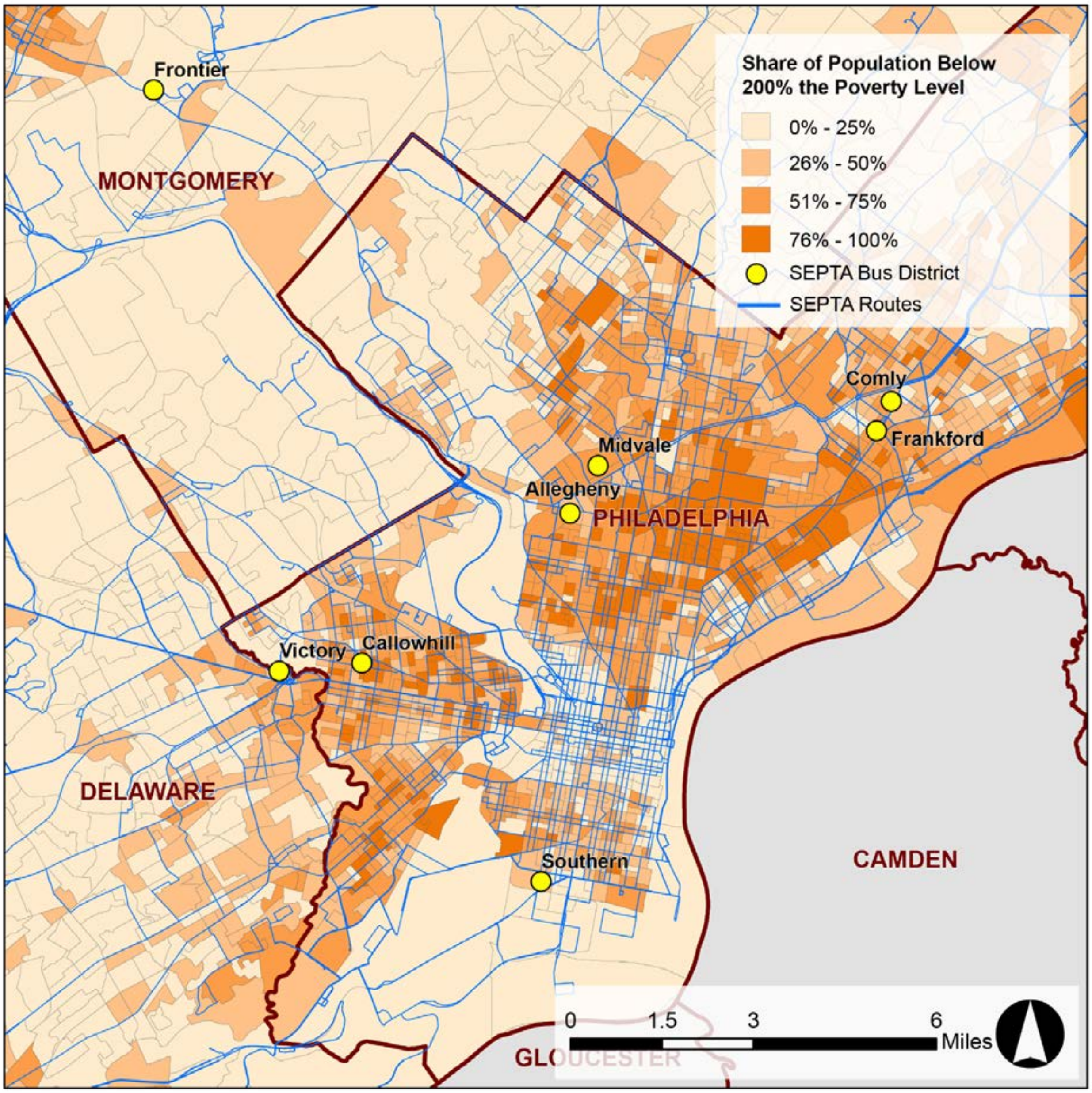

***Figure 8**– Share of population below 200% of the federal the poverty level*

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As seen below in ***Figure 9***, the minority populations within the service area are concentrated within Philadelphia County. All of the bus districts in Philadelphia except Southern serve high minority populations ranging from 80% to 95% (Victory, Callowhill, Allegheny, Midvale, Comly, Frankford). Lower minority population shares are seen near Frontier and Southern Districts.

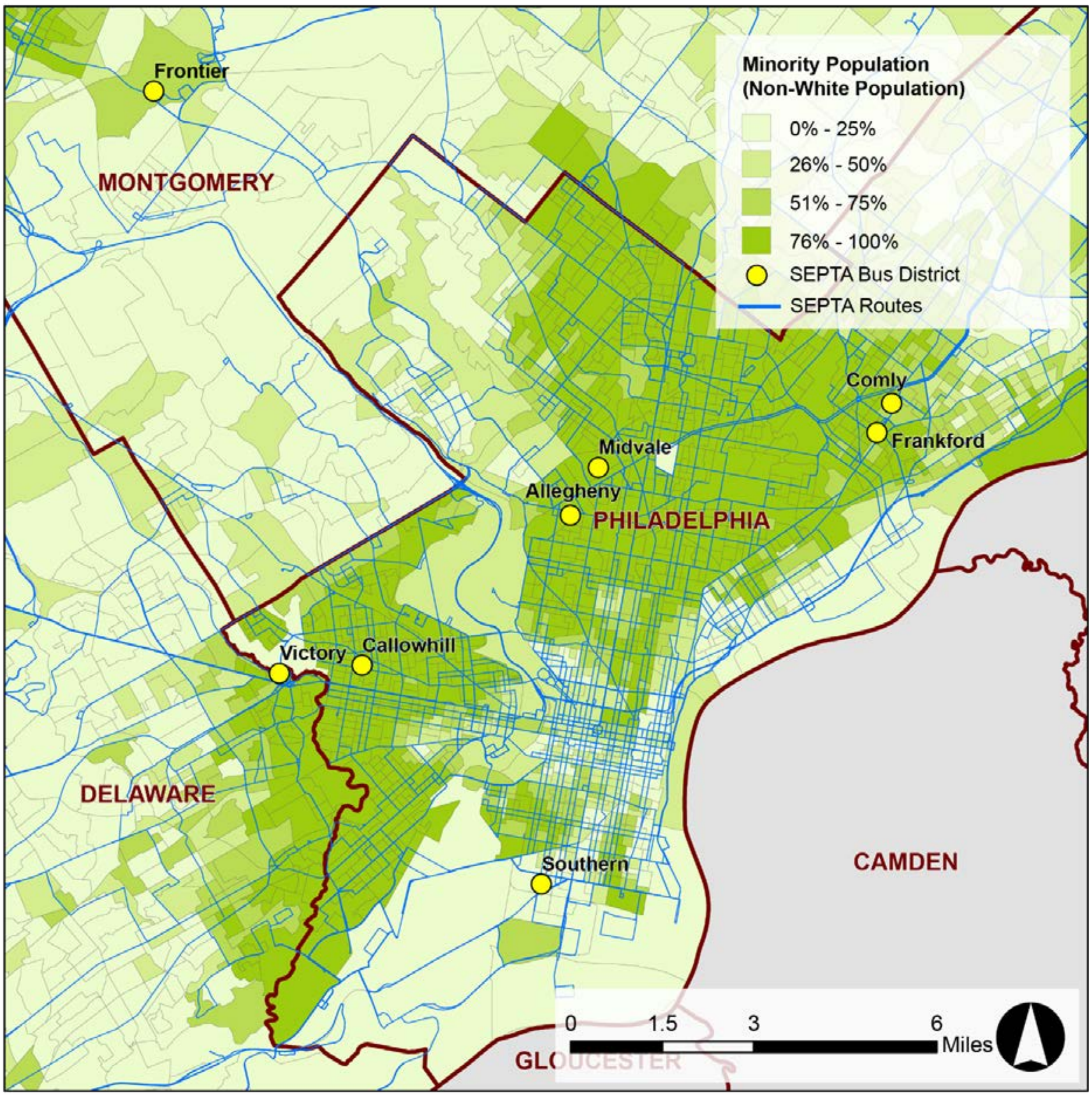

Figure 9 *– Minority population (non-white population)*

Projected Emissions Reductions

As reducing local air pollution and lifecycle carbon emissions is a primary motivator for transitioning to a zero-emission fleet, SEPTA developed emissions projections to compare different future scenarios. This modeling demonstrates that converting to a ZEB fleet will yield significant environmental benefits to SEPTA's service area. The projected emissions reductions consider not only tailpipe emissions, but also upstream emissions related to power generation, fuel production, and delivery. At the end of a transition to an all BEB scenario, annual CO_2 emissions would be 74% less, NO_x emissions would be 94% less, and $PM_{2.5}$ emissions would be 45% less compared to pre-transition figures.

At the end of a transition to the FCEB scenario, annual CO_2 emissions would be 53%-91% less, NO_x emissions would be 91%-95% less, $PM_{2.5}$ emissions would be 58%-86% less. (The range of values depends on whether SEPTA uses "gray" hydrogen produced from fossil fuels via the SMR process, or "green" hydrogen produced using electricity generated from renewable energy sources. As noted earlier, SEPTA's choice of hydrogen fuel type will prioritize more sustainable options to the extent they are available; more detail about the types of hydrogen is presented in Chapter 4.). Note that these projections include both emissions from energy/fuel and from daily fuel delivery to each depot. Fuel delivery can be a substantial source of emissions, given that the nearest hydrogen supplier to SEPTA is over 300 miles away.

The detailed comparison of projected emissions under diesel hybrid, BEB, and FCEB scenarios are shown in ***Figure 10***. These include emissions from tailpipe emissions, power generation, fuel production, and fuel delivery. The emissions reductions will benefit local public health as well as global climate sustainability.

It is worth noting that actual future ZEB lifecycle emissions may be lower than those shown in Figure 10, depending on regional energy trends. If more renewable electricity is added to the grid than anticipated, BEB operational emissions will decrease. If local hydrogen production increases, emissions from hydrogen fuel delivery will decrease. See Appendix I, Emissions Analysis, for more details.

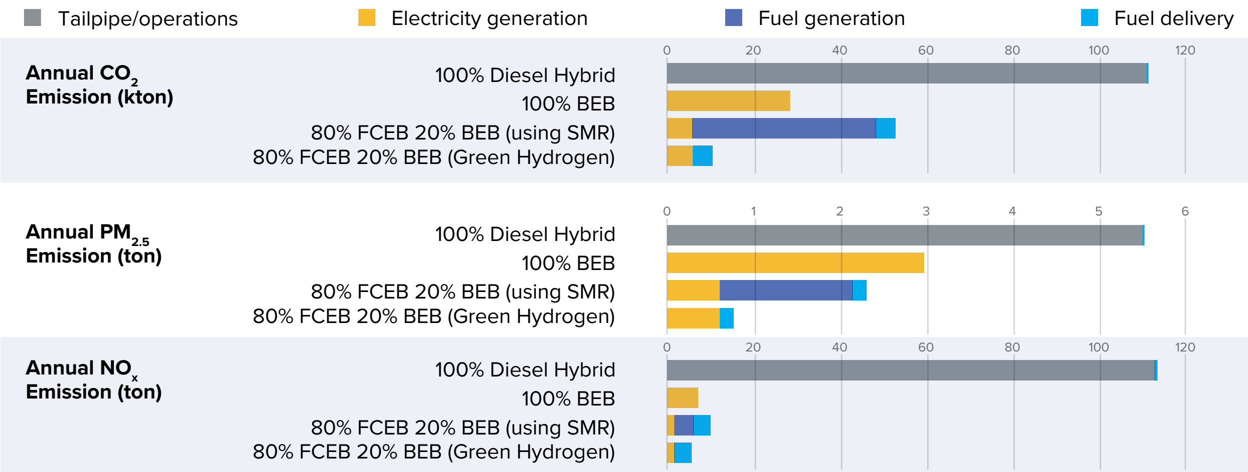

Figure 10 *– Summary of projected emissions in 2040*

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7 Fleet and Facility Plan

Transitioning to a zero-emissions bus fleet requires planning to coordinate the bus fleet with the support facilities needed for charging/fueling and storage. With eight main bus districts and a fleet of over 1,400 buses, the ZEB transition will be a major undertaking lasting 15 years or more. The following section describes a transition plan for SEPTA's bus fleet and facilities over the period 2026-2040. This planning is based on analysis of many strategic considerations, but it is also important that SEPTA can revise these plans in the future in response to new or improved technology, funding availability, changing priorities, or other factors.

Fleet Plans

The SEPTA bus fleet was analyzed based on internal documents that show the age, size, and other characteristics of each bus in the fleet. The current fleet includes standard 40' hybrid buses, articulated 60' hybrid buses, trackless trolleys, and existing BEBs.[11] SEPTA typically keeps buses in service for 15 years, so future bus replacement purchases were projected based on this policy.

11 Note that 30' buses were excluded, as they are not directly operated by SEPTA.

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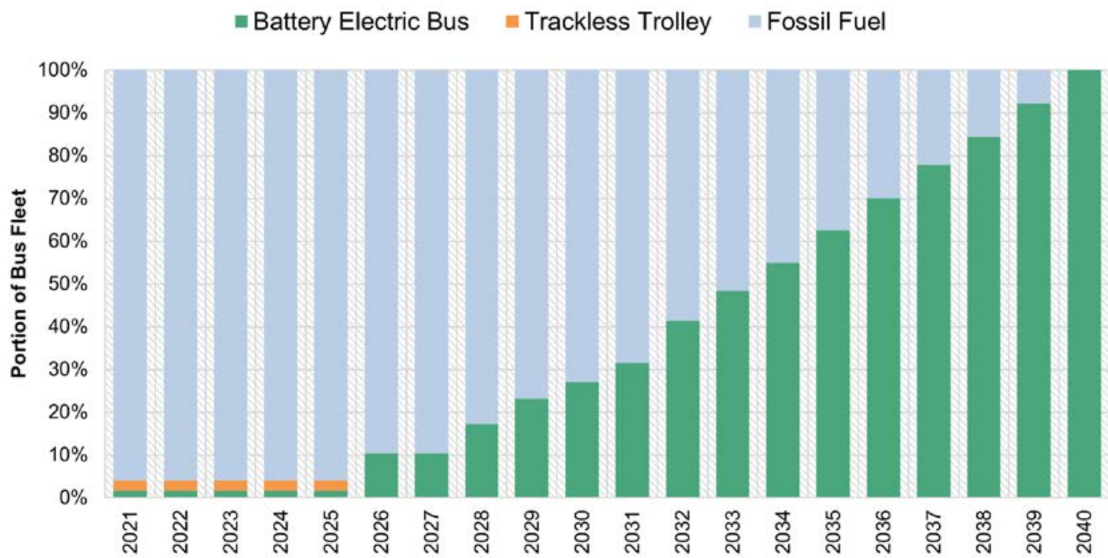

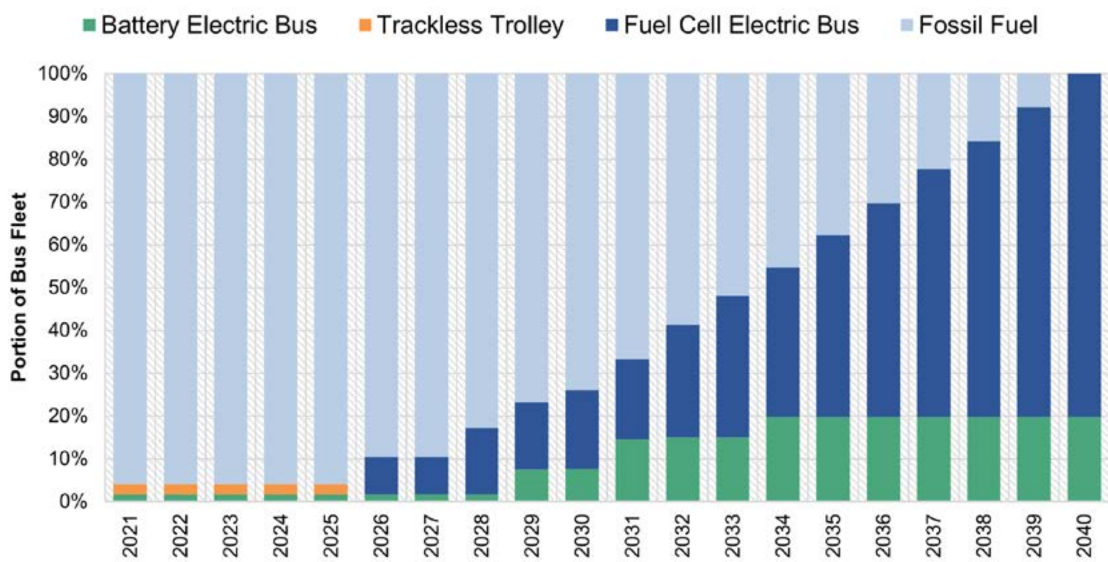

Figure 11 *– Potential future makeup of SEPTA bus fleet, if all bus purchases are ZEBs starting in 2026. (Top graph shows 100% BEB scenario, bottom graph shows 80% FCEB scenario.)*

Battery Electric Bus Fleet Plan

SEPTA's most recent bus procurement commits it to deliveries of hybrid buses through the year 2025, assuming optional purchases are executed. This means that the earliest that SEPTA could begin receiving *only* ZEBs would be 2026. Based on the 15-year bus lifetime, under this scenario the last fossil fuel buses would be replaced in 2040, achieving a fully ZEB fleet. This fleet transition plan is shown in ***Figure 11*** above. A timeline for achieving a fully electric fleet by 2040 aligns well with commitments made by peer agencies such as New York City MTA, NJ Transit and CTA. Note that SEPTA would likely also continue purchasing a small number of ZEBs before 2026, contingent on funding.

Fuel Cell Electric Bus Fleet Plan

A similar fleet planning exercise was completed for an 80% FCEB scenario. This scenario would lead to a fleet that has 80% FCEBs and 20% BEBs. The BEBs would be used at Allegheny and Callowhill, where it is estimated that hydrogen fuel storage is infeasible with current constraints. Similar to the 100% BEB scenario, all bus purchases would be ZEBs starting in 2026. Both scenarios include a small number of additional buses to facilitate splitting up of long blocks as needed for BEB compatibility.

To simplify our analysis, this graph shows existing trackless trolleys being replaced with other vehicle types when they reach the end of their useful life in 2026. However, this is not meant to represent SEPTA's actual plans for the trolley fleet.

Facility Upgrade Plans

Battery Electric Bus Upgrades

A facility planning effort was completed to understand the nature of facility upgrades needed to support a BEB fleet and to develop an appropriate conversion timeline. Burns Engineering reviewed SEPTA's existing bus facilities and developed layout modifications to accommodate charging equipment. This was informed in part by the bus state-of-charge modeling (described in ***Appendix A***) that estimated how much energy buses would need to receive through overnight charging at garages to return to a 90% state of charge for morning pull-outs.

This work ultimately selected a strategy in which each garage would have two fast chargers placed near fueling lanes, which buses could use during their regular servicing process. Currently, the regular process involves buses spending about 15 minutes in the fueling lane for fueling and internal cleaning. Our analysis assumed that fast charging would occur in a similar fashion, though in practice it could change as technology and operations develop. For buses that only need a modest amount of charging, fast charging during servicing could be sufficient to reach an acceptable SOC. For buses that need more charging, the garage charging strategy also provides as many slow chargers as can be accommodated within each facility, based on parking space availability. We anticipate that fast charging appropriate buses may take an average of 17-26 minutes, which would require extra servicing labor compared to the current 15-minute servicing time. Buses that can be appropriately charged using fast charging can be stored in areas without slow chargers (including

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Table 14 – *Summary of chargers and electrical capacity proposed at each bus garage/district*

Garage/District	Slow Chargers at Garage	Fast Chargers at Garage	New Recommended Electrical Capacity for Charging (MW)
Allegheny	29	2	4
Callowhill	46	2	6
Comly	35	2	6.6
Frankford	30	2	8
Frontier	28	2	4
Midvale	83	2	10.5
Southern	49	2	8
Victory	29	2	4.4

This analysis assumes that charger usage is managed in line with bus schedules, such that all chargers are not in use simultaneously.

overflow or other non-traditional parking spaces where buses are currently parking). This garage charging strategy should be piloted at a single facility to understand its performance, including the effectiveness of thermal management strategies in the winter, and to refine the strategy before it is deployed systemwide. Note that fast chargers are assumed to provide 450 kW with a single dispenser, and slow chargers are assumed to provide 180 kW shared among three dispensers. These choices also informed the recommended new electrical capacity at each bus garage, which is shown in the table above.

Facility upgrade plans also include other electrical equipment, utility requirements, and backup power generation for resiliency. This will be important for SEPTA to maintain reliable bus service in the event of a power outage. There may also be need to add clean agent systems for fire suppression in case of an electrical fire. Fire suppression systems in bus storage areas should be evaluated to ensure that they will properly extinguish fires in case of an incident.

The review of SEPTA's bus facilities also revealed three factors that could impact storage capacity under an all-BEB fleet. First, there are a significant number of buses currently stored in non-standard or overflow areas, such as parked on-street or in maintenance areas. BEBs stored in this manner would not be able to use a slow charger overnight. In addition, the installation of charger equipment is expected to reduce storage capacity due to space for footings and tolerances required to accommodate different positioning of charging pantographs among different equipment manufacturers. Finally, schedule compatibility analysis indicated that many vehicle schedules will require modifications to become compatible with BEBs. In most cases these changes can occur during off-peak times that will not impact the overall fleet, but we estimate that a fleet increase of at least 25 buses will be needed in total to ensure schedule compatibility.[12]

Table 15 – *Summary of impacts on bus storage capacity at each garage/district*

Garage/District	Baseline Vehicle Count from SEPTA		Buses Stored in Non-standard or Overflow Parking	Buses Displaced by Chargers & Associated Equipment	Added Buses due to Vehicle Block Changes
	40' Buses	60' Buses			
Allegheny	42	81	0	19	2
Callowhill	181	0	-3	20	3
Comly	165	20	20	10	3
Frankford	142	0	13	14	3
Frontier	102	0	-13	11	2
Midvale	229	83	7	0	5
Southern	207	21	21	7	4
Victory	176	0	55	29	3
Total	1,244	205	100	110	25

In total, this analysis shows that SEPTA's bus storage space deficit could grow to about 235 buses during the transition period. This suggests that SEPTA will likely require new bus garage(s) and/or expansion of existing district(s) as part of its fleet conversion process. More discussion and study will be needed to develop SEPTA's preferred solution to this issue and understand its financial implications. Due to this uncertainty, increased storage capacity is not included in our detailed facility plans at this point.

Fuel Cell Electric Bus Upgrades

Hydrogen fuel is subject to safety regulations that must be considered when planning for facility needs and operations. Organizations with relevant policies include the Occupational Safety and Health Administration (OSHA) and the National Fire Protection Association (NFPA). Like diesel fuel, hydrogen gas is classified as a hazardous material by the US Department of Transportation (DOT) due to its flammability; as a result, fuel deliveries will be subject to hazmat regulations.[13] It is important to understand what local authority will ultimately be responsible for permitting and inspecting fueling infrastructure; this is generically referred to as the Authority Having Jurisdiction (AHJ). Three AHJs that are responsible for permitting and inspecting the SEPTA Bus Depots evaluated for this study, include

12 This estimate is based on our schedule analysis that makes conservative assumptions reflecting near-worst case performance. Note that this may require additional analysis as SEPTA's bus schedules change; if schedules become less peak-focused per the 'Lifestyle Network' vision this could create longer vehicle assignments that are more difficult to operate using BEBs.

13 FCEBs themselves are exempt from hazmat placarding and special driver endorsements.

Plymouth Township Codes Department, Montgomery County; Upper Darby Township Licenses and Inspections, Delaware County and the City of Philadelphia Licenses and Inspections (L&I). These municipalities adopted the Pennsylvania Uniform Construction Code (UCC) which includes the 2018 versions of the International Building Code (IBC), International Fire Code (IFC), International Fuel Gas Code (IFGC) and International Mechanical Code (IMC). These aforementioned codes all align with the NFPA 2 Hydrogen technologies Code which is what AHJs would be referencing when inspecting or permitting Hydrogen storage or dispensing facilities.

Hydrogen Fuel Tanks

As mentioned earlier, liquid hydrogen fuel is stored in tanks as large as 40' long. Hydrogen fuel tanks must be located outside for safety reasons. Fuel tanks can be placed above ground or below ground, but there are no examples below-ground storage at US transit agencies, so SEPTA is ruling out below-ground storage. Above-ground fuel tank siting must meet the following setback requirements in accordance with NFPA 2:

- 50' – 100' from existing facilities, depending on quantity stored
- At least 75' from concentrations of people
- 50' – 100' from any other flammable liquids, including diesel and gasoline storage tanks
- 25' – 75' from lot lines, depending on tank size
- These same clearance requirements also apply for liquid hydrogen delivery trucks

Note that the use of a noncombustible two hour rated fire barrier wall, adjacent to storage tanks, will allow for reduced distances to the setback requirements mentioned above. Commercial fire barrier walls are typically constructed of concrete masonry units (CMU) "cinderblock", brick or poured concrete as defined by the IBC. Depending on the location of a two hour fire barrier wall, setbacks to adjacent buildings, property lines and other hazardous substances could be reduced to five feet or less. SEPTA bus depots are most likely considered noncombustible buildings, since they are built with standard brick and/or CMUs which should reduce buffer requirements allowing for more flexibility in placing hydrogen storage and dispensing systems for already constrained bus depot facilities.

Hydrogen Fuel Dispensing

Hydrogen fuel dispensers can be located indoors or outdoors, though outdoor fueling is significantly less complicated with fewer regulations. Indoor fueling would need to satisfy the regulatory requirements of National Fire Protection Association 70 National Electrical Code Class 1, Division 2, Group C.

Bus Parking

The regulations for FCEB parking will depend on decisions of the local AHJ. As with fuel dispensing, storing FCEBs outdoors is generally less complicated. A requirement to store indoor FCEBs in "a separate building" may be applied, but the interpretation of this requirement can vary. For example, providing a firewall between parking/ maintenance and separate entrances into those sections may be sufficient to meet the requirement. All but two of SEPTA's depots have at least some indoor bus parking that could be subject to these requirements.

Bus Maintenance

Bus maintenance almost always occurs indoors, and the special requirements for indoor facilities will be addressed in the next subsection. However, there are also special maintenance practices that should be incorporated into any plans for adopting FCEBs. Before routine repairs on a FCEB occurs, the bus should be defueled; the fuel can be recaptured into a storage tank for reuse or vented to the atmosphere. For major service on FCEBs (defined as any work that requires use of hydrogen), a dedicated hydrogen service bay must be used. This bay must be separated by a two-hour firewall, have no ignition sources, and be outfitted with the required ventilation, hydrogen and flame detection sensors, and fire suppression systems.

Indoor Facilities

Any indoor facilities used for storage, fueling, or maintaining FCEBs will need upgrades to meet safety requirements:

- → **Ventilation** must be at least 1 cubic foot per minute per square foot. Facility HVAC system upgrades may be necessary.
- → **Flame Detection Systems** are needed to ensure fires are quickly identified. This will utilize infrared cameras to identify hydrogen flames, which may be invisible and do not radiate much heat.
- → **Hydrogen Gas Detection Systems** involve sensors placed at the highest indoor locations because hydrogen gas rises.
- → **An Emergency Shutdown System** will automatically disconnect hydrogen gas if a threat is detected. The shutdown system will be tied to ventilation systems, flame detection sensors, and hydrogen detection sensors.

***Table 16** – Summary of hydrogen fuel storage buffer requirements*

Distance	Object
5 Feet	Noncombustible Buildings
25 Feet	Parked Cars
	Overhead Power Lines
50 Feet	Sprinklered Building
75 Feet	Lot Lines
	Building Doors/Windows
100 Feet	Unsprinklered Building
	Flammable Liquids (Gas/Diesel)

- **A Fire Suppression System** must be connected to the Emergency Shutdown System so that the hydrogen supply is cut off before the suppression system engages, avoiding an explosion hazard.
- **Facility & Work Restrictions** must be applied to ensure safety. No electrical devices should be permitted within 18” of the facility ceilings. This includes light fixtures and junction boxes, though conduits are permitted only if they are rigid and sealed. Similarly, no “hot” work, like welding, may occur near any potential hydrogen sources.

Preliminary Facility Screening

Based on the requirements described above, SEPTA’s existing bus districts were screened to understand whether upgrades to support FCEBs might be feasible. This evaluation focused on identifying outdoor space to store hydrogen fuel, in compliance with required buffers. It also considered the potential routing of fuel delivery trucks. ***Table 17*** below shows the results of this preliminary screening.

Allegheny and Callowhill were determined to be incompatible to store hydrogen fuel. These facilities occupy entire blocks in an urban environment, with no outdoor space available to conceivably site a fuel tank. While these sites are rated as “no” in the table, in principle there are ways for them to accommodate FCEBs without storing the fuel on-site. If suitable space for hydrogen fueling could be secured in the vicinity of these districts, a remote fueling operation might be considered. This could create new operating costs and inefficiencies. Similarly, a new bus district facility could change this result.

Table 17 *– Preliminary Facility Screening by Compatibility with Outdoor Hydrogen Fuel Storage and Delivery*

District	Feasible for Hydrogen Fuel Storage	Feasible for Bus Storage/ Maintenance
Allegheny	No	Yes
Callowhill	No	Yes
Comly	Maybe	Yes
Frankford	Maybe	Yes
Frontier	Yes	Yes
Midvale	Yes	Yes
Southern	Maybe	Yes
Victory	Maybe	Yes

Note: These findings are preliminary, and each district would need to be evaluated in-person prior to making definitive compatibility decisions. Only Midvale and Allegheny were reviewed in-person as part of this effort.

Victory, Southern, Frankford, and Comly were rated as “maybe” compatible to store hydrogen fuel. These locations might require exceptions to some buffer requirements or use of firewalls to reduce setbacks. At Frankford, the fuel tank might interfere with existing trackless trolley infrastructure. (In most cases the fuel tanks would have impacts on outdoor parking or storage, similar to BEB infrastructure.)

Frontier and Midvale were determined to be compatible to store hydrogen fuel. Both locations have existing outdoor parking space that could be safely repurposed to house fuel tanks. There may still be some need for firewalls or reduced setbacks. Parking impacts would need to be addressed, and at Midvale there could also be complications related to a sewer easement. Detailed drawings of the analysis that informed this preliminary screening are available in ***Appendix H***.

More detailed analysis and design will be required to confirm the precise impacts of FCEB infrastructure at SEPTA facilities and to verify facility compatibility for the locations rated as “maybe.” This work can also verify the impacts on facility space and storage (at a minimum 1,700 sq ft per tank stored vertically as well as access for hydrogen delivery trucks), which could contribute to the need for a new bus district. Coordination with the local AHJ will be important to confirm the building upgrades that will be required. Additionally, if SEPTA wishes to house FCEBs at Allegheny and Callowhill, further investigation of nearby sites for remote fueling operations will be needed.

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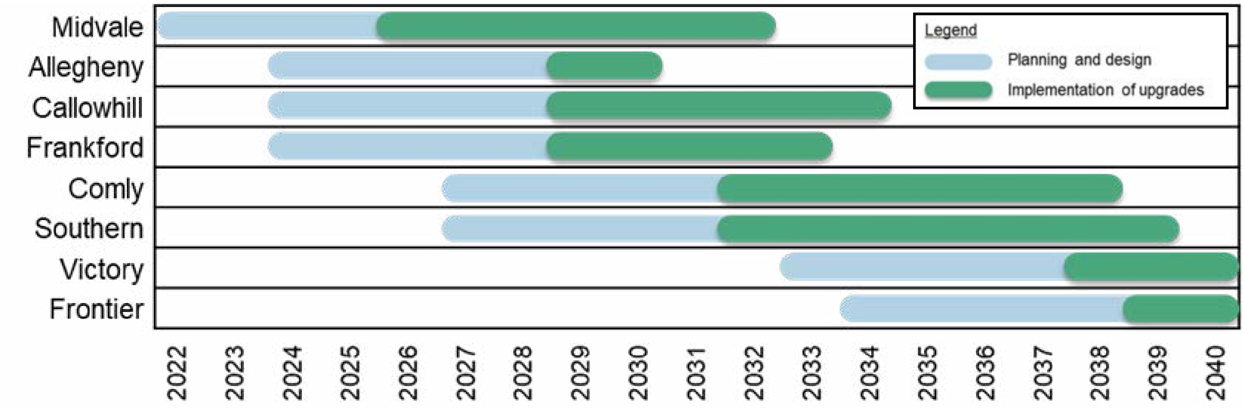

Figure 12 *– Potential timeline of facility improvements. Planning and design should begin approximately 5 years before a district needs to begin receiving zero-emission buses.*

Timeline and Sequence of Upgrades

An important element of a facility upgrade plan is the timeline and sequencing of the facility upgrades. A sequence was developed (as shown in ***Figure 12***) that considers equity factors, schedule compatibility, storage impacts, and the extent of required structural/ civil modifications. The first five garages all serve areas with high proportions of low-income and minority populations, who are disproportionately impacted by air quality issues today. The table also includes information about where, under a BEB scenario, the proposed on-route charging locations might be shared between different garages; the first two garages of Midvale and Allegheny have significant overlap where buses could share this infrastructure. To inform FCEB scenarios, the table shows which districts are estimated to have suitable space for hydrogen fuel storage.

Tables 18 and 19 also show that the final two districts to convert would be the suburban districts of Victory and Frontier. This is in part a result of their longer routes that lead to low schedule compatibility (less than 30% of vehicle blocks on all schedule days.) Equity considerations also drive their placement in the sequence. However, later years of the transition plan should be revisited as zero-emissions bus technologies continue to evolve.

The upgrades at a given district would not necessarily occur in a single year. We anticipate that these upgrades could be completed in more incremental pieces that roughly align with the growth of the ZEB fleet. ***Figure 12*** above shows a potential conversion timeline in which upgrades at several garages are completed over the course of six or seven years. The blue color indicates the planning and design before each garage upgrade, while the green color indicates the period over which upgrades are implemented. This timeline also considers the anticipated purchases of 40’ vs. 60’ buses at each district to ensure that district upgrades are completed in time to accommodate anticipated bus purchases of each type.

Table 18 *– Prioritization order for BEB district upgrade sequencing, including factors that were used to inform the sequence*

Notes: Berridge is a maintenance facility that would only need modest upgrades. A new garage or expansion of existing districts should be considered as an addition to this sequence.

Garage/ District	Indoor or Outdoor?	Equity Prioritization	Where are On-route Chargers Shared?	Schedule Compatibility (Weekdays)	Storage Impacts	Structural/ Civil Modifications	Capital Upgrade Costs
Midvale	Indoor	High	Allegheny	Medium	Low	Low	$52.0M
Berridge	Indoor	—	—	—	—	Low	$0.38M
Allegheny	Indoor	High	Midvale	High	Medium	Low	$25.1M
Callowhill	Indoor	High	Comly/Southern	High	Low	Low	$27.9M
Frankford	Mixed	High	Frontier	High	High	Medium	$21.5M
Comly	Mixed	High	Callowhill/Frankford	Medium	Medium	High	$30.0M
Southern	Mixed	Medium	Midvale	Medium	High	High	$34.5M
Victory	Outdoor	Medium	Callowhill/Southern	Low	High	High	$27.7M
Frontier	Outdoor	Low	Frankford	Low	Medium	Low	$31.5M

Table 19 *– Prioritization order for hydrogen FCEB district upgrade sequencing, including factors that were used to inform the sequence*

Garage/ District	Indoor or Outdoor?	Equity Prioritization	FCEB Schedule Compatibility	Feasible for Hydrogen Fuel Storage	Feasible for Bus Storage/ Maintenance	Capital Upgrade Costs
Midvale	Indoor	High	High	Yes	Yes	$22.8M-$45M
Berridge	Indoor	—	—	—	—	—
Allegheny	Indoor	High	High	No	Yes	$10.9M-$21M
Callowhill	Indoor	High	High	No	Yes	$12.6M-$25.8M
Frankford	Mixed	High	High	Maybe	Yes	$11.4M-$22.5M
Comly	Mixed	High	High	Maybe	Yes	$12.6M-$25.8M
Southern	Mixed	Medium	High	Maybe	Yes	$13.6M-$25.8M
Victory	Outdoor	Medium	High	Maybe	Yes	$11.9M-$31.1M
Frontier	Outdoor	Low	High	Yes	Yes	$10.3M-$19.4M

During the planning and design for upgrades at each district, SEPTA should also consider the phasing of on-route charging locations to align with its district upgrades and the percentage of BEBs in the fleet. The 32 on-route charging locations identified in the schedule compatibility analysis have very different levels of expected usage; the highest-usage locations should be prioritized, and the lowest-usage locations could be re-evaluated at technology improves over time. The priority of these locations also varies over time; an on-route charger becomes more useful as more of the buses from the districts that use it are electric. The phasing of on-route chargers will likely be an incremental process as SEPTA identifies what routes should be electrified during each phase of implementation.

Fleet Transition Cost Comparison and Funding Options

Cost Modeling of ZEB Scenarios

Note: A more detailed version of this analysis is included as ***Appendix E***.

This analysis seeks to understand the costs that SEPTA should expect over the course of a transition to a ZEB fleet. We have projected various operating costs and capital costs associated with the SEPTA bus fleet over the period 2022-2040. These costs are calculated in year of expenditure (YOE) dollars, including inflation at a 2% annual rate. The specific cost categories included in our analysis are listed below.

Operating Costs

- Diesel Fuel
- Hydrogen Fuel
- Electricity
- Maintenance of buses and chargers
- Labor from Schedule Changes

Capital Costs

- Vehicle Purchases
- Chargers
- Facility Upgrades
- Anticipated Subsidy

The costs identified above were used to compare three scenarios for the SEPTA bus fleet: a baseline scenario that continues usage of hybrid buses, a BEB scenario that transitions to 100% BEBs, and a fuel cell scenario in which the fleet would be 80% FCEBs and 20% BEBs. The baseline scenario maintains the current fleet size and does not include any facility improvements. The 100% BEB scenario increases the bus fleet size by 25, in order to split apart long vehicle assignments, and includes investments in on-route chargers and garage upgrades. The 80% fuel cell scenario requires a smaller increase in the bus fleet (5 buses) and electrical infrastructure aligned with its smaller BEB subfleet. The scenarios follow facility upgrade plans and fleet purchasing plans that are described in the Implementation Plan section.

The overall results of our cost modeling for the fleet transition period of 2022-2040 are shown in ***Table 20*** below. This shows that modeled operating costs would be lower for the ZEB fleet scenarios compared with the hybrid fleet baseline over the 2022-2040 transition period: 6% lower for the BEB scenario or 4% lower for the 80% FCEB scenario. However, modeled capital costs for the ZEB scenarios would be higher compared with the hybrid fleet baseline: 12% higher for the BEB scenario or 3% to 19% for the 80% FCEB scenario. In total, we anticipate that the BEB fleet scenario adds a cost of $46m over the transition period, while the FCEB fleet scenario could range from a net savings of $58m to a net cost of $262m.

There are several reasons that the ZEB scenarios could be more costly than shown. Our estimates do not consider the cost of a new garage, which will likely be needed to address existing capacity issues that would be exacerbated with the addition of new fueling equipment or charging equipment at districts and which could significantly increase the capital investment. The ZEB scenarios also do not address any existing state of good repair needs or structural upgrades that may need to be addressed in conjunction with upgrades to accommodate ZEBs at each district. For BEBs, there will also be costs associated with bringing additional PECO service to districts and on-route charging locations and further coordination with PECO will be needed to identify these costs. There is also a risk that the anticipated subsidies do not continue at the level assumed.

However, there are also reasons that the ZEB scenarios may be more attractive than shown. The transition period includes the continued operation of hybrid buses until 2040, so full operational savings from transitioning will not be experienced until the end of the period. In addition,

Table 20 *– Total costs for each scenario and each cost category over the period 2022-2040, in millions of YOE dollars*

Operating Costs	Hybrid Scenario ($M)	Electric 100% BEB Scenario ($M)	Fuel Cell 80% FCEB Scenario ($M)	Capital Costs	Hybrid Scenario ($M)	Electric 100% BEB Scenario ($M)	Fuel Cell 80% FCEB Scenario ($M)
Diesel Fuel	$716	$392	$392	**Vehicle Purchases**	$2,021	$2,175	$2,155 to $2,250
Hydrogen Fuel	$0	$0	$218	**Charger Infrastructure**	$0	$90	$23
Electricity	$0	$114	$41	**Facility Upgrades**	$0	$252	$156 to $253
Maintenance	$2,337	$2,288	$2,266	**Anticipated Subsidy**	$0	-$252	-$248 to -$262
Schedule Changes	$0	$62	$13				
Operating Costs Total	$3,054	$2,856	$2,930	**Capital Costs Total**	$2,021	$2,265	$2,087 to $2,407
				Total Operating & Capital Costs	$5,075	$5,121	$5,017 to $5,337

Note that the 80% FCEB scenario includes some costs associated with a 20% BEB fleet, such as chargers and electricity. Note also that additional PECO service is not included in either scenario.

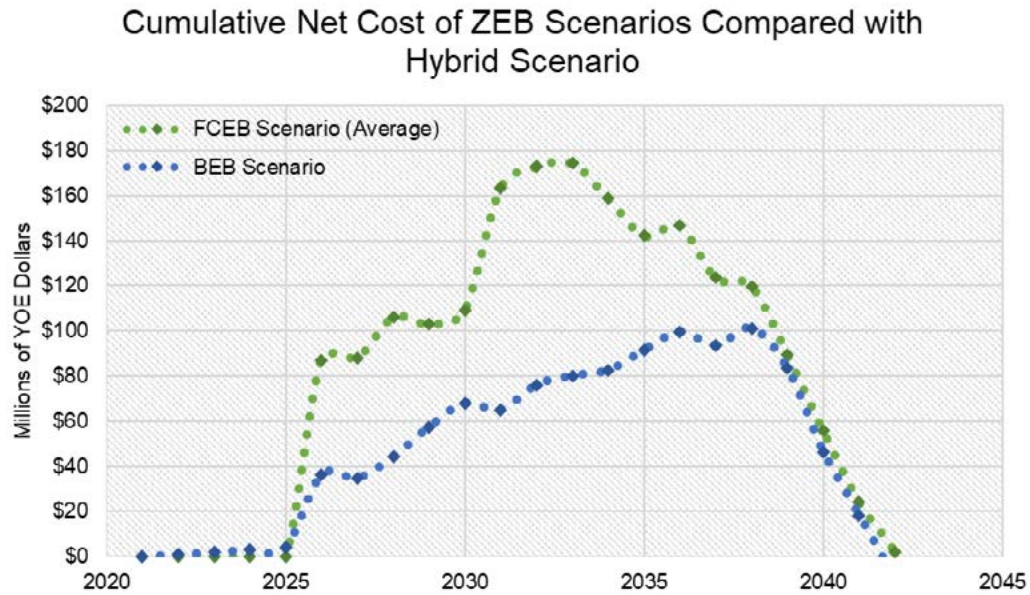

Figure 13 *– Cumulative net cost of ZEB scenarios compared with hybrid scenario*

the transition period includes capital investments to support the new fleet that would not be part of the ongoing financial picture.

The cost model can also be used to understand cost trends over time. ***Figure 13*** shows the cumulative net cost of selecting either ZEB scenario (100% BEB or 80% FCEB) compared with the hybrid fleet scenario. The lines represent the total additional cost that SEPTA would be projected to pay, above this hybrid fleet baseline. This shows that the net cost grows from 2026 (when SEPTA starts buying only ZEBs) until the mid 2030s, when most capital investments are complete. At the end of the 2030s, the cumulative net costs begin to decline as SEPTA reaps the benefits of reduced operating costs. The cost model shows that the cumulative costs of the two scenarios would break even in 2042 or 2043, shortly after the transition is complete.

Funding and Project Delivery Options

In order to potentially help offset the additional projected costs associated with a transition to zero-emission buses, potential federal and state funding sources have been identified. Most of the funding sources are application-based grant programs and so the amount of funding that could be obtained from these programs is uncertain. In addition, other partnerships, turnkey solutions and project delivery alternatives are described and could also be considered to help finance and facilitate a full transition to zero-emission buses.

Public Funding – Federal Funding

LOW OR NO EMISSION (LOW-NO) GRANT PROGRAM

The Low or No Emission competitive Federal Transit Authority (FTA) grant program supports funding to state and local governments for the purchase or lease of zero-emission and low-emission transit buses. Eligible projects include: (1) purchasing or leasing low- or no-emission buses; (2) acquiring low- or no-emission buses with a leased power source; (3) constructing or leasing facilities and related equipment (including intelligent technology and software) for low- or no-emission buses; (4) constructing new public transportation facilities to accommodate low- or no-emission buses, and/or (5) rehabilitating or improving existing public transportation facilities to accommodate low- or no-emission buses.[14] In the 2022 fiscal year, FTA is providing $1.1 billion in funding through this grant program. This is a significant increase from the $192 million provided in 2021 and the $129 million provided in 2020.

GRANTS FOR BUSES AND BUS FACILITIES PROGRAM

The Grants for Buses and Bus Facilities Program is administered by the FTA to replace, rehabilitate, and purchase buses and related equipment to construct bus facilities. Previous project selections include the City of Hazleton, PA which received $10 million for constructing a new bus maintenance and storage facility. SEPTA was also a past recipient of the program, receiving $2 million to fund and construct new bus stations to extend its Roosevelt Boulevard Direct Bus Service from Frankford Transportation Center to Wissahickon Transportation Center.

TARGETED AIRSHED GRANTS PROGRAM

The Targeted Airshed Grants program, administered by the US Environmental Protection Agency (EPA), assists local, state, and tribal air pollution control agencies with developing plans and conducting projects to reduce air pollution in non-attainment areas that EPA determines are the top five most polluted areas for ozone and $PM_{2.5}$ National Ambient Air Quality Standards. The program has approximately $59 million for the 2021 Fiscal Year. In 2020 the Allegheny County Health Department in Pennsylvania received approximately $5.6 million in funding to replace public transit buses with zero-emission alternatives. The California Air Resources Board in Nevada County also received approximately $2.4 million in 2020 to replace public transit buses with zero-emission buses.

CLEAN FUELS GRANT PROGRAM

The Clean Fuels Grant Program is administered by the FTA to assist in maintaining National Ambient Air Quality Standards for ozone and carbon monoxide, as well as support emerging clean fuel technologies for transit buses. This includes the purchase or lease of clean fuel buses; construction or leasing of bus fueling or charging facilities and equipment; projects related to clean fuel, biodiesel, hybrid-electric, or zero-emissions technology; and buses that have lower emissions than existing clean fuel or hybrid electric technologies. Funds for a project are available over a three-year period.

14 USDOT FTA. Source URL: https://www.transit.dot.gov/lowno

ENERGY EFFICIENCY AND CONSERVATION BLOCK GRANT (EECBG)

The EECBG program is administered by the US Department of Energy (DOE) to support and manage projects that improve energy efficiency and decrease energy use and fossil fuel emissions. This program received one-time funding under the American Recovery and Reinvestment Act (ARRA) of 2009. The EECBG program will receive $550 million through the Infrastructure Investment and Jobs Act for a new round of grants to state and local governments for clean energy investment projects, loan programs, and energy saving performance contracting programs (i.e., budget-neutral approaches to make improvements that reduce energy use and pay for them through future energy savings usage).[15] [16] In the 2009 round of funding, the City of Boston received approximately $6.5 million toward reducing fossil fuel emissions, reducing total energy use, and improving energy efficiency in the building sector.[17]

THE INFRASTRUCTURE INVESTMENT AND JOBS ACT – CARBON REDUCTION PROGRAM

The newly passed federal Infrastructure Investment and Jobs Act has over $1 trillion in federal infrastructure investment. The legislation establishes guaranteed funding levels through Fiscal Year 2022-2026 and is not a one-time stimulus. Its focus is to provide a foundation for a long-term surface transportation reauthorization bill. The legislation also includes investments in aviation, EV charging infrastructure, resiliency, and more.

Within the legislation is a Carbon Reduction Program that will distribute approximately $6.4 billion over 5 years to states for investment in projects that will help reduce transportation emissions. Eligible projects include transportation electrification, EV charging, public transportation, infrastructure for bicycling and walking, infrastructure that would support congestion pricing, diesel engine retrofits, port electrification and intelligent transportation systems (ITS) improvements. Approximately 65% of this funding would be allocated by population to projects in local communities.[18]

Public Funding – State Funding

CONGESTION MITIGATION AND AIR QUALITY (CMAQ)

The Congestion Mitigation and Air Quality (CMAQ) program provides funds to States for transportation projects that are designed to reduce traffic congestion and improve air quality. In Pennsylvania, the funds are distributed by the Delaware Valley Regional Planning Commission (DVPRC). CMAQ is not a grant, and its sponsors are reimbursed for costs after receiving funding authorization and a notice to proceed. SEPTA has been a recipient in the past, receiving up to $3.8 million for diesel engine replacement.

15 Office of Energy Efficiency & Renewable Energy. Source URL: https://www.energy.gov/eere/slsc/energy-savings-performance-contracting

16 Office of Energy Efficiency & Renewable Energy. Source URL: https://www.energy.gov/eere/femp/energy-savings-performance-contracts-federal-agencies

17 ProPublica. Source URL: https://projects.propublica.org/recovery/gov_entities/8900/list/1

18 The Bipartisan Infrastructure Investment and Jobs Act of 2021, U.S. Senate Committee on Environment and Public Works. Source URL: https://www.epw.senate.gov/public/_cache/files/2/e/2e879095-7fcd-4f6e-96fd-a4ad85afa0cc/7D48782E0BEB430002A767AC75961EB0.bif-highway-one-pager-final-2.pdf

ALTERNATIVE FUELS INCENTIVE GRANT (AFIG)

The Alternative Fuels Incentive Grant program is overseen by the Pennsylvania Department of Environmental Protection. The program helps support new markets for alternative fuel to enhance energy security. Approximately $5 million in grants are awarded each year. At least 20 projects were awarded a total of more than $3.4 million statewide in 2020. The largest grant went to Tri-County Transportation for $313,500 toward the purchase of 33 propane school buses. Allegheny County also received approximately $30,000 to purchase four EVs. For 2021, priority funding is going to businesses located in Pennsylvania; zero-emission vehicle projects; renewable natural gas vehicle and infrastructure projects; projects located in and serving environmental justice areas; minority, veteran, or woman-owned business applicants; publicly accessible alternative fuel refueling infrastructure projects; and fleet charging equipment projects.[19]

Private Partnerships

PECO

PECO, the local utility serving SEPTA properties, has proposed a $246 million increase in electric distribution rates to support investment in infrastructure that will enhance the local electric grid and increase advancement in clean technologies. At least $1.5 million will be invested towards incentives to expand public electric vehicle charging infrastructure to support commercial, industrial, and public transit customers with a focus on reducing emissions in disadvantaged communities. If approved, the actions for this proposal will take effect on January 1, 2022.

TURN-KEY OPTIONS

A turn-key option can offer an implementation package that includes vehicles, infrastructure, fuel – either hydrogen or electric – and a repair and maintenance package for a single fixed monthly cost. Some original equipment manufacturers (OEMs) are currently offering turn-key options to support battery-electric technology. This means the company will offer support in every stage for clients who want to make the switch to zero-emission buses, including planning, design, financing, operations, maintenance, and energy optimization. This can make the process of switching to ZEBs both customizable and comprehensive and create a one stop shop experience for clients interested in EV fleets.[20] Companies may also offer battery leasing, performance standards throughout the life of the vehicle, and a battery performance warranty as an alternative to including the cost of bus batteries with vehicle purchases. Battery leasing has the advantage of shifting the risk of expensive battery replacements to the OEM.

ZEB LEASING

Some bus manufacturers offer leasing of ZEBs. This leasing service provides the option of a monthly operating expense instead of the higher up-front cost for ZEBs. In Los Angeles County, the Antelope Valley

19 Pennsylvania Department of Protection. Source URL: https://www.dep.pa.gov/Citizens/GrantsLoansRebates/Alternative-Fuels-Incentive-Grant/pages/default.aspx

20 Insideevs.com. Source URL: https://insideevs.com/news/350119/proterra-energy-turnkey-approach-fleets/

Transit Authority found a cost savings of more than $46 million (lifetime cost) by electrifying its buses through a leasing program by saving money on diesel fuel which would have cost them $46,000 per bus in a year.[21]

CHARGING AS A SERVICE

There are also companies that offer a charging-as-a-service solution, which provides the full ecosystem for electric vehicle propulsion through a single vendor. The service includes charging equipment procurement, installation, operations, maintenance, automated charging operations, clean energy sourcing, fuel credit management, and more. Such a service could be evaluated for cost-effectiveness and flexibility compared to other procurement and delivery options.

Infrastructure Delivery Approaches

DESIGN-BID-BUILD

This is a widely used project delivery method that separates the design and construction phases of a project. The design phase is led by the local agency/owner, which includes developing project plans and specifications and typically accounts for about 5-10% of the project's total cost. The construction phase typically accounts for 90-95% of the total project cost and is awarded through a bid after the design phase is completed by the owner. This is usually awarded to the lowest reasonable bidder. This delivery approach gives the project owner the most control over how the project is designed but can entail higher project costs and a longer project schedule compared other delivery approaches.[22] Since the bidding process cannot start until designs are 100% complete, this schedule for delivering a project with this approach can take longer. Also, since there are multiple contracts due to there being separate design and construction teams, there are multiple points of contacts for the owner of the project which can add additional coordination time to the project schedule.[23]

DESIGN-BUILD

An alternative to the design-bid-build approach, the owner contracts to one entity to lead both design and construction. The project owner does not complete a detailed design project plan with specifications, but instead provides a basic concept for the project. The owner then evaluates which bidder offers the best value, qualifications, and price. Disadvantages to the design-build approach include the potential for reduced project quality, with an incentive to design for lower construction cost. This approach also entails less flexibility for the owner to separately select partners for the design and construction phases of the project.[24]

21 Metro Magazine. Source URL: https://www.metro-magazine.com/10032528/byd-partners-to-launch-first-ever-electric-bus-leasing-program?force-desktop-view=1

22 Senate Committee on Local Government. Source URL: https://sgf.senate.ca.gov/sites/sgf.senate.ca.gov/files/DBbriefingmemopublic%20%281%29.pdf

23 Watchdog Real Estate Project Management. Source URL: https://watchdogpm.com/blog/project-delivery-methods-design-bid-build/

24 Senate Committee on Local Government. Source URL: https://sgf.senate.ca.gov/sites/sgf.senate.ca.gov/files/DBbriefingmemopublic%20%281%29.pdf

DESIGN-BUILD-OPERATE-MAINTAIN

This is a project delivery method that is not common within the US. It is also referred to as 'turnkey' procurement, where the main contractor designs and constructs the project. The contractor is also responsible for operating and maintaining the project and the contractor may benefit from operational income. Disadvantages include the owner having less control, therefore unless needs are fully specified or identified to the contractor, overall project specifications may not be met. Financing is secured by the public sector project sponsor.[25]

DESIGN-BUILD-FINANCE-OPERATE-MAINTAIN

These types of partnerships include private operations and maintenance as part of project delivery. Long-term operations by the same party can provide incentives for better lifecycle cost management but allow for less operational control by the project owner.[26] Two potential advantages of the DBFOM method are: (1) it allocates risk for project delivery to a private sector contractor, and (2) it allocates responsibility to a contractor with expertise in areas the owner/agency does not have.

Workforce Impacts

A transition to ZEBs should include a review of recruitment and hiring practices to ensure that personnel with the proper skillsets and training are in place.

Vehicle Maintenance: The vehicle mechanic training and recruitment programs will need to be modified to accommodate a transition to ZEBs. Existing employees must be trained on new skills and recruitment of new employees must focus on different skills sets than those of traditional mechanics. Apprenticeship programs may be a valuable source of talent for SEPTA but must be established at least two years prior to buses arriving on property. OEMs have approached organizations such as the National Institute of Automotive Service Excellence to design certifications related to ZEBs, however, as of 2021, there are no ZEB-specific certifications in the transit industry.

In general, mechanics trained in conventional operating systems can perform most of the routine maintenance tasks for BEBs. After the bus is de-energized, many service and maintenance tasks are similar to those of diesel buses. The maintenance tasks that require additional training and skills include de-energization, use of high voltage PPE and tools, and servicing battery packs, generators, inverters, and motors. Good computers skills are essential as many OEMs provide troubleshooting software to diagnose issues.[27]

Training programs that meet the needs of staff are important to maintaining maintenance costs. Other agencies have reported an increase in maintenance costs as the warranty period ends and agency staff take over the maintenance of the ZEBs from OEMs and vendors. Costs tend

25 Federal Highway Administration. Source URL: https://www.fhwa.dot.gov/ipd/alternative_project_delivery/defined/new_build_facilities/dbom.aspx

26 Federal Highway Administration. Source URL: https://www.fhwa.dot.gov/ipd/pdfs/fact_sheets/techtools_P3_options.pdf

27 Transportation Learning Center, Battery Electric Bus Familiarization for Transit Technicians – Session 2, October 2020.

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to increase as maintenance staff learn to troubleshoot and repair ZEBs and then decrease as staff become more familiar with the vehicles.[28]

Charging or Fueling Infrastructure Maintenance: SEPTA will need to develop maintenance capability among staff to troubleshoot, repair, and replace charging infrastructure at both district and on-route locations. SEPTA may need to recruit and train additional staff to maintain the network of on-route chargers. Sufficiently trained staff will be needed to conduct scheduled maintenance activities, maintain an inventory of spare parts, and be available to quickly respond to charger failures.

The type of charging technology selected will affect the maintenance tasks and skillsets required and will also help to inform the development of maintenance training programs and staffing needs. As of 2021, there is limited history on charging infrastructure maintenance for any type of charging equipment due to the emerging nature of the technology. In general, staff should be trained and have the skillset to conduct scheduled maintenance activities such as visual inspections, cleaning filters and equipment surfaces, tightening connectors, and installing software updates. Chargers that are used most often may require replacement of connectors and cables and more frequent scheduled maintenance. Upon selection of the preferred charging technology, SEPTA should request maintenance manuals from OEMs that outline preventative maintenance activities and the time and skills to complete them.

There are a variety of available resources for Maintenance Training Programs. The following provides an overview of some of the available training programs:

- West Coast Center of Excellence in Zero Emission Technology: West Coast Center of Excellence in Zero Emission Technology | SunLine Transit Agency
- California Transit Training Consortium (CTTC): Home - SCRTTC.com
- Center for Transportation and the Environment (CTE): Zero Emission Bus 101 Course – Center for Transportation and the Environment (cte.tv)
- Transportation Learning Center (TLC): Bus Courseware | Battery Electric Bus Familiarization (transittraining.net)
- Union Internationale des Transports Publics (UITP): || Electric Buses for North America | UITP ||

28 TCRP Guidebook for Deploying Zero-Emission Transit Buses, 2021, p. 120.

8 Implementation Plan

Long Term Facility Improvement Program

Compatibility of SEPTA's existing bus districts and services with different ZEB technologies must be a key consideration in confirming the preferred implementation plan. The preceding chapters have shown that some districts face challenges related to BEB schedule compatibility and equipment space constraints, while other districts face challenges related to storing hydrogen fuel.

According to the district phasing plan, the first four districts for transition based on equity considerations will be Midvale, Allegheny, Callowhill, and Frankford. Midvale has been rated as feasible for hydrogen fuel storage, Allegheny and Callowhill were rated as not feasible, and Frankford was rated as maybe feasible. As a next step, SEPTA will simultaneously advance these four districts to more detailed design, which will help further determine the feasibility of ZEBs at these districts and may also consider remote fueling operations. The determination of feasibility for FCEBs at these districts will further inform SEPTA's longer-term technology strategy and relative emphasis on BEBs vs FCEBs in its fleet transition.

Note that we also recommend coordinating the design of some facilities that are located near each other, as hydrogen fueling for a pair of districts could potentially take place at a single district.

- **Midvale and Allegheny** – While Midvale is estimated to be compatible to store hydrogen fuel, the nearby district Allegheny is not considered compatible. When these districts proceed into detailed design, SEPTA should evaluate whether it would be feasible to pursue a remote fueling strategy, in which buses from Allegheny travel to Midvale or another site for fueling. If not, BEBs should be used for Allegheny.
- **Callowhill** – Callowhill is not considered compatible to store hydrogen fuel, but the nearby district of Victory is estimated to be compatible. As Callowhill proceeds to detailed design, Victory should also be studied to determine whether it would be feasible to pursue a remote fueling strategy, in which buses from Callowhill travel to Victory or another site for fueling. Note that Victory has a lower priority in the transition timeline, which could impact the transition of Callowhill to FCEBs.
- **Frankford** – Both Frankford and the nearby district of Comly were rated as "maybe" compatible to store hydrogen fuel. As Frankford proceeds to detailed design, Comly should also be studied to determine whether one or both districts are able to store hydrogen fuel. If not, BEBs should be used for this pair of districts.

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SEPTA FORWARD
Zero-Emission Bus PLAYBOOK

Additionally, planning for a new bus garage facility will be critical regardless of what ZEB technologies are implemented. This can serve to offset the space impacts of BEB chargers and electrical infrastructure, FCEB fuel tanks and associated infrastructure, and existing space deficits. As technology preferences are confirmed, SEPTA should investigate potential sites for the facility and determine its appropriate placement in the timeline of capital investments.

Recommended Long Term Fleet Management Plan

While it might be simplest for SEPTA to select a single vehicle technology fleetwide (either BEBs or FCEBs), both technologies involve certain practical challenges that might lead to a mixed fleet strategy. This Playbook has provided analysis that illustrates these key tradeoffs, and as SEPTA advances to more detailed facility design, the preferred fleet makeup should become clearer. Taking a Playbook approach allows SEPTA to be flexible, advancing some elements of its strategy in the near term while other elements may depend on additional information, accelerated innovation and uncertain future conditions.

SEPTA's long-term fleet management plan should achieve a fully ZEB fleet by 2040, following the graphs of potential future fleet makeup shown in Chapter 7. To achieve this, all new bus purchase should be ZEBs effective in 2026. The specific types of ZEBs will be confirmed through additional facility analysis and internal deliberation. Fleet plans should also account for the modified operating requirements associated with Bus Revolution and additional buses needed to split long blocks for BEB schedule compatibility, as needed.

Next Steps for Planning and Implementation

According to the implementation timeline, Midvale will need to begin receiving ZEBs in 2026, and Allegheny, Callowhill and Frankford will need to begin receiving ZEBs in 2028-2029. Detailed design, environmental review and construction may take up to five years, and so more detailed planning and design for these districts should begin in 2022-2023. In addition, a more detailed plan for phasing and design of on-route charging locations used by routes operating out of these districts may also need to be undertaken in tandem.

To inform the design and operations plans for these initial districts, SEPTA may want to conduct a pilot of fast-charging BEBs and storing them outdoors, unconnected to chargers, overnight in the winter. Peer agencies such as TransLink in Vancouver, King County Metro in Seattle and the Chicago Transit Authority also plan to pilot this approach in the coming years. Thermal management to keep batteries warm overnight without heating the cabin is expected to use up to 7% of the battery's charge, leaving much of the battery's charge available to complete service the following day. However, this approach has not been thoroughly tested. The addition of hybrid on-board heaters may augment the ability of these buses to complete service schedules. A pilot of this charging approach can inform the viability of planning to continue to store buses in overflow and non-traditional parking spaces at districts after they have been fast-charged. If this approach is determined to not be viable, buses that are currently parked in overflow and non-traditional parking spaces would need to be relocated to a climate-controlled indoor facility or a facility where they can be connected to a slow charger overnight. This would add greater urgency to the need for a new garage to accommodate existing and expected capacity issues.

SEPTA also may want to pilot the use of 60' ZEBs ahead of anticipated procurements that would begin delivery in 2028. Performance data from such a pilot could be used to do more detailed schedule compatibility analysis on 60' buses with local conditions.

In addition, SEPTA may want to continue evaluating different types of bus heaters. SEPTA's current electric BEB heaters significantly increase battery consumption during winter conditions, which results in lower schedule compatibility levels. Other heaters could be considered, including diesel-electric hybrid heaters; these could be beneficial as a means to increase schedule compatibility with minimal emissions. They could also be used as an interim strategy to increase compatibility and forgo the need for some on-route charging locations while battery technology improves in the coming years.

Planning for Additional Analysis and Technology Evaluation

The implementation plans above provide the basis for next steps towards a zero-emissions bus fleet. At the same time, this playbook is not meant to give rigid directives; in the coming years SEPTA should be flexible in response to changing conditions related to zero-emissions buses. The following next steps are recommended as areas where SEPTA can conduct further strategic analysis and correct course as needed:

- → **Develop a strategy to incorporate a new bus garage or expansion of existing storage.** Addressing expected capacity issues may impact the timeline of garage conversions, especially if there is a desire to use the additional capacity to help stage buses during other conversions.
- → **Evaluate how the Bus Revolution initiative impacts schedule compatibility and charging strategies.** This reexamination of the SEPTA route network has been well-coordinated with the ZEB strategy, and the new network may increase overall compatibility with electrification by using shorter routes and/or consolidating terminal locations. To that end, SEPTA may consider using transit scheduling software modules that are designed to ensure compatibility of new schedules with electric buses. The Bus Revolution recommendations could be used as an opportunity to refine the network of on-route charging locations that are most justified.
- → **Continue evaluating FCEB technologies.** While FCEBs are less prevalent than BEBs, they have greater range that could be valuable for SEPTA's bus service. One likely challenge could be the supply of clean hydrogen.

Resiliency Strategies

While the emissions reduction benefits of zero-emission buses are important, SEPTA must also be cognizant of its core mission to provide reliable transit service. In order to retain transit riders and attract new riders, transit service needs to maintain reliability. For day-to-day reliability, conservative assumptions were used for modeling the ability of BEBs to complete scheduled service. But bus service may also be a critical component of emergency and evacuation planning. Therefore, to the extent that SEPTA utilizes BEBs, they should develop plans to be able to continue to operate bus service during potential power outages that would affect SEPTA's ability to charge BEBs.

The following resiliency strategies can be considered for incorporation into more detailed designs for each district.

→ Solar photovoltaic + on-site energy storage

- May only be able to provide 5-10% charging needs at each district
- May be able to offset some peak-period demand charges or provide some resiliency in the event of a power outage
- Feasibility may be limited by space constraints at facilities.

→ Vehicle-to-vehicle or vehicle-to-grid charging

- Not yet feasible due to grid connected generation and plug standards
- Equipment may be selected to allow for this as a future capability

→ Islanded back-up standby diesel generator

- Feasibility may be limited by space constraints at facilities.

→ Paralleled natural gas generators owned and operated by a third party

- Reduce PECO capital costs and provide additional revenue opportunities
- Bi-directional power flow option increases feasibility
- Feasibility may be limited by space constraints at facilities

→ Automatic demand management and charge management (already included in SEPTA's BEB specification)

- Uses software to allow load reduction through multiple stakeholders
- Provides additional cost reductions
- Does not directly provide resiliency in the event of a power outage

→ Mixed fleet incorporating some FCEBs

- Resilient to operate during power outages
- Reliable performance during extreme temperatures


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Appendix A: BEB State of Charge Analysis

Background and 2019-2020 Pilot

This appendix seeks to assist SEPTA in analyzing its existing bus network to determine where service is most suitable for electrification, taking into consideration performance data gathered from the Proterra BEB pilot on Routes 29 and 79. As technologies continue to improve in the coming years, this work will also provide tools for SEPTA to evaluate multiple potential scenarios and make adjustments for future technology performance. Our results will help inform a framework for SEPTA to work toward its goal of full bus fleet electrification, while also providing pragmatic information about planning for uncertainty.

From June 2019 to February 2020, SEPTA piloted 25 Proterra BEBs on Route 29 Pier 70 to 33rd–Dickinson and Route 79 Columbus Commons to 29th-Snyder, two relatively short routes operating in South Philadelphia. This deployment provided invaluable insights into the performance of BEBs in the SEPTA operating environment. Data from this period shows an average energy consumption rate of 2.9 kWh/mi. However, on days below 40°F, battery consumption could rise as high as 4.15 kWh/mi. (These observed energy consumption rates are much greater than Proterra's advertised energy consumption rate of 1.75 kWh/mi.) The increased winter energy consumption is driven in large part by the usage of electric interior heating. The buses were removed from service in 2020 due to warranty and reliability issues.

Schedule Analysis

A detailed simulation of BEB operations was undertaken to understand what portion of SEPTA bus service would be compatible to operate with BEBs under different scenarios. The model is designed to predict the state of charge (SOC) of BEBs as they travel through a day's worth of assigned trips. This daily assignment, called a vehicle block, is the main unit of analysis in our modeling. To simulate the SOC of BEBs, the project team developed several assumptions and scenarios that address BEB technology performance, charging mechanics, and on-route charging networks.

Assumptions

In collaboration with SEPTA staff, the project team developed assumptions and scenarios that address the performance of BEB batteries, the mechanics of daily operations, the mechanics of on-route charging, and potential on-route charger networks. Below are the baseline assumptions regarding BEB batteries:

- → The stated battery capacity is 440 kWh. This matches SEPTA's current BEB fleet, though other vehicles are available with higher battery capacity.
- → A 20% capacity reduction is applied to reflect that the highest and lowest charge levels are not readily accessible based on battery chemistry.
- → A 20% capacity reduction is applied to reflect battery degradation by the time a bus reaches mid-life. Manufacturer

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warranties will typically only guarantee 70% to 80% of nameplate capacity, so this assumption aligns with those policies. It is reasonable to presume a BEB will outperform the projections outlined in this document during the first half of its service life.

- With these reductions, we find an effective battery capacity of 282 kWh.

Another set of assumptions was made regarding the daily operations of BEBs:

- Buses are assumed to begin each vehicle block with a 90% SOC. This implies that charging practices at districts will be effective at keeping batteries highly charged.
- As a bus travels its assigned service, the battery energy is consumed at a base rate of 4.15 kWh/mi.
    - This value was selected to reflect SEPTA's 90th percentile worst conditions experienced on days below 40°F during the winter of 2020. This consumption rate includes the energy needed for electric heating of the bus interiors – this adds about 1 kWh/mi compared to peer agencies that utilize diesel auxiliary heaters. It is reasonable to presume that a BEB operating in moderate temperatures will outperform the range projections used as a part of this analysis. Additional study is needed to evaluate the case for using a different type of auxiliary heaters as a means to reduce energy consumption and increase cold weather range.
    - The battery consumption rate is also varied to reflect different levels of topographic variation. SEPTA has categorized its operating districts as having high, medium, and low topographic variation. The base battery consumption rate applies at districts when topographic variation is low. Districts with medium topographic variation have their battery consumption rate increased by 5.3% and districts with high topographic variation have their battery consumption rate increased by 10.6%.[29]
- The minimum acceptable reserve SOC is set at 20%. If our modeling shows a vehicle falling below that level, its block is considered incompatible for electrification; the bus would need to be sent back to the district to avoid a road call.

Additional assumptions were made regarding the on-route charging of BEBs:

- First, connecting with and disconnecting from an on-route charger are each assumed to take one minute.
- The layover time available for charging is adjusted based on real-world reliability data from 11 weeks in Fall 2019. The average observed layover was about 79% of its scheduled time, but there was significant variation by route, direction, and time of day.

29 S. Borén, L. Nurhadi, H. Ny. Preference of Electric Buses in Public Transport: Conclusions from Real Life Testing in Eight Swedish Municipalities. International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, 2016.

- → On-route charging analysis also considered whether a queue of buses would accumulate at on-route charger locations at different times of day. Our team calculated the number of buses scheduled to be present at each layover location at each minute of the day, and this was then compared with the number of available chargers to determine availability.
- → At locations where on-route chargers are included, they are assumed to be fast chargers rated for 450 kW power.
- → BEBs may only be able to accept a portion of the charger's maximum power, depending on battery SOC. When the SOC is relatively high or low, the battery will accept a reduced portion of the charger's rated power level. The graph below shows the relationship between the power accepted from a charger and battery SOC, based on peer agency experience.

Combining these assumptions, we find that SEPTA's BEBs should have a worst-case operating range of 43 to 47 miles in winter conditions (before factoring in on-route charging). This is certainly less than the manufacturer claim of 251 miles, but using conservative assumptions will help SEPTA plan for reliable operations. The addition of on-route chargers will extend this range significantly. The addition of diesel auxiliary heaters on cold days would be estimated to extend the worst-case operating range to 56 to 62 miles.

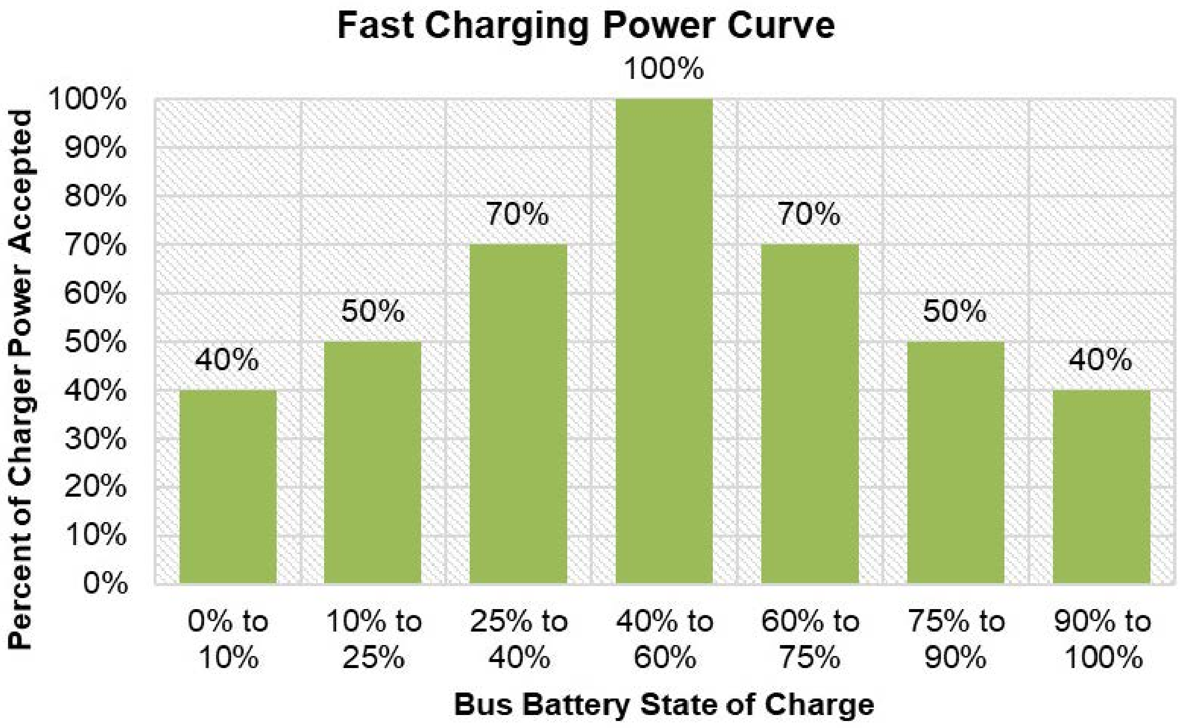

***Figure 14** – Graph showing how the power that BEBs accept from fast chargers varies based on bus battery state of charge*

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Note that we apply the same technology and operating assumptions to both 40 ft and 60 ft buses. While the current performance of articulated BEBs is different from that of 40 ft BEBs, SEPTA selected this approach to streamline the schedule analysis. Additionally, SEPTA's articulated bus fleet is not close to retirement, so the performance of 60 ft BEB technology is likely to be different by the time they must be replaced.

On-Route Charging Network

Our schedule modeling aims to compare several scenarios with different potential networks of on-route chargers. To develop these networks, first SEPTA staff evaluated the feasibility of its layover locations to potentially accommodate on-route chargers. This evaluation considered factors such as whether the location was a transit center, a bus turnaround loop, or on-street, whether there was space to install necessary electrical infrastructure, and whether the location was owned by SEPTA, another government entity, or a private entity.

Next, schedule modeling was run using an unrealistic scenario that included on-route chargers at all 294 layover locations. The purpose of this was to test how much charging would be possible at each layover location, which would inform the selection of charger locations for other more-realistic scenarios. This test also revealed information about how badly needed different chargers might be – for example, if the majority of blocks passing through a layover location see their SOC falling below 50%, providing a charger there might be more important than another location where most blocks stay close to a full charge.

Using this information, we defined four charger networks to evaluate:

- → Only garage/district-based charging
- → On-route charging at 32 SEPTA-owned locations
- → On-route charging at 32 SEPTA-owned locations + 49 other publicly-owned locations
- → On-route charging at every layover location (294 locations)

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Figures 15 through **Figure 18** illustrate the charger locations that would be included in each of the four charger networks. The first scenario, with only garage/district-based charging, represents one extreme that does not provide enough charging to electrify a majority of SEPTA's bus service. The second scenario, with on-route chargers at 32 SEPTA-owned locations, may be more realistic. The 32 locations were selected such that each would see at least three hours of usage daily. The third scenario, which adds on-route chargers at 49 other publicly owned locations, is more ambitious in prioritizing on-route charging to electrify more service. It may not be feasible to secure chargers at all 49 locations, but some of the more important locations might be prioritized. Finally, the scenario with on-route chargers at every layover location is not realistic, though modeling it can yield useful information.

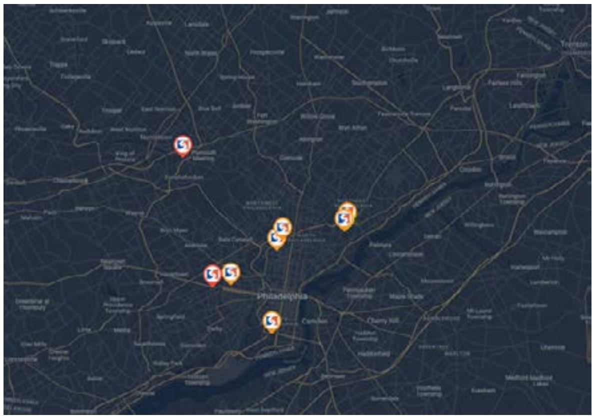

Figure 15 *– Charger locations included in the scenario with only garage/district-based charging*

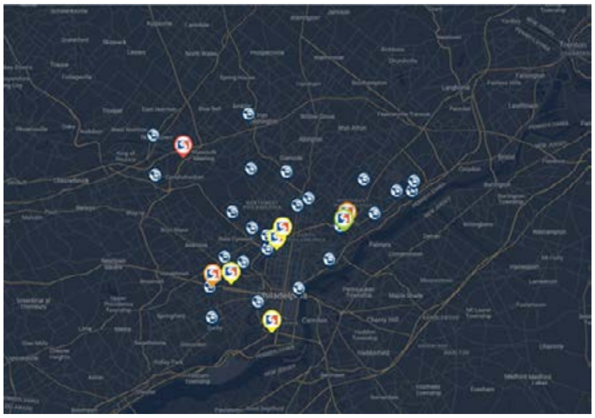

Figure 16 *– Charger locations included in the scenario with on-route charging at 32 SEPTA-owned locations*

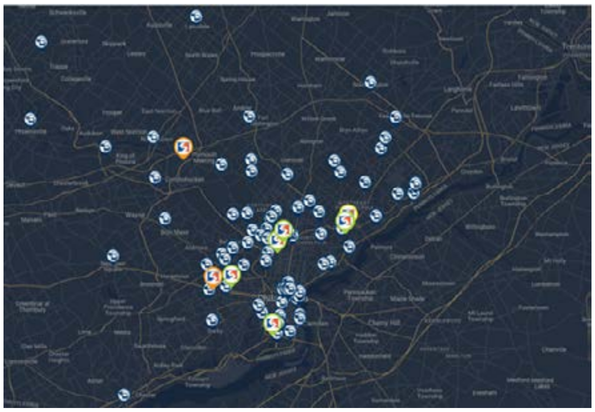

Figure 17 *– Charger locations included in the scenario with on-route charging at 32 SEPTA-owned locations plus 49 other publicly-owned locations*

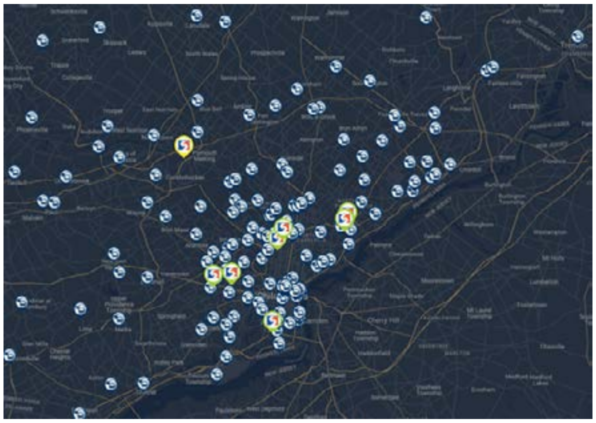

Figure 18 *– Charger locations included in the scenario with on-route charging at every layover location (294 locations)*

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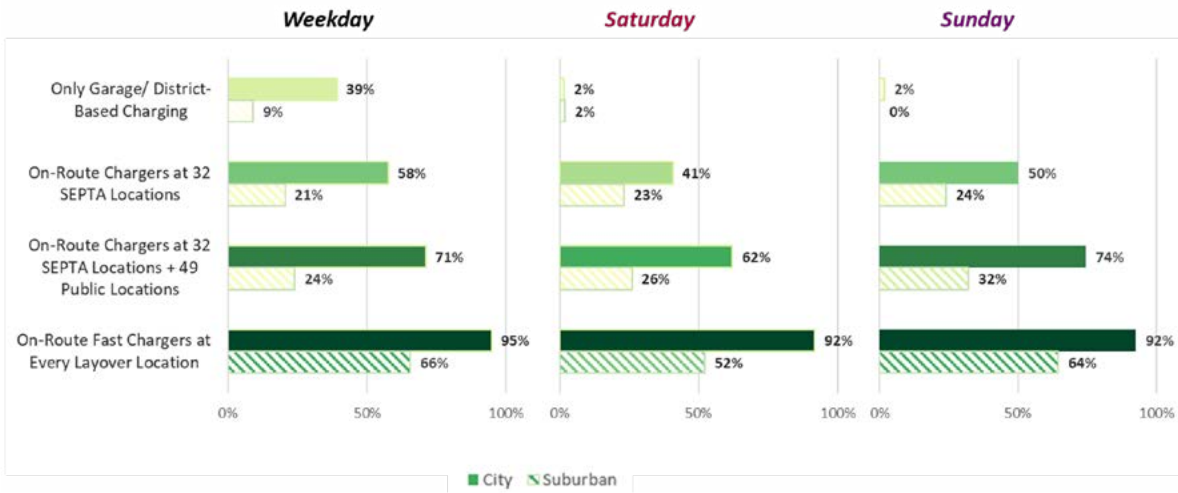

Figure 19 *– Percent of blocks suitable for electrification under different charging infrastructure scenarios*

Conclusions

The modeling and analysis conducted for this study analyzed the suitability of vehicle block electrification under the four different charging infrastructure scenarios. This analysis also evaluated the differences in service schedules for weekdays, Saturdays, and Sundays. The results of each of the charging infrastructure scenarios and each day's schedule are shown in ***Figure 19***. One clear conclusion is that weekend service is more challenging to electrify than weekday service, due to differences in the distances buses must operate.

Because SEPTA's garages serve different neighborhoods with different route characteristics, the findings are summarized into two categories, 'Suburban Districts' and 'City Districts.' The suburban districts include the Frontier and Victory garages. These buses operate an average of 123 miles per weekday block and represent 14% of SEPTA's bus service. The city district category includes six bus garages: Comly, Frankford, Midvale, Allegheny, Callowhill, and Southern. Buses in these districts operate 58 miles on average per weekday block and account for 86% of SEPTA's bus service. Based on average route mileage, it is not surprising that a larger proportion of the vehicle blocks are suitable for electrification in the City Districts than Suburban Districts.

The model results were also reported for SEPTA's individual bus districts. The table below shows these compatibility results at each district and for each service day. Note that the Frankford Trackless service is included only to test the potential for future BEB conversion.

Table 21 *– Percent of blocks suitable for electrification at each bus district on each service day, if on-route chargers are provided at 32 SEPTA-owned locations*

	District	Weekday	Saturday	Sunday
City	**Frankford** (Trackless)	100%	100%	100%
	Frankford (Bus)	73%	65%	78%
	Allegheny	72%	67%	80%
	Callowhill	67%	46%	50%
	Midvale	56%	37%	50%
	Southern	54%	28%	28%
	Comly	44%	20%	40%
Suburban	**Victory**	22%	29%	29%
	Frontier	19%	14%	17%

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Sensitivity Analysis

Conservative technology assumptions were used in the baseline scenario providing a reliable basis to plan for future electrification. A range of different scenarios were also tested to represent future improvements in technology, different on-route charger power levels, and variations in how the system would perform at different starting SOC. The network of 32 on-route charger locations was used for all sensitivity testing.

First, we tested the potential impact of using diesel auxiliary heaters instead of electric heaters. While this has the downside of creating a small amount of tailpipe emissions during the winter, it also produces dramatic improvement in compatibility results. This technology could increase compatibility results by 16 to 19 percentage points.

For future improvements in technology, several different options were modeled. Larger batteries of 525 kWh and 660 kWh were tested with the battery consumption rate adjusted proportionally according to the OEM published values. Additionally, in the coming years battery densities are expected to triple, reducing the overall weight of the battery. Accommodating battery weight currently accounts for about 9% of BEB power usage, so an increase in battery density would reduce battery consumption rates by 6%. This reduction in battery consumption rate due to an increase in battery density was also a scenario that was tested. Using a larger battery with 525 kWh or 660 kWh significantly increases the percent of vehicle blocks that are suitable for electrification, while an increase in battery densities has a minimal impact on the percent of vehicle blocks that are suitable.

Alternative power levels for on-route chargers were also tested (300 kW and 600 kW) to understand how different power levels would impact the percent of blocks that are suitable for electrification. While there are minor changes between the baseline scenario and the alternative power options on weekdays, the impact on compatibility for weekend service is more significant.

We also tested a model adjustment in which battery consumption rates would vary by speed. This was estimated using data from a BEB trial in Canada that showed the relationship between battery consumption and speed as a “consumption rate curve”. The Canadian consumption rate curve was scaled to match SEPTA’s experience by using battery consumption data from SEPTA Route 29. The impacts of bus speed indicate that faster routes should have improved battery performance compared with slower routes. Overall, making this adjustment for speed could yield a 10 percentage point increase in the blocks that are suitable for electrification as compared to the baseline scenario. However, there is considerable uncertainty in this finding because the data relating battery consumption with speed is still limited.

The fast-charging power that is accepted by buses varies based on battery SOC, with batteries at higher and lower SOC accepting significantly less than the full power from the charger. This relationship could change as technology develops, so we tested the impact of having the buses accept full power from the charger regardless of SOC. This yielded minor increases in the percent of blocks suitable for electrification during weekday service and about an 8 percentage point increase for weekend service.

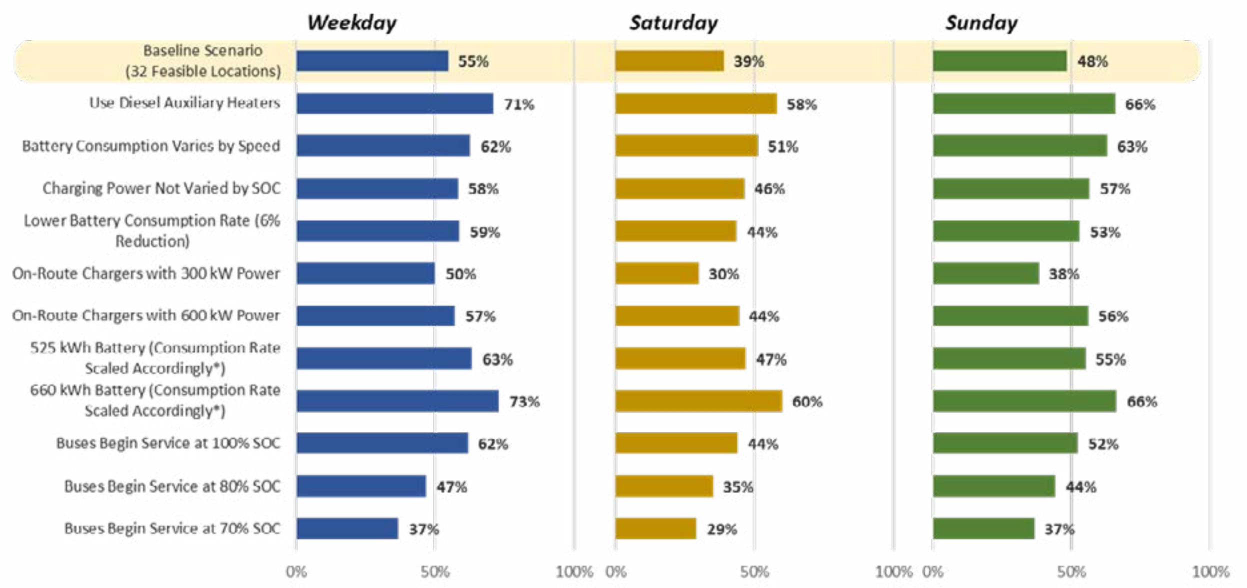

Figure 20 *– Schedule compatability results of sensitivity testing*

Lastly, to understand how beginning service at different levels of SOC would impact the percent of vehicle blocks that would be suitable for electrification, three different beginning levels of SOC were modeled. As expected, as the SOC at the beginning of service decreases, the percent of vehicle blocks that are suitable for electrification also decreases compared to the baseline scenario.

The complete results of these different scenarios, as well as the baseline scenario, are shown in ***Figure 20***.

Resiliency Screening

Resilience of an BEB fleet is a concern that many agencies have, especially as new and different resiliency strategies may be required in case of a power outage. Understanding how an BEB system would perform in case of a power outage is necessary to be able to properly plan for resilience. Using the baseline scenario with 32 on-route chargers available, we tested what percentage of blocks could be operated using only on-route chargers in the event of a power failure at the districts. The results of the analysis showing the percent of blocks that would be operational for one, two, and three days and indefinitely without garage charging are shown in ***Table 22***.

Table 22 *– Percent of vehicle blocks that are operational with only on-route chargers, assuming on-route chargers at 32 SEPTA locations*

	Without Garage Charging, Operate at Least 1 Extra Day	Without Garage Charging, Operate at Least 2 Extra Days	Without Garage Charging, Operate at Least 3 Extra Days	Without Garage Charging, Operate Indefinitely
Weekday	**22.4%**	**11.6%**	**7.6%**	**0.8%**
Allegheny	49.2%	35.6%	27.2%	3.7%
Callowhill	26.2%	8.2%	3.4%	0.0%
Comly	16.1%	8.2%	5.7%	0.0%
Frankford (Bus)	29.5%	13.9%	7.6%	0.0%
Frankford (Trackless)	94.4%	75.9%	55.6%	11.1%
Frontier	7.9%	4.0%	1.6%	0.0%
Midvale	12.6%	5.1%	2.6%	0.0%
Southern	21.7%	9.2%	6.5%	1.2%
Victory	5.4%	1.6%	1.6%	0.0%
Saturday	**26.0%**	**17.3%**	**13.6%**	**2.0%**
Allegheny	59.6%	46.8%	45.7%	12.8%
Callowhill	36.0%	24.6%	13.2%	0.0%
Comly	10.5%	7.6%	2.9%	0.0%
Frankford (Bus)	35.2%	23.9%	16.9%	2.8%
Frankford (Trackless)	100.0%	91.3%	91.3%	17.4%
Frontier	8.5%	2.8%	1.4%	0.0%
Midvale	18.0%	8.8%	6.0%	0.0%
Southern	18.9%	11.0%	9.4%	0.0%
Victory	14.1%	6.1%	5.1%	0.0%
Sunday	**33.4%**	**22.5%**	**17.1%**	**2.0%**
Allegheny	72.9%	54.3%	45.7%	10.0%
Callowhill	45.6%	30.0%	21.1%	0.0%
Comly	10.8%	4.8%	1.2%	0.0%
Frankford (Bus)	63.3%	55.0%	41.7%	5.0%
Frankford (Trackless)	95.0%	95.0%	85.0%	20.0%
Frontier	11.4%	8.6%	8.6%	0.0%
Midvale	28.3%	14.5%	9.4%	0.0%
Southern	11.4%	5.7%	4.8%	0.0%
Victory	17.1%	4.3%	1.4%	0.0%

Appendix B: Equity Analysis

Background

Deploying ZEBs will create many benefits for residents of the SEPTA service area by reducing air pollution and traffic noise. Reduced air pollution can help address public health issues such as asthma and cardiovascular conditions. There is currently a disparity such that these issues disproportionately affect low-income and minority communities in the Philadelphia region. SEPTA already has analysis on how service decisions impact low-income and minority communities, in compliance with federal requirements, and a similar analysis was conducted to understand how the rollout of ZEBs could impact these communities. This fleet transition could be an opportunity to prioritize benefits for disadvantaged communities where air pollution and health impacts are greatest.

Methodology

The equity analysis seeks to help prioritize ZEB deployments among different operating districts by understanding the demographics of the areas served. Specifically, we calculated the percent low income and percent minority within a half mile of each of the eight SEPTA bus garages and within a quarter mile of the routes operated by the same bus districts. Percent low income represents the share of population below 200% of the poverty level. Percent minority represents the non-white share of the population. The Equity Analysis utilized census tract level data from the American Community Survey (2015-2019) five-year estimates. The percentage results are found below in ***Table 23***.

Findings

The overall equity analysis values and priority ratings are shown in ***Tables 23 and 24*** below. "Low" ratings were given for low-income or minority values below 30%, "medium" ratings were given for values between 30% and 45%, and "high" ratings were given for values greater than 45%. Districts with high overall equity rating include Allegheny, Callowhill, Comly, Frankford, and Midvale. Districts with medium overall equity rating include Southern and Victory. The only district that had a low overall equity rating is Frontier.

Table 23 *– Percent low-income and minority within a half and quarter mile of each bus district*

District	% Low Income (in area within ½ mile of depot)	% Low Income (in area within ¼ mile of depot's routes)	% Minority (in area within ½ mile of depot)	% Minority (in area within ¼ mile of depot's routes)
Allegheny	60.7%	44.0%	95.1%	62.1%
Callowhill	58.4%	42.7%	98.9%	62.2%
Comly	47.8%	39.0%	80.0%	52.7%
Frankford	54.3%	44.4%	85.6%	61.9%
Frontier	15.1%	20.1%	39.4%	27.6%
Midvale	51.2%	40.0%	87.1%	59.2%
Southern	21.1%	48.1%	10.2%	72.3%
Victory	41.6%	24.1%	80.6%	36.6%

Table 24 *– Equity prioritization per bus district*

District	% Low Income (in area within ½ mile of depot)	% Low Income (in area within ¼ mile of depot's routes)	% Minority (in area within ½ mile of depot)	% Minority (in area within ¼ mile of depot's routes)	Overall Equity Rating
Allegheny	High	Medium	High	High	High
Callowhill	High	Medium	High	High	High
Comly	High	Medium	High	High	High
Frankford	High	Medium	High	High	High
Frontier	Low	Low	Medium	Low	Low
Midvale	High	Medium	High	High	High
Southern	Low	High	Low	High	Medium
Victory	Medium	Low	High	Medium	Medium

We also mapped low-income and minority populations to understand their geographic distribution. As seen below in ***Figure 21***, the share of population below 200% the federal poverty level is mostly concentrated within Philadelphia County. Allegheny, Midvale, Comly, Frankford, Victory, and Callowhill Districts have a range between 42% to 61% in this low-income category. The Frontier and Southern Districts have 15% to 21% of population in this low-income category.

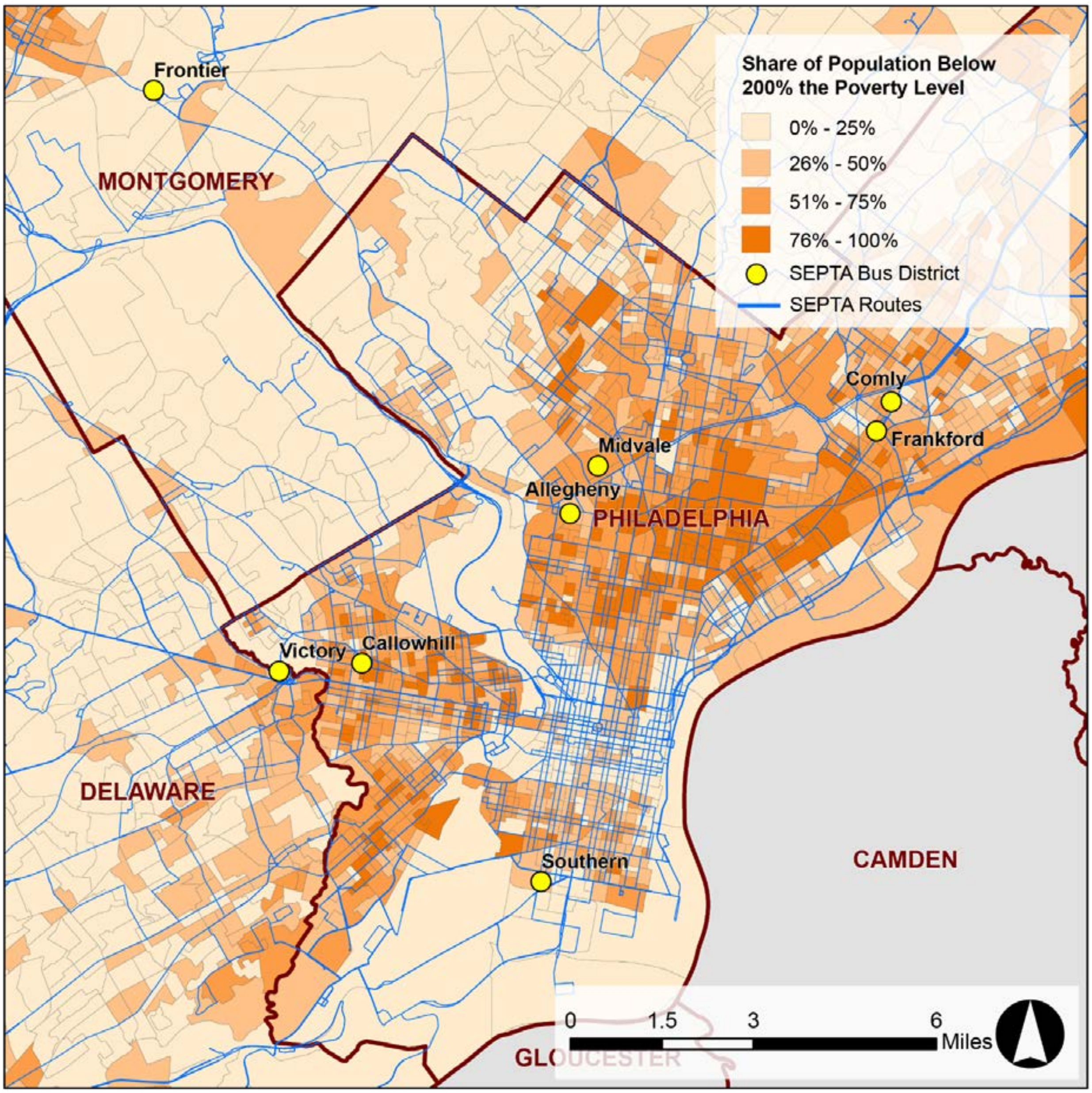

Figure 21 *– Share of population below 200% of the federal the poverty level*

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Zero-Emission Bus PLAYBOOK

As seen below in ***Figure 22***, the minority populations within the service area are concentrated within Philadelphia County. All of the bus districts in Philadelphia except Southern serve high minority populations ranging from 80% to 95% (Victory, Callowhill, Allegheny, Midvale, Comly, Frankford). Lower minority population shares are seen near Frontier and Southern Districts.

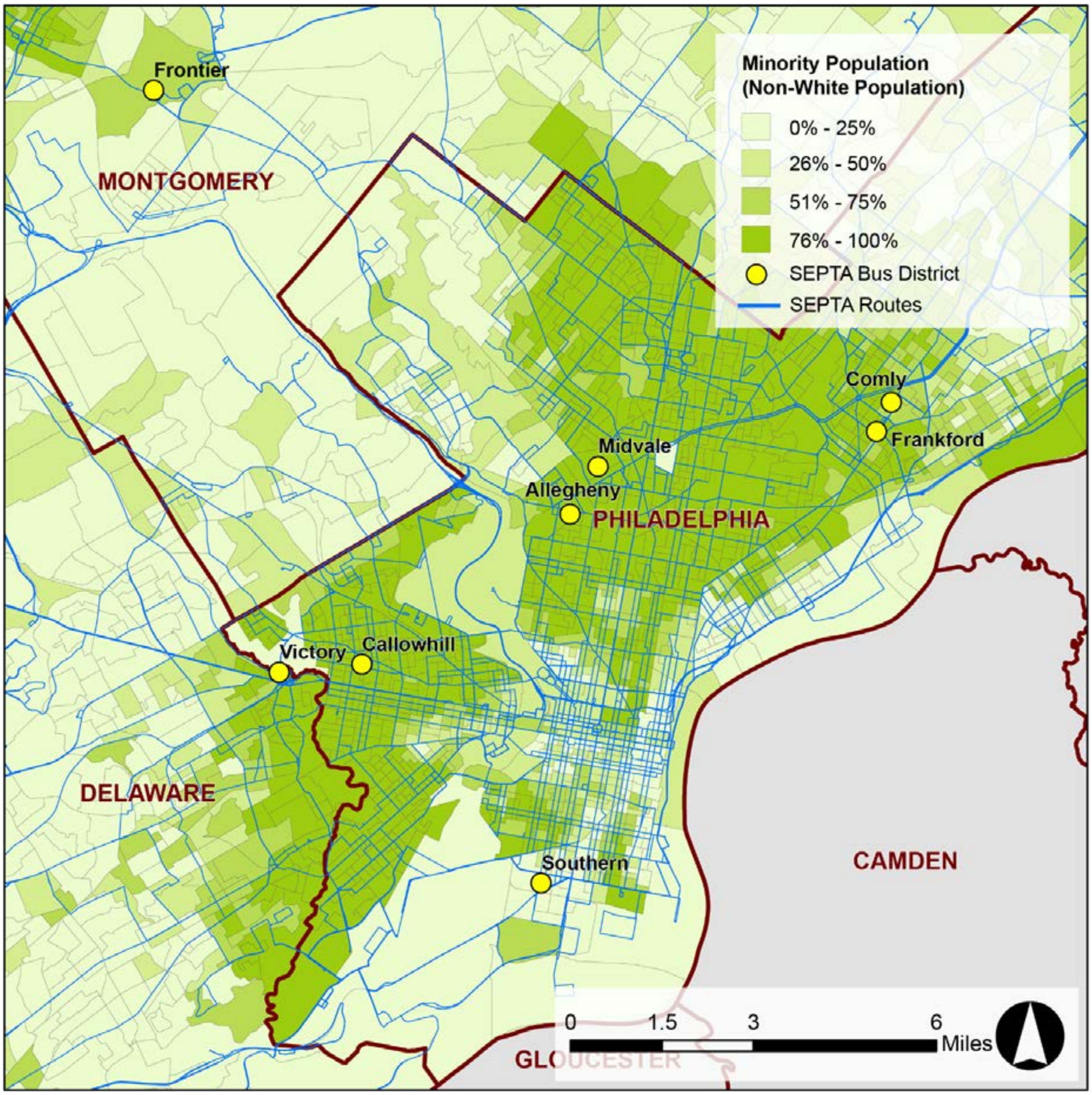

Figure 22 *– Minority population (non-white population)*

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Appendix C: District Design, Operations and Maintenance

This appendix details the design, operations and maintenance considerations that informed the concept drawings in ***Appendix D.***

Standardization of Charging Technology

The Society for Automotive Engineers (SAE) International is leading an effort to develop uniform standards for charging equipment. Charging equipment standards ensure consistency and interoperability between charging equipment and buses. Standardization reduces the likelihood of charging equipment becoming obsolete thereby lowering the risk of stranded assets for transit agencies. Standardization also simplifies operations by streamlining parts inventories and preventative maintenance activities. As the BEB industry is rapidly evolving, the current standards are subject to change to keep pace with technological advances.

The standards that relate to potential charging solutions for SEPTA include:

- → SAE J1772 "Electric Vehicle and Plug-In Hybrid Electric Vehicle Conductive Charger Coupler" (October 2017)
- → SAE J3105 "Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices" (January 2020). The subsection J3015/1 "Infrastructure-Mounted Cross Rail Connection" details the inverted pantograph (pantograph down) configuration that is of interest to SEPTA.
- → SAE J2954/2 "Wireless Power Transfer of Heavy-Duty Plug-In Electric Vehicles and Positioning Communication" is currently being developed.
- → SAE J2931 Charging Data Communication Protocol

The SWIFTCharge Alliance is also working on a universal inductive charging standard. The Alliance was developed in response to the need for a global industry standard for inductive charging that assures interoperability of systems. The standard will cover the full spectrum of practical power ranges with full interoperability between OEMs, geographies, and power levels.[30]

Garage Charging Considerations

Physical Constraints

Larger BEB deployments require significant space at districts to install charging infrastructure. SEPTA's bus districts have considerable space constraints due to vehicle operational flow, facility age, unique district building architecture, and storage

30 Momentum Dynamics presentation to SEPTA staff, November 2020.

requirements. Therefore, it is important to understand the specific space-related opportunities and challenges for BEB infrastructure at districts.

The type of charger selected has a considerable impact on the amount of space that must be allocated to charging infrastructure. A typical charging station includes multiple pieces of equipment, including a transformer, switchgear, charger, and dispenser. Plug-in chargers often require more space compared to other charging options, especially when slow charging ground-mounted configurations are selected. Generally, facilities can easily accommodate plug-in chargers for a smaller-sized fleet but finding space to install plug-in chargers for a full fleet of BEBs may be more challenging.

There are some alternatives to installing charging equipment directly adjacent to a bus parking spot. Space-saving configurations for plug-in charging equipment include placing the dispenser remotely from the rest of the charging equipment, so that charging cables can be pulled down from the ceiling. With this setup, cord retractors with power and controls must be incorporated into the design to raise and lower the charging cables from the ceiling. While overhead installations will reduce the space requirements, they may add cost due to the need to reinforce the overhead structure so that it can support the additional weight. There is also a limit to the length of the charging cables. The maximum distance for DC power distribution is between 300 and 500 feet, depending on the charging equipment manufacturer. This means the distance between the charging cabinet and dispenser is limited to 300 to 500 feet, including vertical drops or rises.

Overhead conductive charging and inductive charging are other options to accommodate large-scale BEB fleets with limited space at the district for chargers. “Fast charging lanes” equipped with high-powered chargers can provide buses with the opportunity to recharge batteries upon arrival at the district or during servicing. Higher-powered chargers located in designated charging lanes decrease the required charging time on a slow charger and reduce the number of slow chargers needed in bus at individual bus parking spaces. Overhead conductive chargers must be located in a place where the ground is relatively level. A sloped surface will interfere with the contact between the pantograph and the charge rails on the bus. Slope tolerances vary by charging equipment manufacturer.

Given the space constraints facing SEPTA’s bus districts, bus length is another important consideration. SEPTA’s existing bus fleet is primarily comprised of 40-foot buses. While the majority of the 40-foot BEB offerings on the market measure precisely 40 feet in length, some BEB manufacturers’ “40-foot buses” have an actual length that is 2.5 feet longer. When building a fleet of BEBs, this difference in length can result in a critical loss of storage capacity at an already space constrained district.

District Power Infrastructure (Substations, Etc.)

With the exception of Southern District – SEPTA's first BEB pilot location – SEPTA's bus district facilities are powered by a 13.2kVAC single line feed from PECO, which is then converted to 480VAC through a step-down transformer. Each facility has a transformer rated to support its existing power demand. Though these facilities do not use the full capacity of their respective transformers, the excess capacity cannot support the minimum power demand of each district when the bus fleet is fully electrified.

In order for each district's infrastructure to support the full electrification of SEPTA's bus fleet, additional power sources must be employed. SEPTA's power source options include increasing the number of PECO feeds at the facility; using SEPTA's on-site micro-grid as a source of power; and using available capacity from a nearby SEPTA traction-power substation.

- **PECO:** Service upgrade in order to provide enough power to support the BEB infrastructure. (Refer to Electrical Capacity section, below).
- **Micro-grid (CHP):** Power from a combined heat and power micro-grid to support BEB infrastructure.
- **Traction power substation:** SEPTA's traction-power substations are configured with dual PECO feeds to support SEPTA's Broad Street Subway and Market-Frankford Elevated transit lines. The substations' common bus, supported by the two incoming PECO feeds, can provide 4MW of redundant power to the BEB infrastructure at each of the traction power substation locations.

Location of Charging Infrastructure

Introducing new equipment and infrastructure will require creative use of existing district space, potentially stacking, hanging, or mounting proposed equipment and associated infrastructure. Conceptual layouts utilize modular units containing charging equipment and infrastructure in an effort to centralize equipment and minimize spatial impacts at districts. In the event of stacking and/or mounting equipment to an existing structure, engineering evaluation and design will be necessary to retrofit the structure. The location of the charging infrastructure or equipment will need to be located to maintain necessary clearances for bus maneuvers and space usage. Underground utilities and infrastructure (basins, tanks, etc) add complexity to engineering design of new equipment pads and foundations.

If existing space and/or capacity is determined to be insufficient, potential adjacent and/or new property acquisition may be required. The benefits of property acquisition include the ability to phase and stage the transition to a zero-emission bus fleet, while reducing impacts to existing districts and operations by temporarily relocating some functions to the new facility.

Electrical Capacity

Table 25 below summarizes the existing average electrical demand at each district, as well as anticipated capacity necessary to transition the fleet to BEBs. PECO coordination was not performed during this phase of study, but it is expected in upcoming phases.

Table 25 *– Summary electrical capacity at each bus garage/district*

District	PECO Account Number	Existing Demand (MW)	Proposed Capacity (MW)	Quantity of 15kV PECO Feeders Expected
Allegheny	90343-01916	0.39	4.0	1
Callowhill	22491-00206	1.56	6.0	2
Comly	26159-01405	0.52	6.6	2
Frankford	97344-01705	0.47	8.0	3
Frontier	79605-01707	0.20	4.0	1
Midvale	81500-00504	1.12	10.5	4
Southern	00271-00903	0.49	8.0	2
Victory	09353-01806	0.43	4.4	2

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Tariffs and Rates

PECO's Electric Service Tariff is defined in Supplement No. 56 to Tariff Electric Pa. P.U.C. No. 6.[31] Pennsylvania has comparatively low supply rates.

SEPTA's bus districts would fall into one of three different PECO rate classes, either the high-tension (HT), primary distribution (PD), and electric propulsion (EP) rate classes. For on-route charging locations, if the demand is 1.5MW or less the on-route charging location would fall under the general service (GS); if it is larger, it would fall under the HT rate class and would require a medium voltage switch and transformer capital expenses. ***Table 26*** below summarizes the different rate classes, including their fixed charges and charges per kW.

Currently, SEPTA's bus districts typically fall under the HT rate class but could conceivably fall under the EP tariff. ***Table 27*** below summarizes potential savings related to PECO tariffs if each district were to switch to the electric propulsion rate class for existing service. By switching to this rate class, it would also reduce the delivery costs for the new service. The savings detailed below are annual and do not include any new BEB infrastructure, only existing loads for illustrative purposes.

Table 26 *– Charges by rate class*

Rate Class	PD	HT (15kv)	EP (15kv)	GS
Fixed Charge	295.95	353.85	1292.35	
$/kW Charge	7.26	4.98	4.44	
PLC (assume annual demand)	$0.63/kW	$0.63/kW	$0.63/kW	$0.00211/kWh

Table 27 *– Potential annual savings related to PECO tariffs*

District	Demand	Re-circuited demand charges	Existing Demand Charges	Approximate Demand Charge Savings
Allegheny	388.8	$20,715	$33,872	$13,157
Callowhill	1564.8	$83,373	$136,325	$52,953
Comly	521	$27,759	$45,390	$17,631
Frankford	465.12	$24,782	$40,521	$15,740
Frontier	198.53	$10,578	$17,296	$6,718
Midvale	1118.8	$59,614	$97,477	$37,863
Southern	494.4	$26,342	$43,072	$16,730
Victory	433.6	$23,102	$37,775	$14,673
Total		$276,264	$451,729	$175,465

31 Available online at www.peco.com/SiteCollectionDocuments/current%20elec%20tariff%20Oct%201%202021.pdf

Charge Management

Charge management systems allow transit agencies to be able to monitor and manage the charging process for their fleet of vehicles. There are a variety of charge management solutions available that allow for transit agencies to control when, for how long, and how quickly an electric vehicle charges. Garage staff do not need to manually plug and unplug vehicles once the desired state of charge (SOC) is reached, which decreases the chance for errors. BEBs can be plugged into the chargers and the charge management system can manage the process for when each bus is charged and for how long. These systems allow transit agencies to optimize charging and reduce the peak power draw by spreading out the demand to save money. Charge management solutions are also useful in managing larger fleets of electric vehicles since a centralized system would show the SOC of each bus without having staff manually check on each one. These systems can also improve battery health as the system can turn off the power supply once the desired SOC is reached.

Charging schedules can be created and many solutions have product offerings that integrate route schedules to generate an optimized charging plan for the facility. This can help prioritize the vehicles to charge first or charge faster based on their scheduled departure times. These charging schedules can also be adjusted based on variable power costs to further lower utility costs.

These systems can regulate how quickly or slowly a bus charges, allowing to stay within the grid capacity. Along with controlling the speed of charging, power can be limited to a group of chargers as well. Depending on when the charge management system is deployed, they can lower infrastructure investment costs at the facility by reducing the need to upgrade the connection to the main power grid.

Smart charging systems interact with multiple charging devices at a given location to strategically output power to meet vehicle charging needs while optimizing costs. BEBs can be plugged into the chargers and the smart charging technology system can manage the process for when each bus is charged and for how long. The key primary benefits of such a platform include:

- → Meeting all fleet operation requirements to ensure that every bus is charged and ready before departure
- → Reducing the cost of energy, by automatically charging at the right time and rate, without impacting fleet operations
- → Maximizing the charging infrastructure available and reducing the need to invest in extra infrastructure
- → Comprehensive reporting on energy, charging stations, and buses
- → Improving battery health as the system can turn off the power supply once the desired state of charge is reached

When evaluating smart charging technology, SEPTA should consider a fleet dashboard with real-time monitoring, energy management, and comprehensive reporting of vehicle and charger status including the following:

- → Time to complete charging
- → Transaction start time
- → Current power level
- → Available power level
- → Current energy dispensed
- → Total energy expensed
- → Battery state-of-charge
- → Charger status
- → Vehicle status
- → Connected services status

One of the main drawbacks to implementing smart charging technology is that the system may be costly, and depending on the provider, an agency may need to purchase several different modules for the system to fulfill all of their charge management needs.

As infrastructure continues to be more interconnected through the internet, the threat of cyberattacks will only continue to increase. Researchers at the Southwest Research Institute found that they were able to hack into the electric vehicle charging equipment and harm the system by overcharging the battery, blocking the vehicle from charging, and limiting the charging rates. While a cybersecurity threat to a BEB fleet has yet to occur, agencies should be prepared for this threat and work with their Information Technology departments and the charge management solution provider to secure their systems.

Smart charging technologies are designed to be interoperable and should work with a variety of different charging types and BEB manufacturers. Recently, there has been a push towards standardization of the charging communication between the vehicle and the charging point as well as the charging point and the charge management system. The Open Charge Point Protocol (OCPP) is the current communication protocol between the charging infrastructure and the communication system. The agency's chargers will need to be set up with OCPP version 1.6 or later to work with smart charging technology as well as access to the internet.

Structural Considerations

There are structural considerations that would need to be accounted for when planning for BEB charging infrastructure. Additional study will be necessary to determine if hanging or mounting the proposed equipment and associated infrastructure is an appropriate solution. The following provides a brief overview of the potential structural capacity at each of SEPTA's bus districts and maintenance facilities:

- → **Berridge:** A portable charging station is anticipated at the facility with no impact to the structure. Currently, the facility has solar installed on the roof of the building.
- → **Comly:** It is anticipated that there is some reserve structural capacity because the original built-up roofing (BUR) system was replaced with conventional modified bitumen roofing. The original building roof structure is an quite dated, and it is unclear what the structural capacity would be.

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However, the building addition may have more capacity and appears to have fewer overhead conflicts.

- **Callowhill:** There are concerns related to available structural capacity. The facility has solar installed on the roof and the structural loading would need to be verified.
- **Frankford:** The structure is a precast system, and there is potential for reserved capacity in the existing structure. SEPTA may need to consider removing the ballast on the roof.
- **Midvale:** There are concerns related to available structural capacity.
- **Southern:** There are long-span joists with a metal deck, which have similar problems as the precast system found at Frankford, though they would be easier to reinforce. Strategic placement and reinforcing of the structure would be necessary for concentrated loads of the suspended equipment. However, the facility likely does not have much reserve capacity.
- **Allegheny:** There are concerns related to available structural capacity.
- **Frontier:** There are concerns related to available structural capacity.
- **Germantown:** A portable charging station is anticipated at the facility with no impact to the structure. There are similar concerns at this district as with Comly and Frankford.
- **Victory:** There are concerns related to available structural capacity.

At districts where outside storage and depot charging is proposed, a gantry and/or canopy system is proposed to maximize the ability to mount equipment above for potential space savings. A canopy system could be evaluated for solar installation.

District Infrastructure

There is existing district infrastructure that would need to be updated or removed as the diesel and hybrid bus fleet transitions to an all-BEB fleet. As SEPTA transitions away from diesel buses, the districts will no longer need to utilize vehicle exhaust equipment with the BEB fleet. This vehicle exhaust equipment could either be abandoned in place or removed. Additionally, there would be a reduction in the fluid dispersion and disposal of motor oil and other maintenance tasks related with internal combustion engines. Further coordination with SEPTA System Safety is required for existing above ground and below ground storage tank evaluation and removal.

With the transition to BEBs, the fire suppression systems at the districts will need to be evaluated in battery storage areas to ensure that they would properly be able to extinguish a fire in case of an incident. There may be a need to add clean agent systems, which are electrically non-conductive, volatile, or gaseous, to a district's fire suppression systems in the case of an electrical fire. These clean agent fire suppression systems are also beneficial as they do not leave any residue after evaporation and require minimal clean up.

In future design interactions, the designer of record (DOR) will be responsible for evaluation of site development, erosion and sedimentation control, and stormwater management impacts based on earth disturbance.

Appendix D: District Concept Plans

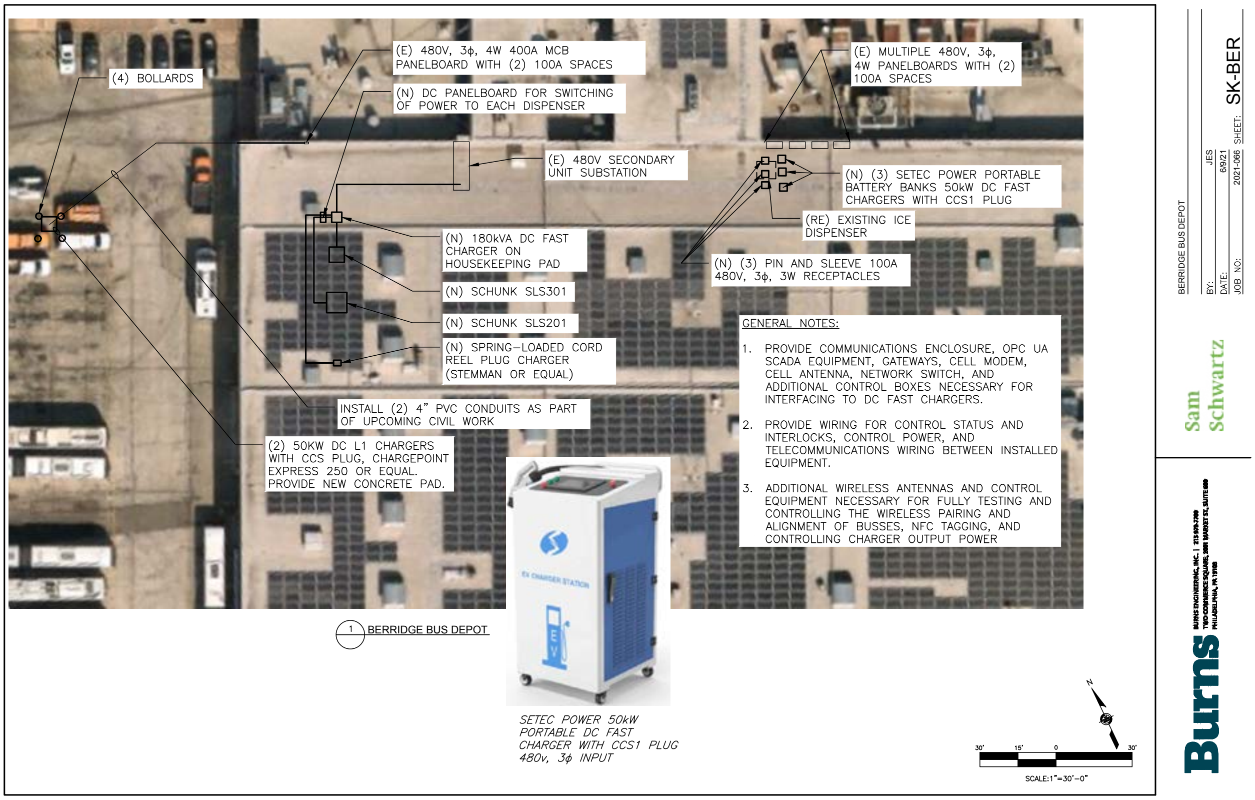
SEPTA's current bus fleet operates out of eight districts responsible for the operations, maintenance, and storage of vehicles. Most facilities were initially built or modified to operate and maintain a diesel bus fleet and are equipped with fueling lanes, bus washers, and maintenance equipment. Each district is responsible for operating specific bus routes. The total number of buses assigned to each district is based on facility capacity and route requirements from each location.

SEPTA's districts vary in size, age, and condition. On average, each district houses 167 buses. Of the eight facilities, three were built before 1930, three between 1950 and 1970, and two between 1986 and 1996. The largest district, Midvale, provides service to the City of Philadelphia and houses 312 buses (21% of fleet).

Concept drawings for each district are included on the following pages and show strategies for incorporation of fast and slow charging for BEBs at each district.

Table 28 *– Potential annual savings related to PECO tariffs*

SEPTA Location	Address	# of Buses	% of Fleet	Year Built	Facility Size (Sq. Ft.)
Allegheny	2600 W. Allegheny Ave. Philadelphia, PA 19132	123	8%	1986	208,000
Callowhill	5801 N. Vine St. Philadelphia, PA 19131	181	12%	1913	213,000
Comly	6000 Penn St. Philadelphia, PA 19149	185	13%	1921	105,000
Frankford	Bridge St. & Frankford Ave. Philadelphia, PA 19124	142	10%	1957	102,000
Frontier	1525 Alan Wood Rd. Conshohocken, PA. 19428	102	7%	1950	45,000
Midvale	4301-15 Wissahickon Ave. Philadelphia, PA 19129	312	22%	1996	443,000
Southern	1934 Johnston St. Philadelphia, PA 19145	228	16%	1924	217,000
Victory	110 Victory Ave Upper Darby, PA 19082	176	12%	1950	32,000



Berridge Bus Depot

Germantown Bus Depot

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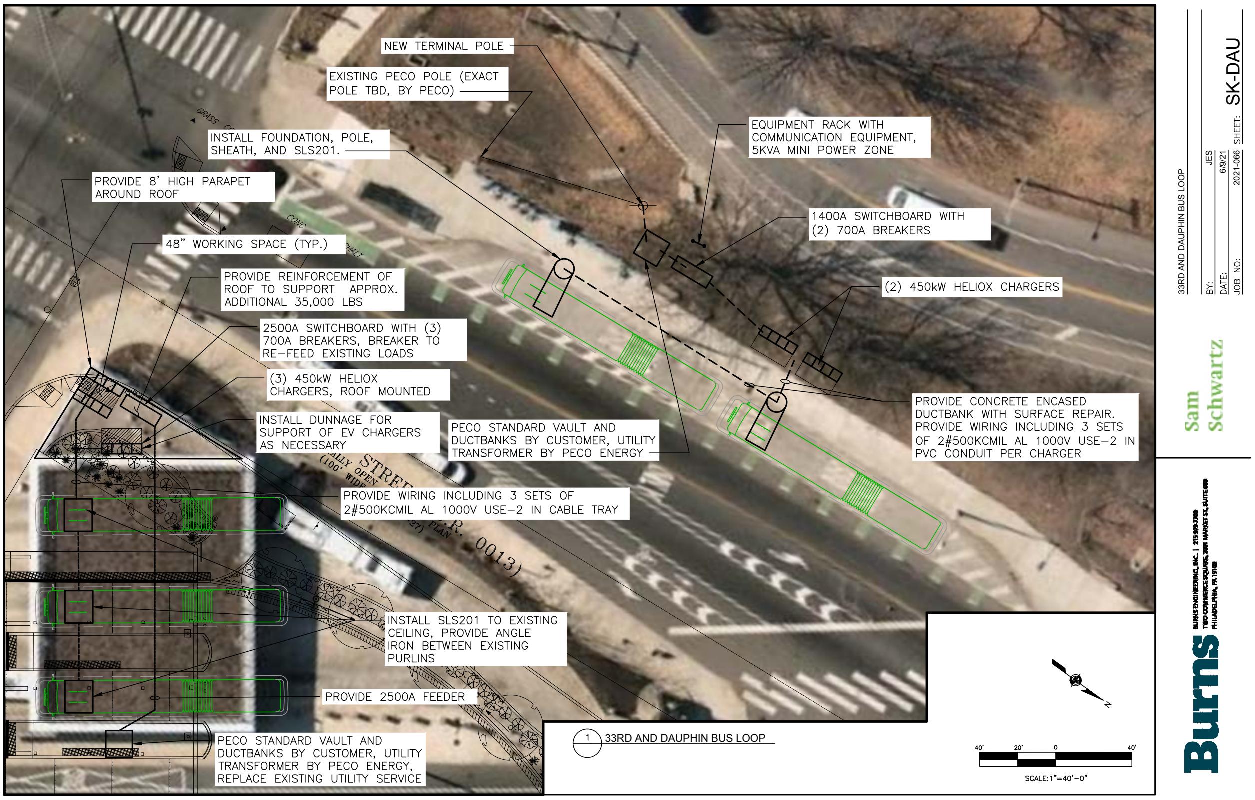
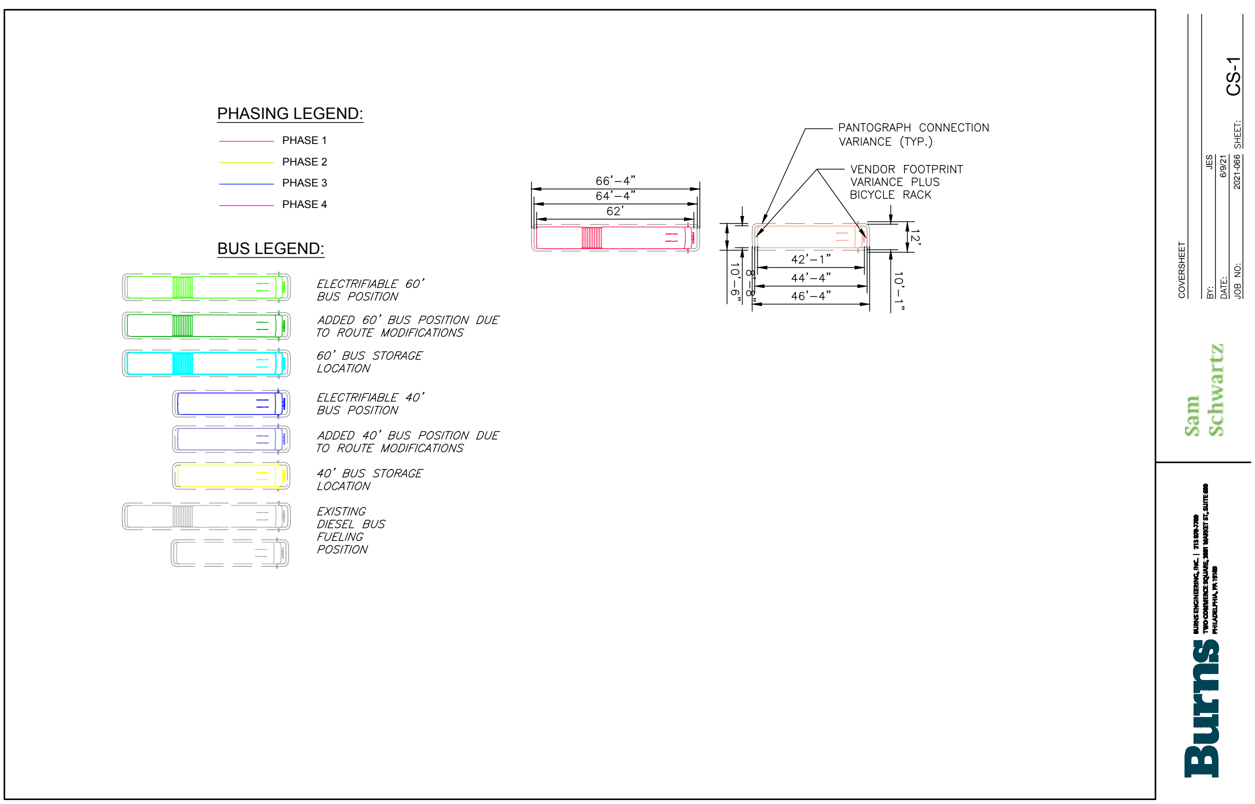


33rd and Dauphin Bus Loop



Coversheet

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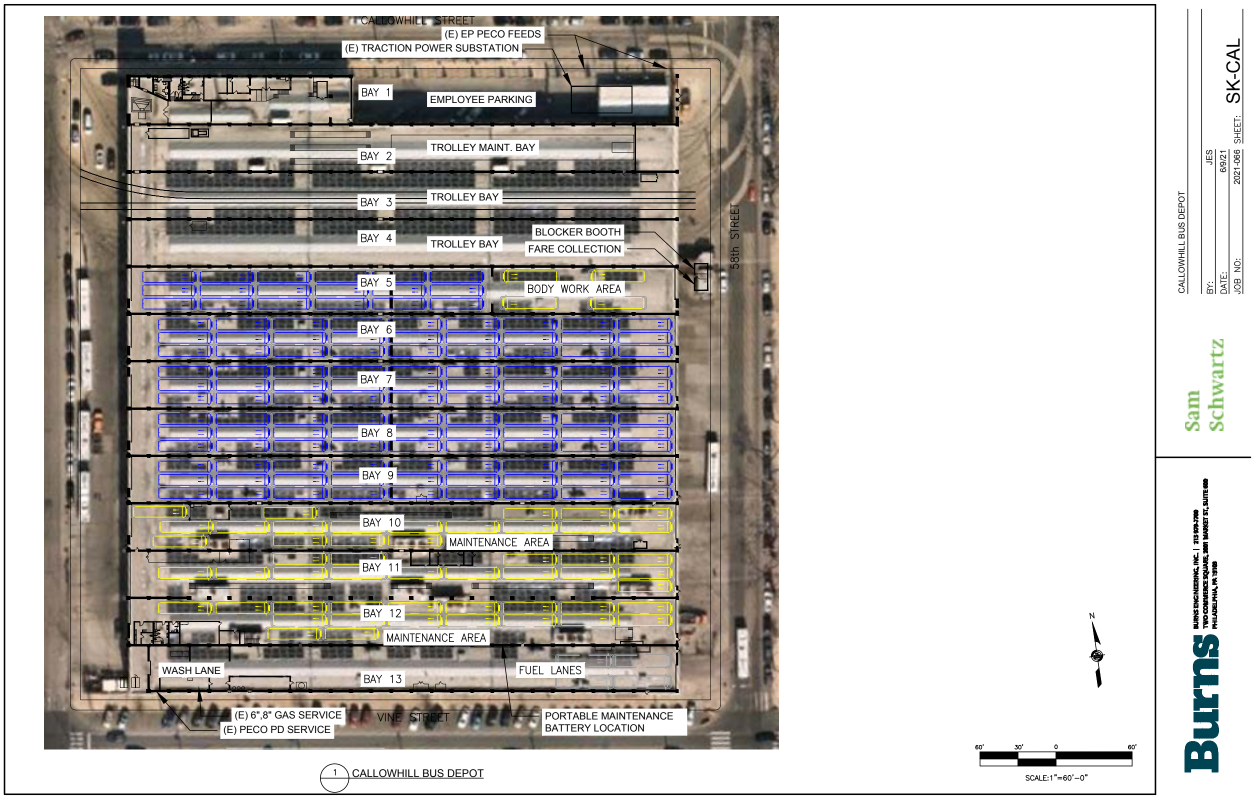
Allegheny Bus Depot



Callowhill Bus Depot

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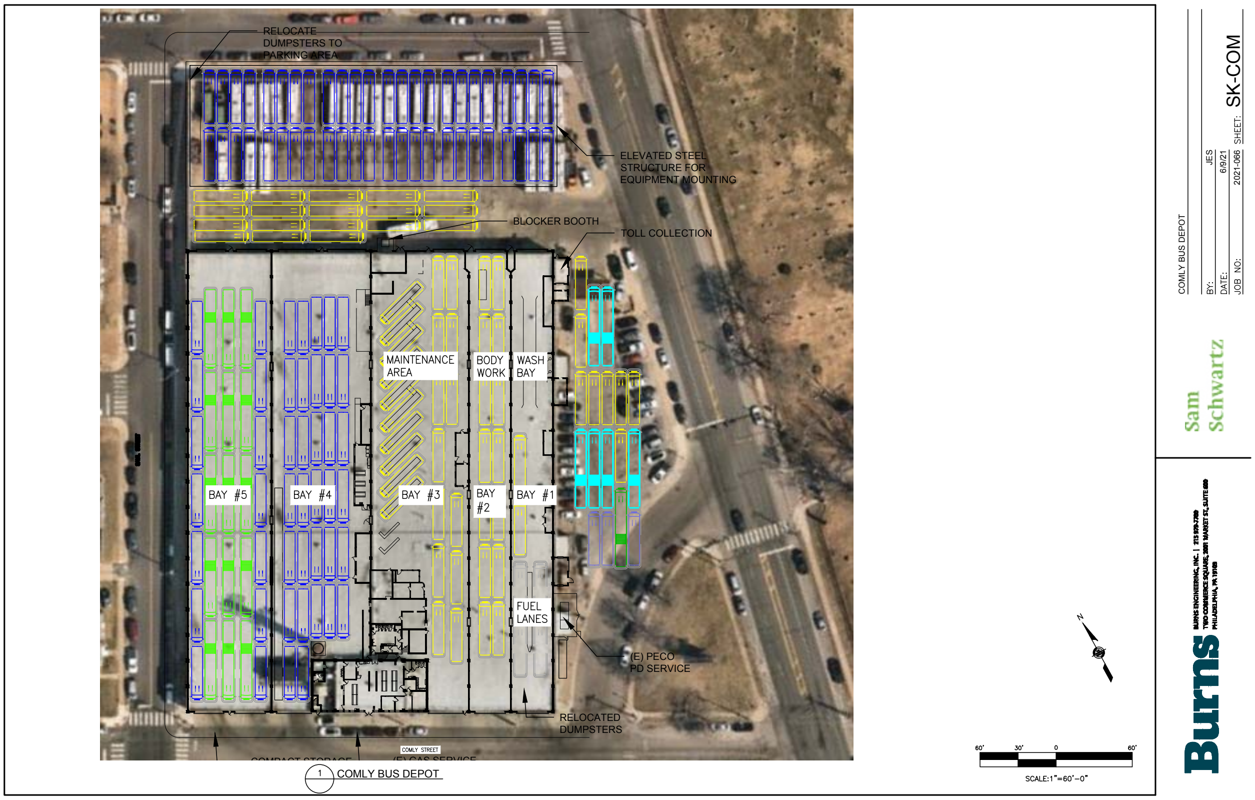
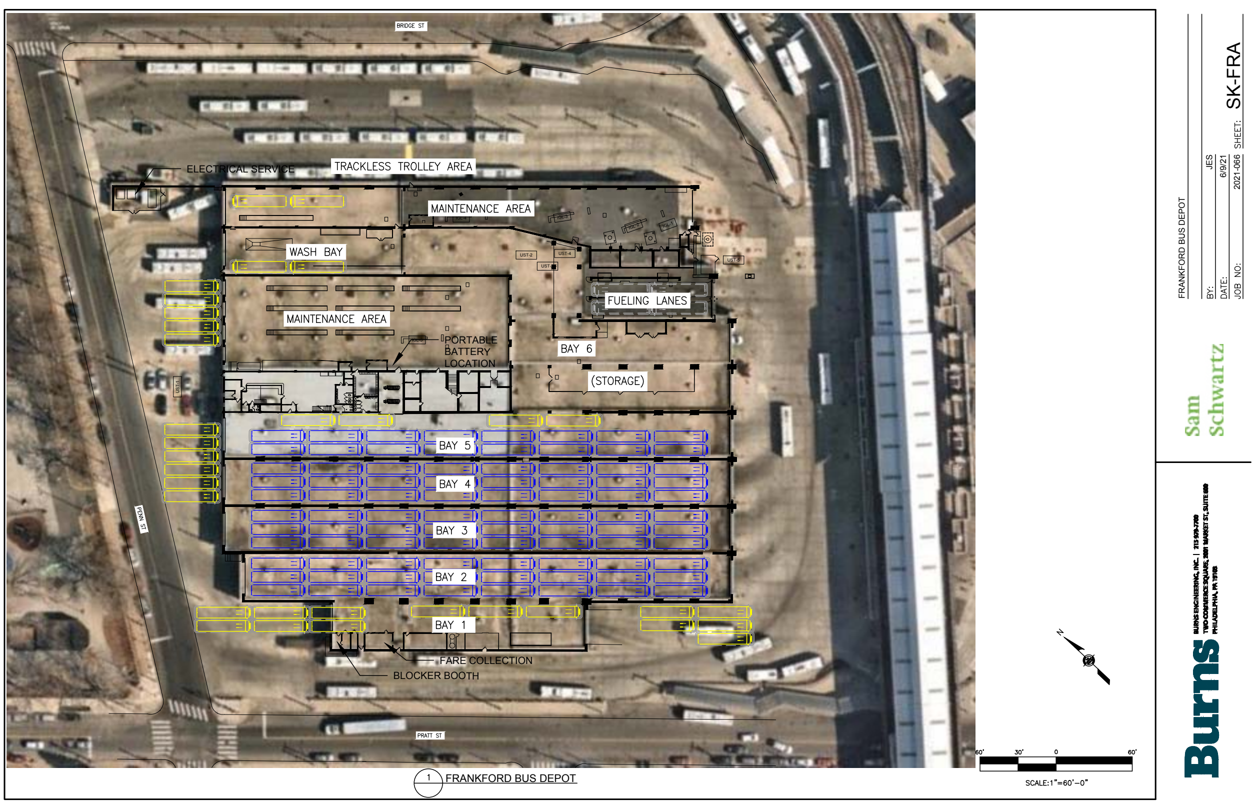
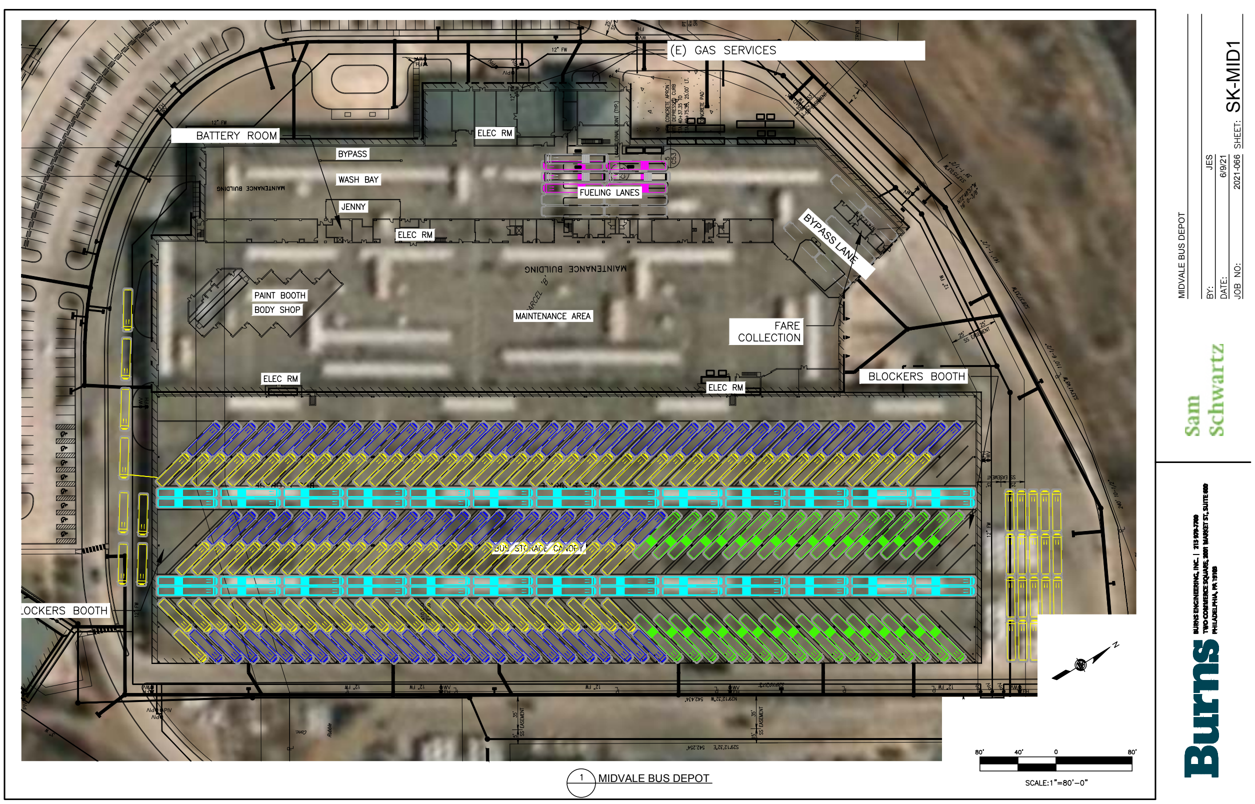


Comly Bus Depot



Frankford Bus Depot

Frontier Bus Depot



Midvale Bus Depot

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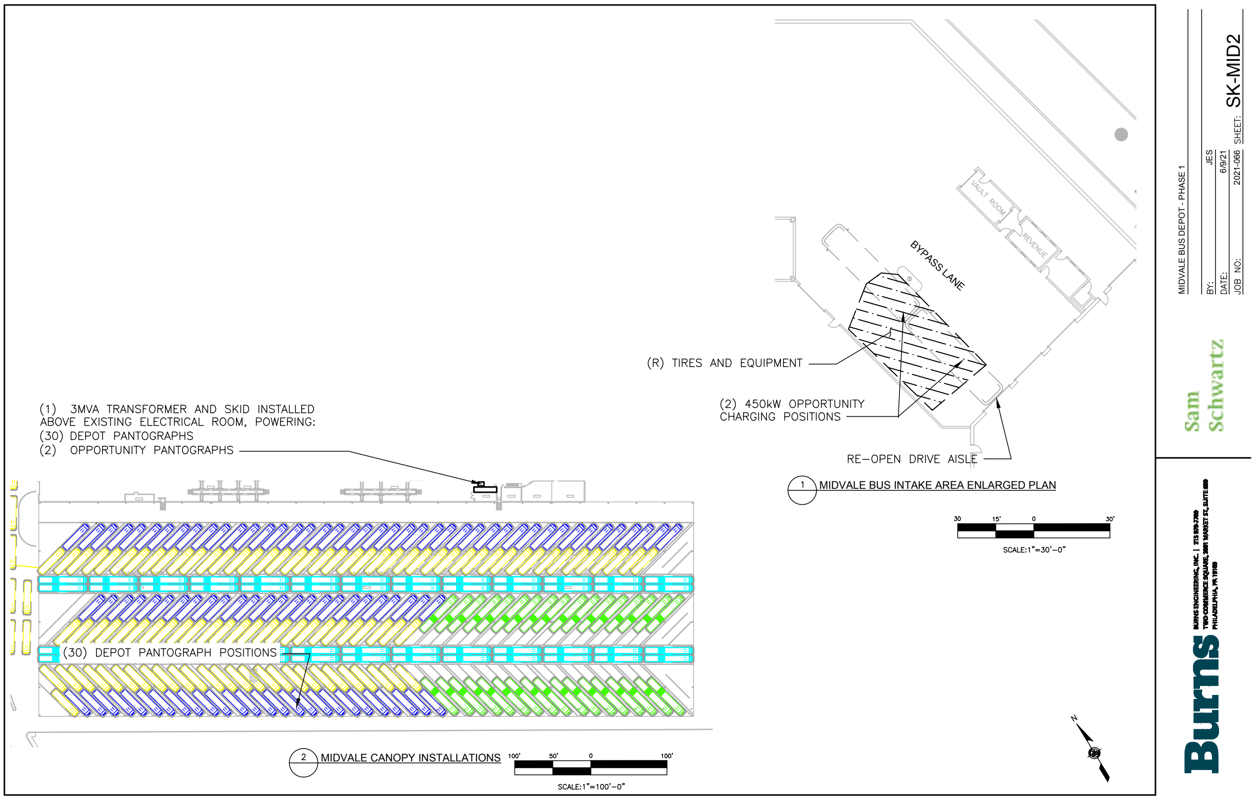
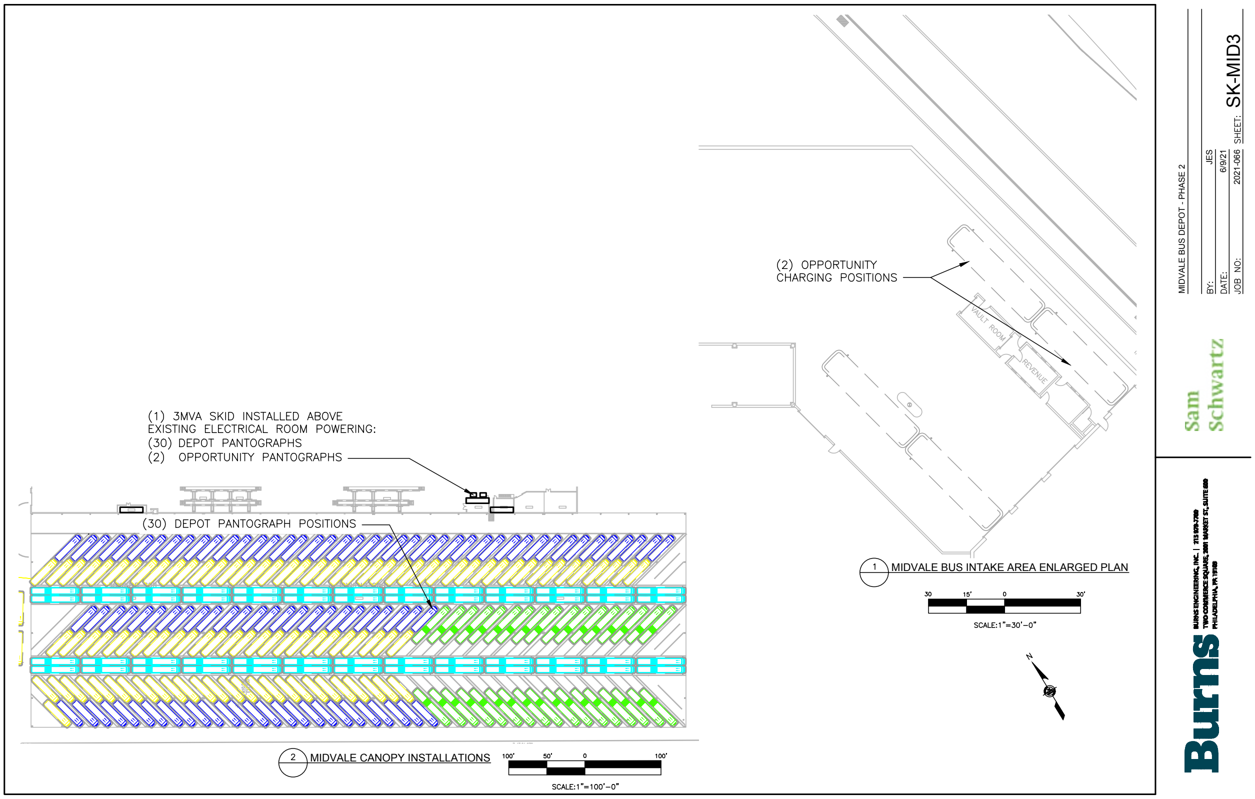


Midvale Bus Depot – Phase 1



Midvale Bus Depot – Phase 2

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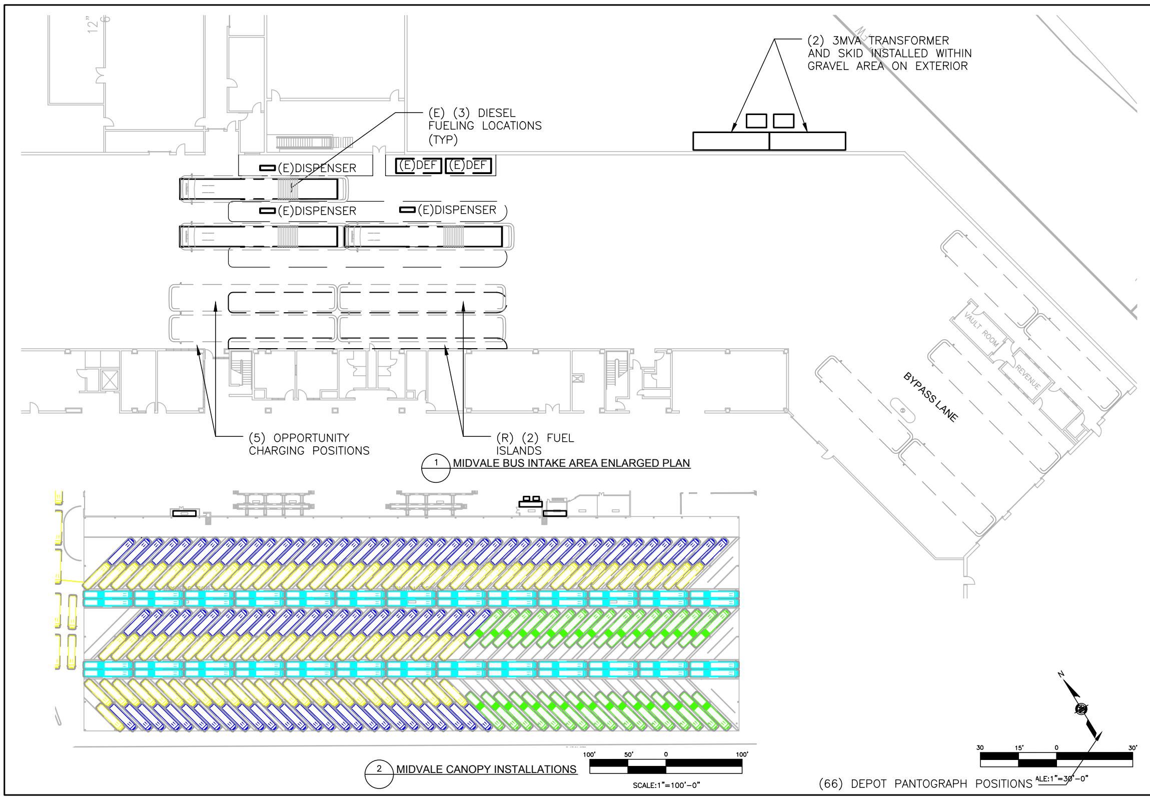
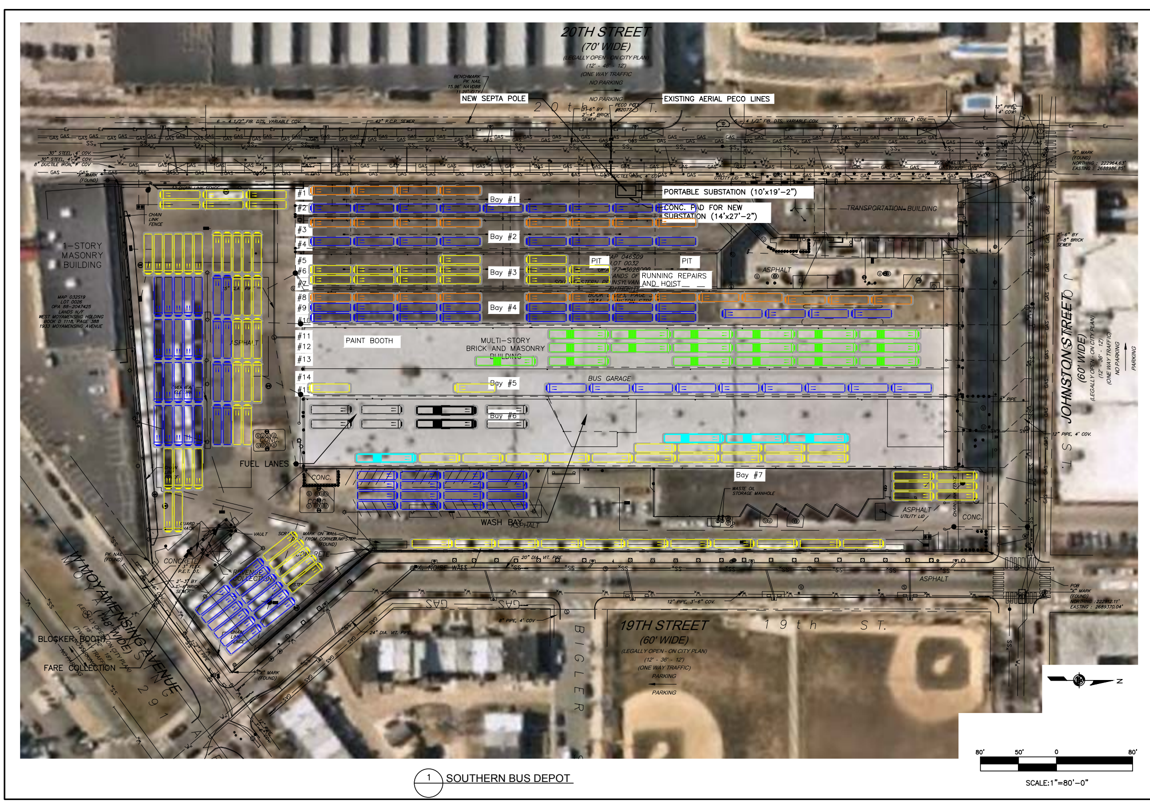


Midvale Bus Depot – Phase 3



Southern Bus Depot

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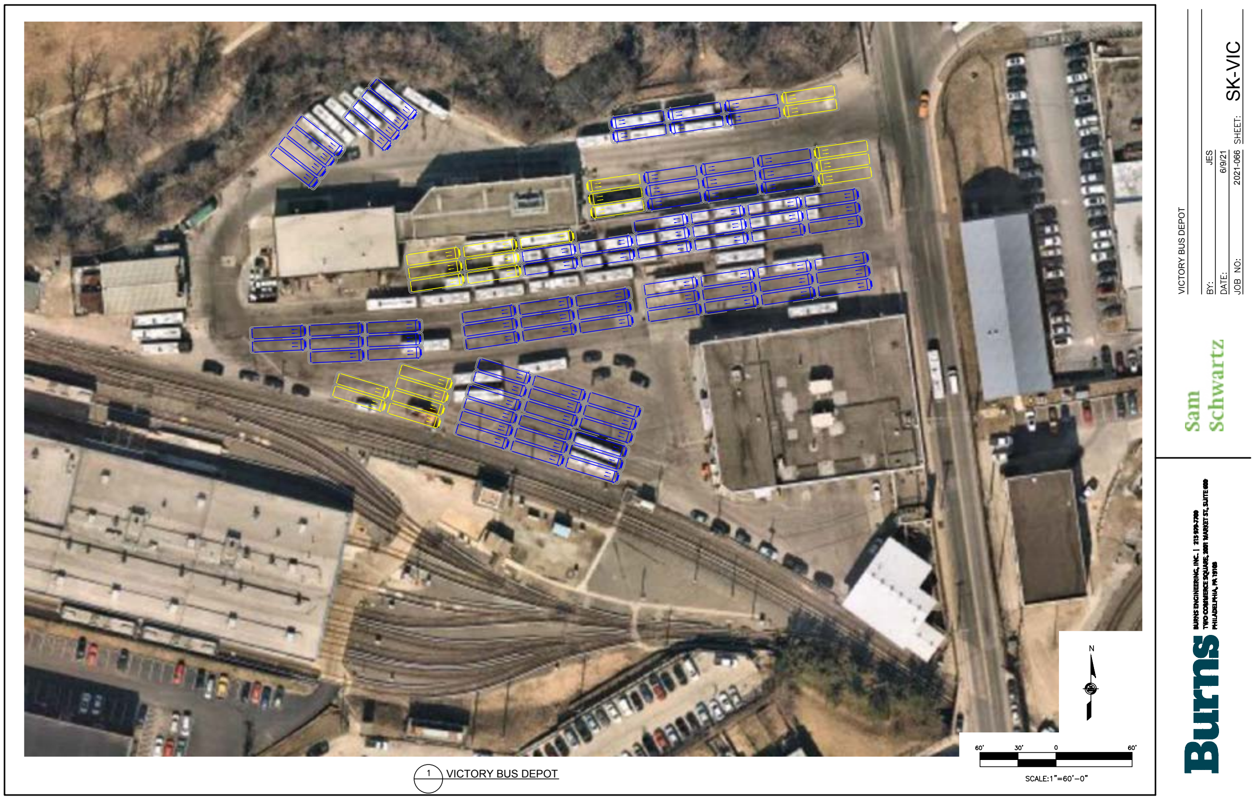

Victory Bus Depot

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SEPTA FORWARD

Zero-Emission Bus PLAYBOOK

Appendix E: Fleet Transition Cost Analysis

Key Cost Elements And Assumptions

This analysis seeks to understand the costs that SEPTA should expect over the course of a transition to a ZEB fleet. We have projected various operating costs and capital costs associated with the SEPTA bus fleet over the period 2022-2040. These costs are calculated in year of expenditure (YOE) dollars, including inflation at a 2% annual rate. The specific cost categories included in our analysis are described below. Social and environmental costs and benefits are discussed in Section 6, Sustainability and Equity Analysis, and Appendix I, Emissions Analysis.

Operating Costs

Diesel Fuel

Diesel fuel costs were calculated for every hybrid bus in the SEPTA system over each year of the transition period. SEPTA's buses are estimated to travel an average of 32,000 miles annually, and their fuel efficiency ranges from 4.54 to 2.80 miles per gallon depending on vehicle type. These figures allow us to calculate the gallons of diesel fuel consumed annually. We also know that SEPTA's current price per gallon of diesel fuel is $2.53 including delivery, and this price is anticipated to grow over time based on projections developed by the US Energy Information Administration, allowing us to project total diesel fuel costs each year.

Electricity

Electricity costs were projected for BEBs based on the current rate structures for PECO electrical delivery and Constellation NewEnergy (CNE) electrical supply. Rate calculations were completed for each bus garage and for each on-route charging location, using the electric propulsion rate class. The specific amount of energy used at each location was calculated using schedule modeling results that indicated usage of on-route chargers as well as the end-of-service battery levels to be addressed through garage charging. At garages, we assumed that charging can be managed to occur primarily during off-peak overnight periods, such that daytime power demand can be limited to 50% of the peak overnight power demand. Note that the results were adjusted to represent typical battery consumption conditions (rather than adverse winter conditions) and scaled according to what percentage of each location's buses are electric in each year of the transition. We also assume that electricity prices will follow growth projections developed by the US Energy Information Administration in future years.

Hydrogen Fuel

Hydrogen fuel costs were calculated for every FCEB in the SEPTA system over the transition period. These calculations assumed that the price per kg of hydrogen fuel declines over time, based on HDR projections shown in ***Figure 23***. Our calculations also utilized hydrogen fuel efficiency of 7.96 to 6.37 mi/kg depending on vehicle type. These projections reflect a market dominated by gray hydrogen; note that green hydrogen will likely be more expensive.

Maintenance

Maintenance costs for buses were calculated on a per-mile basis. Existing hybrid buses have a maintenance cost of $2.20 per mile, but ZEBs are expected to have lower maintenance costs due to having fewer moving parts. We assumed the maintenance cost reduction was 9.1%; this is based on an 18.5% estimate by Proterra, but to be conservative, their estimated reduction was only applied to materials and not labor.[32]

For chargers, maintenance costs are estimated using annual values. Each slow charger was assumed to require $2,500 of annual maintenance, while each fast charger was assumed to require $15,000 of annual maintenance. These values include parts and labor for preventative and corrective maintenance and are based on peer agency estimates.

For hydrogen fueling infrastructure, maintenance costs are also estimated using annual values. Maintenance of this infrastructure is estimated to cost $230,000 per 100 buses annually. This is based on experience from AC Transit.

Labor from Schedule Changes

To the extent that the SEPTA bus fleet transitions to BEBs, we anticipate that some vehicle schedule modifications will

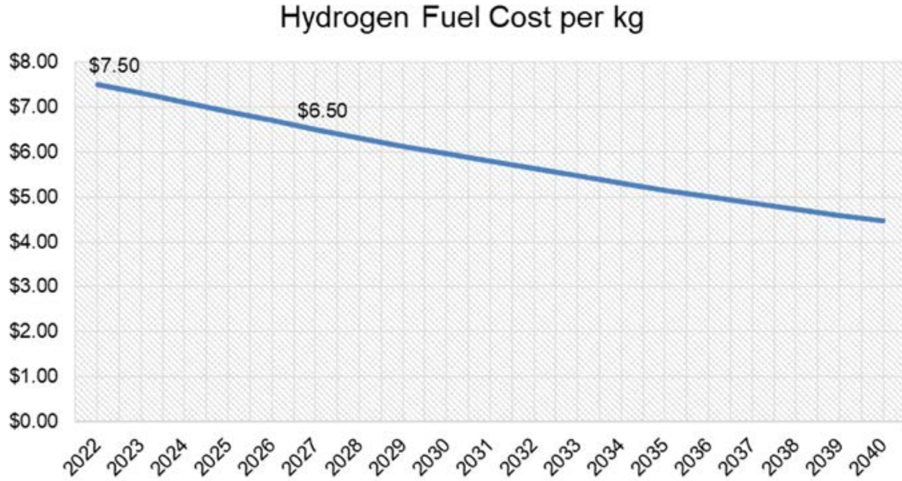

Figure 23 *– Assumed trend in the market price of hydrogen fuel (dominated by gray hydrogen)*

32 Catalyst Total Cost of Ownership Advantage

be needed to split long blocks into shorter assignments to ensure service is fully compatible with electrification.[33] The costs of these changes were calculated by assuming that splitting a block adds two new 15-minute trips, going to and from a garage. The cost of this added operation was estimated using fully-loaded operating costs that range from $55.12 to $68.47 per hour. We assumed that SEPTA will avoid making these changes for as long as possible, and the changes will only occur when required to continue electrification of blocks that would not otherwise be compatible according to the fleet transition timeline. We should also note that some of these blocking changes could require adding buses to the fleet if they occur during peak times; these impacts on fleet size and purchases are also addressed elsewhere in this playbook for consistency.

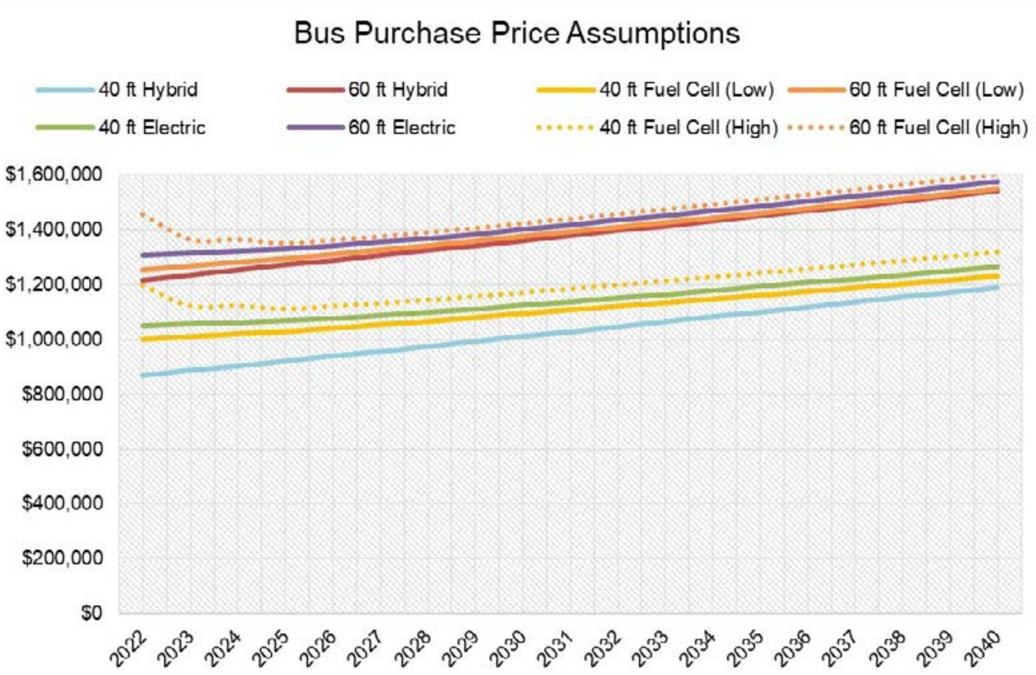

Figure 24 – *Bus purchase price assumptions*

33 Note that these changes will not impact customer-facing schedules.

Capital Costs

Vehicle Purchases

Bus purchase costs were modeled based on the planned bus purchases specified in our fleet transition timeline. This timeline builds upon SEPTA's Projected Quarterly Bus Fleet Size spreadsheet, and anticipates future purchases based on a 15-year vehicle lifetime. The specific assumptions for bus purchase prices over time are shown in the figure below. The 2021 pricing for hybrid buses and BEBs was set based on figures provided by SEPTA. For FCEBs, high and low estimates are used to reflect uncertain pricing. The trends for price growth are based on information from the American Public Transportation Association and the California Air Resources Board.[34,35]

Chargers

The costs of chargers at garages and at on-route locations were estimated using quotes from Heliox. These estimates assume typical prices of $55k per slow charger and $233k per fast charger. Other directly related costs included in our estimates are pantograph dispensers, conduit, and cabling. At garages, we assume that these costs occur proportionally as the electrified storage capacity grows. At on-route charging locations, we assume that these costs occur in the first year that any buses would potentially need to charge at each location. We also assume that chargers have a 15-year lifetime, and replacements are anticipated when retirement age is reached.

Facility Upgrades

The costs of facility upgrades needed to support BEBs were estimated by subconsultant JCMS. These facility upgrades include a range of elements such as concrete work, structural steel, communications equipment, electrical cabling and conduit, transformers and switchgear, backup gas generators, and allowances for demolition, relocations, and removal of hazardous materials. All facility costs include installation. Facility costs do not include the costs of new/upgraded PECO service to accommodate chargers, any facility additions or expansions needed to address storage capacity needs, or state-of-good-repair needs or structural modifications that may be needed to accommodate charging equipment at districts.

33 California Air Resources Board Transit Fleet Cost Model, 2020.
34 American Public Transportation Association Fact Book, Appendix A, 2020.

At garages, we assume that these costs occur proportionally as the electrified storage capacity grows. At on-route charging locations, we assume that these costs occur in the first year that any buses would potentially need to charge at each location.

The costs of facility upgrades needed to support FCEBs were estimated by subconsultant HDR. These facility upgrades include fuel tanks, pumps, vaporizers, maintenance bay upgrades, dispensers, and station modules. The upgrade costs are shown as a range to reflect uncertainty.

Anticipated Subsidy

SEPTA's ZEB purchases to date have been subsidized by external partners such as the Federal Transit Administration, and it is anticipated that comparable subsidies will continue in future years. Specifically, we assumed that SEPTA will receive funding that matches 11% of the cost of each ZEB purchased. These subsidies were counted as negative costs that help offset other capital spending.

Cost Modeling Scenarios

The cost inputs above were used to compare three scenarios for the SEPTA bus fleet: a baseline scenario that continues usage of hybrid buses, a scenario that transitions to 100% BEBs, and a scenario that transitions to 80% FCEBs and 20% BEBs. The baseline scenario maintains the current fleet size and does not include any facility improvements. The electric scenario increases the bus fleet size by 25, in order to split apart long vehicle assignments, and includes investments in on-route chargers and garage upgrades. The 80% FCEB scenario requires a smaller increase in the bus fleet (5 buses) and electrical infrastructure aligned with its smaller BEB subfleet. The scenarios follow facility upgrade plans and fleet purchasing plans that are described in the Implementation Plan section.

Summary of Cost Modeling Results

The overall results of our cost modeling for the fleet transition period of 2022-2040 are shown in ***Table 29***. This shows that modeled

Table 29 *– Total costs for each scenario and each cost category over the period 2022-2040, in millions of YOE dollars*

Operating Costs	Hybrid Scenario ($M)	Electric 100% BEB Scenario ($M)	Fuel Cell 80% FCEB Scenario ($M)	Capital Costs	Hybrid Scenario ($M)	Electric 100% BEB Scenario ($M)	Fuel Cell 80% FCEB Scenario ($M)
Diesel Fuel	$716	$392	$392	**Vehicle Purchases**	$2,021	$2,175	$2,155 to $2,250
Hydrogen Fuel	$0	$0	$218	**Charger Infrastructure**	$0	$90	$23
Electricity	$0	$114	$41	**Facility Upgrades**	$0	$252	$156 to $253
Maintenance	$2,337	$2,288	$2,266	**Anticipated Subsidy**	$0	-$252	-$248 to -$262
Schedule Changes	$0	$62	$13				
Operating Costs Total	$3,054	$2,856	$2,930	**Capital Costs Total**	$2,021	$2,265	$2,087 to $2,407
				Total Operating & Capital Costs	$5,075	$5,121	$5,017 to $5,337

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operating costs would be lower for the ZEB fleet scenario compared with the hybrid fleet baseline over the 2022-2040 transition period: 6% lower for the 100% BEB scenario or 4% lower for the 80% FCEB scenario. However, modeled capital costs for the ZEB scenarios would be higher compared with the hybrid fleet baseline: 12% higher for the 100% BEB scenario or 3% to 19% higher for the 80% FCEB scenario. In total, we anticipate that the BEB fleet scenario adds a relatively modest cost of $46m over the transition period, while the 80% FCEB fleet scenario could range from a net savings of $58m to a net cost of $262m.

There are several reasons that the ZEB scenarios could be more costly than shown. Our estimates do not consider the cost of a new garage, which will likely be needed to address existing capacity issues that would be exacerbated with the addition of new fueling equipment or charging equipment at districts and which could significantly increase the capital investment. The ZEB scenarios also do not address any existing state of good repair needs or structural upgrades that may need to be addressed in conjunction with upgrades to accommodate ZEBs at each district. For BEBs, there will also be costs associated with bringing additional PECO service to districts and on-route charging locations and further coordination with PECO will be needed to identify these costs. There is also a risk that the anticipated subsidies do not continue at the level assumed.

However, there are also reasons that the ZEB scenarios may be more attractive than shown. The transition period includes the continued operation of hybrid buses until 2040, so full operational savings from transitioning will not be experienced until the end of the period. In addition, the transition period includes capital investments to support the new fleet that would not be part of the ongoing financial picture.

Figure 25 below gives a more detailed picture of operating costs over the transition period. This shows that the ZEB fleet scenarios generate a substantial reduction in diesel fuel costs. While they also add new costs associated with electricity, schedule changes, and hydrogen fuel, these are not large enough to offset the savings from fuel.

Figure 26 below shows the modeled capital costs in greater detail. The ZEB fleet scenarios are anticipated to require greater capital spending for vehicle purchases, facility upgrades, and chargers. While we anticipate a large subsidy totaling over $250m to support vehicle purchases, this still could leave a similar amount of additional capital costs that SEPTA would bear.

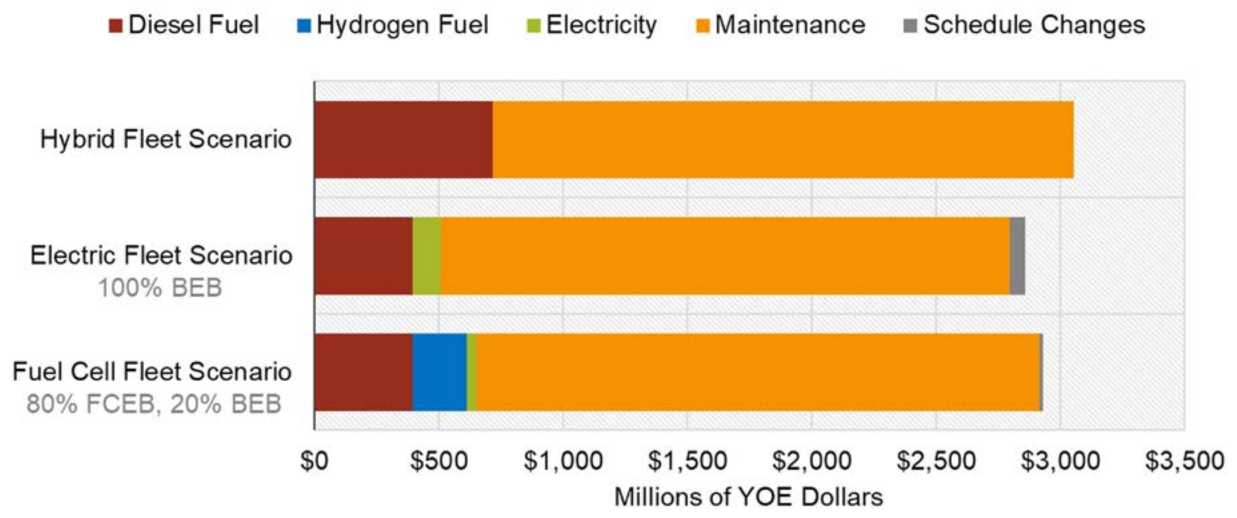

Figure 25 *– Comparison of projected operating costs over 2022-2040*

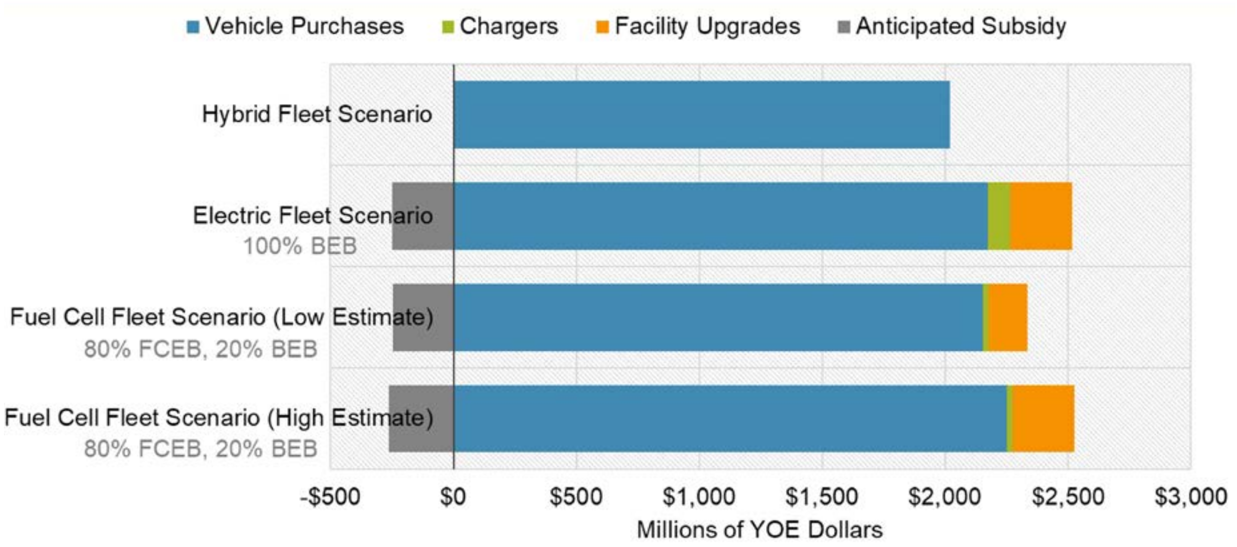

Figure 26 *– Comparison of projected capital costs over 2022-2040*

The cost model can also be used to understand cost trends over time. ***Figure 27*** shows the cumulative net cost of selecting the 100% BEB scenario or the 80% FCEB scenario over the hybrid fleet scenario. This shows that the net cost grows from 2026 (when SEPTA starts buying only ZEBs) until the mid 2030s, when most capital investments are complete. At the end of the 2030s, the cumulative net costs begin to decline as SEPTA reaps the benefits of reduced operating costs. The cost model shows that the cumulative costs of the two scenarios would break even in 2042 or 2043, shortly after the ZEB transition is complete.

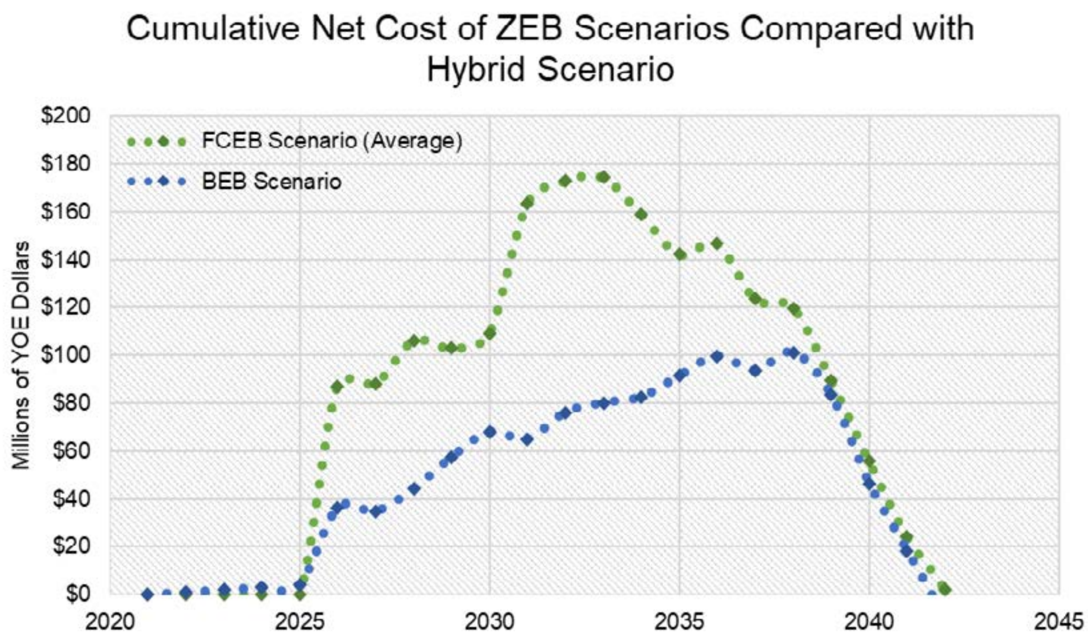

Figure 27 *– Cumulative net cost of electrification scenario compared with hybrid scenario*

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Appendix G: Maintenance and Weight Considerations

Vehicle Maintenance Considerations

This section provides an overview of key considerations related to vehicle maintenance and performance that should be taken into account during a transition to an electrified bus fleet.

Weight of Buses

BEBs are typically heavier than diesel buses largely due to the weight of the battery packs. Some available BEBs have limited passenger carrying capacity due to the additional weight of the batteries. Preliminary research on BEB performance and maintenance requirements suggests that suspension wear may also be higher due to the increased curb weight.[36] The heavier vehicles may also have a greater impact on road infrastructure.

Table 30 shows the variation in weight and battery sizes among 40-foot BEBs from the top three OEMs in the North American market. Depending on manufacturer, 40-foot BEBs have a curb weight of approximately 26,600 – 35,000 pounds. The larger battery offerings from each manufacturer correspond to a heavier bus.

Table 30 *– Weight, battery size, and occupant capacity of 40-foot BEBS*
Source: Burns Engineering, Inc. SEPTA Sustainable Vehicle Technology Report (March 2021)

Criteria	BYD BEB	Gillig BEB	GreenPower BEB	New Flyer BEB	Nova BEB	Proterra BEB	New Flyuer FCEB	El Dorado FCEB
Curb Weight (lbs)[1]	32,190	35,000	33,805	28,850	32,612	26,649	32,250	33,520
					35,458	29,849		
						33,149		
Occupant Capacity (Sitting/Standing)	37	38/37	40	40/43	41/27	40	40/42	43
Battery Size(s) (kWh)	324	444	430	350	376	225		
	500			440	564	450		
				525		675		

[1] Weights are approximate and vary with selected energy storage system configuration

36 TCRP, BEB State of Practice, 2018, pg. 16.

For comparison, the curb weight of 40-foot diesel buses is typically between 26,000 – 28,000 pounds. Although BEBs are heavier than diesel buses, SEPTA's existing lifts are expected to be able to accommodate the added weight of the BEBs. The only commercially available 40-foot BEB with a similar curb weight to a diesel bus is the Proterra bus with the smallest battery. Proterra buses with the largest batteries and BEBs from the other manufacturers are heavier than the typical diesel bus. Extended range BEBs have the largest batteries and can weigh as much as 5,000 pounds more than a diesel bus.

The structural materials of a Proterra bus contributes to the lower curb weight. Proterra utilizes a fiberglass composite to construct the load bearing structure, walls, floor, and roof. All other manufacturers use a welded tubular steel frame, with steel, aluminum, or composite body panels connected to the frame which is similar to the construction of diesel buses. The composite material of Proterra buses is lighter than steel and will not corrode but may exhibit deterioration over time due to structural stress. During a crash, the composite material behaves differently than steel and will require different repair methods.

With the advances in battery technology and manufacturing, battery energy density has increased over time and is expected to continue to do so. This means that as advances occur, battery packs will have a greater energy capacity with less weight. It is likely that battery offerings will continue to evolve for all OEMs and, as a result, the weight of the bus will vary as well.

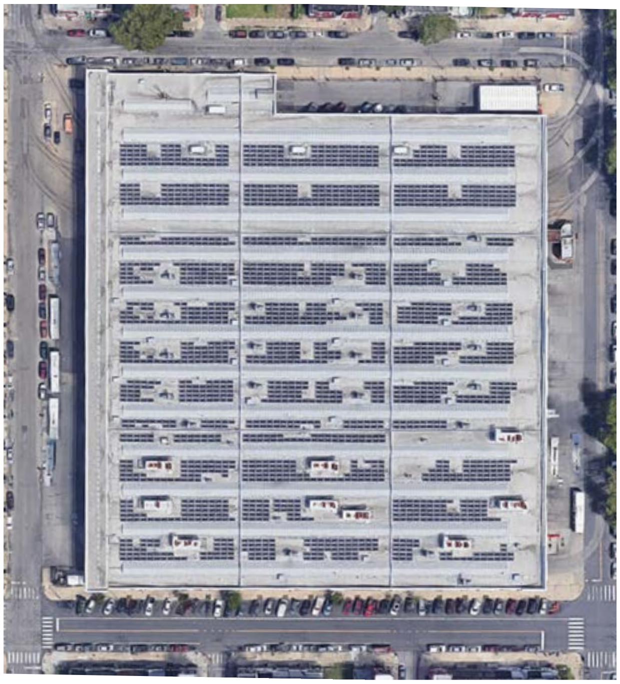
Appendix H: Review of Bus Depots to Accommodate FCEBs

This appendix documents a preliminary review of SEPTA bus depots that sought to estimate whether outdoor hydrogen fuel storage and delivery would be feasible at each facility. Note that the findings in this appendix are preliminary, and each district would need to be evaluated in-person prior to making definitive compatibility decisions. Only Midvale and Allegheny were reviewed in-person as part of this effort. Bus storage and maintenance would be feasible at all facilities with improvements. Storage space impacts were not quantified or considered in this preliminary evaluation.

The table below summarizes the preliminary findings from this process:

Table 31 *– Summary of preliminary findings regarding depot space for FCEB infrastructure*

District	Space for FCEB Infrastructure?
Allegheny	**No**
Callowhill	**No**
Comly	**Maybe**
Frankford	**Maybe**
Frontier	**Yes**
Midvale	**Yes**
Southern	**Maybe**
Victory	**Maybe**

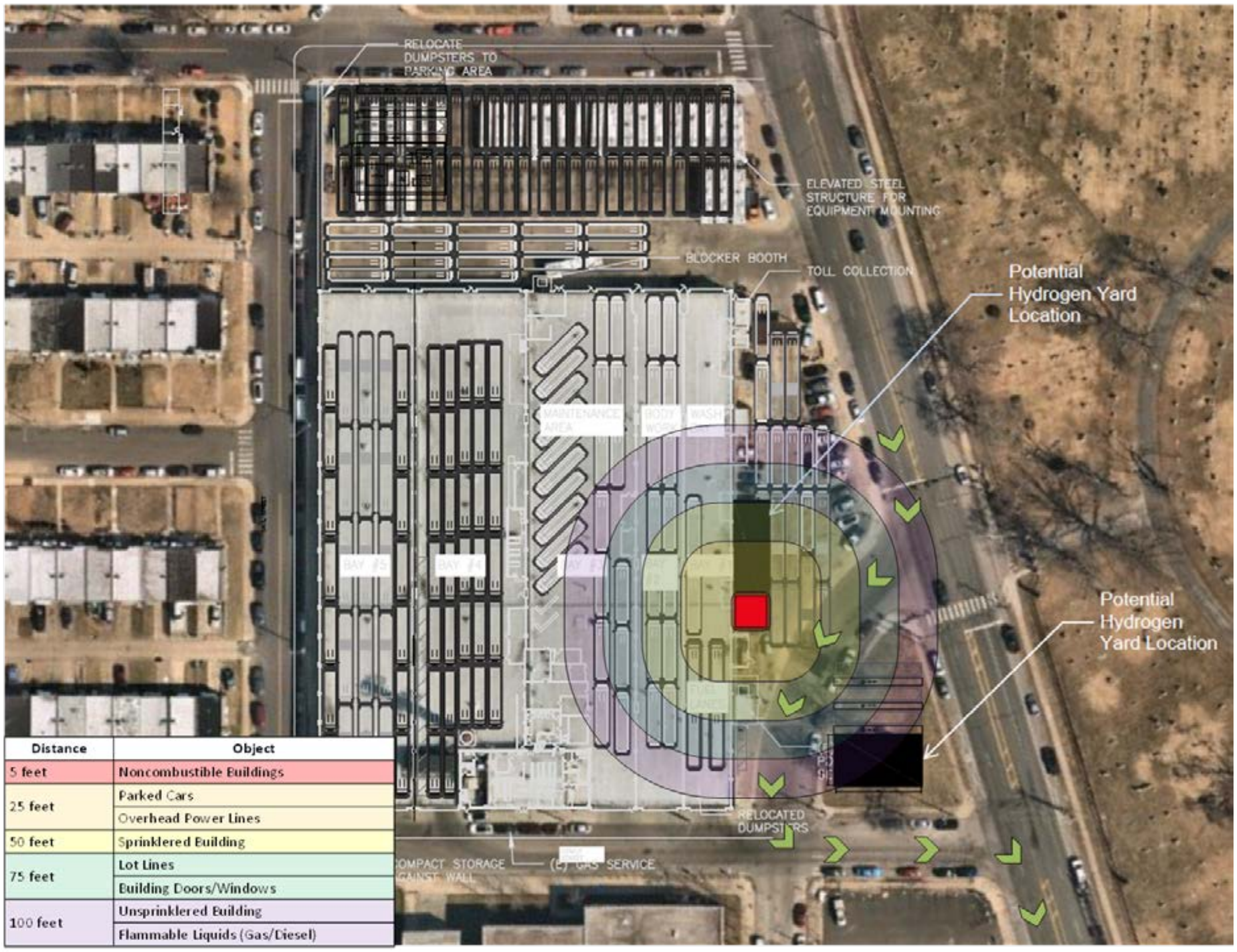


Allegheny and **Callowhill** were rated as “No” with regard to having space to support FCEB fueling infrastructure. These are both fully indoor facilities, and hydrogen storage and fueling may not take place indoors. However, additional options may exist for these two depots:

→ Potential hydrogen fueling for these districts at a nearby depot with fuel storage capacity

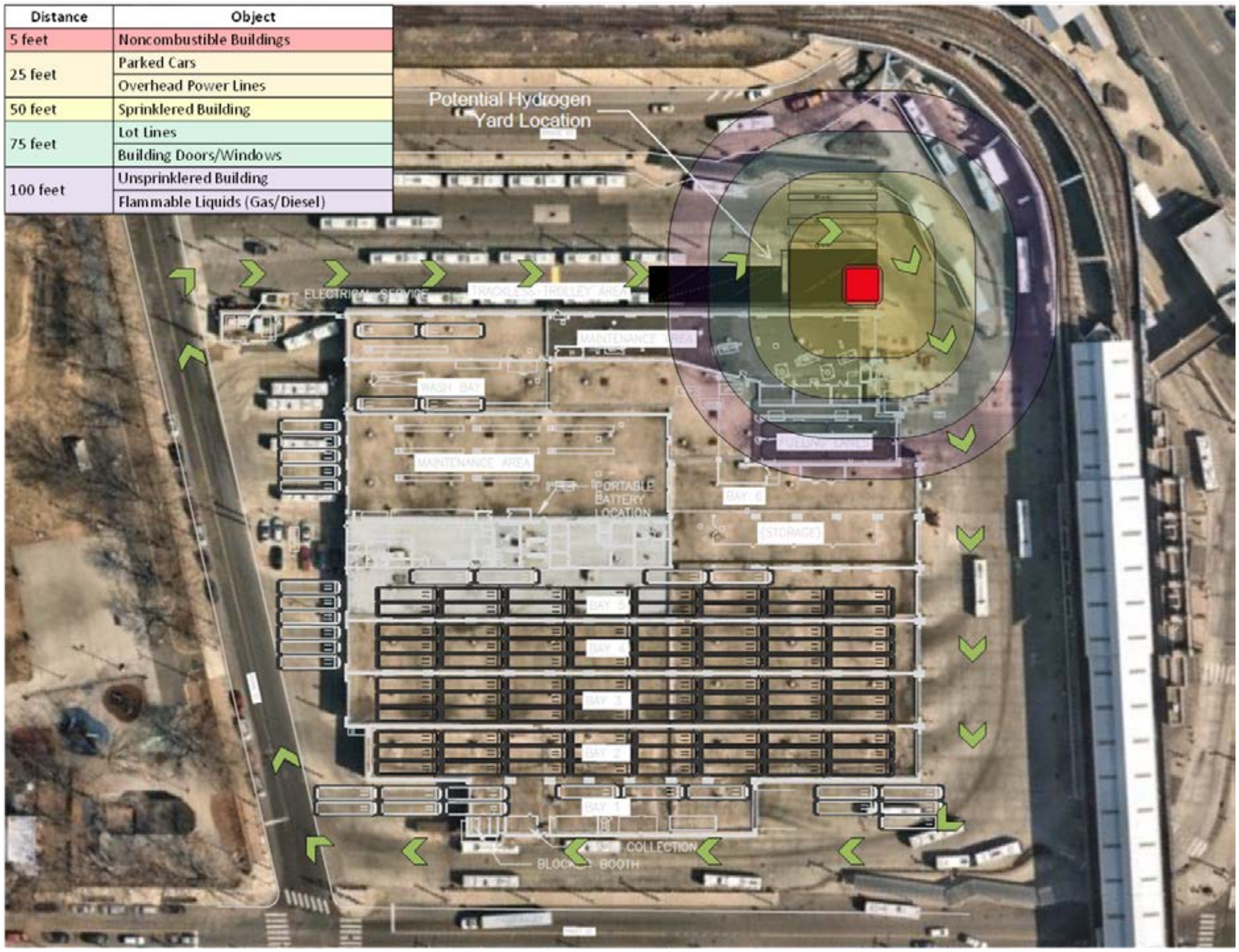
→ Potential hydrogen fueling for these districts at another off-site facility

→ New bus district facility

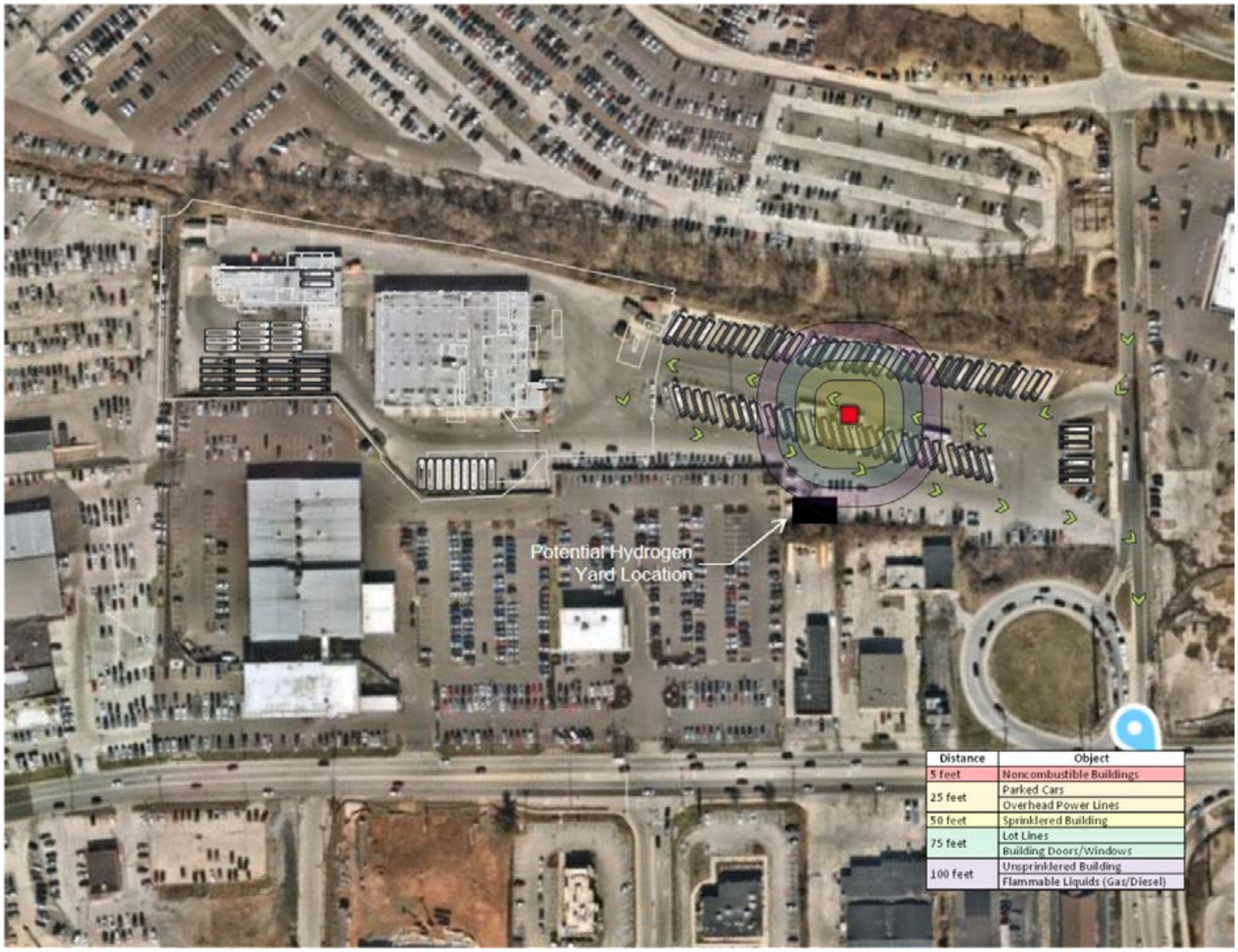


Comly was rated as "Maybe" with regard to having space to support FCEB fueling infrastructure. The fuel tank location most likely to be feasible would be aboveground next to the depot building; this would require firewalls for reduced setbacks dependent on the local authority having jurisdiction.

The graphic below also shows a potential hydrogen storage location on a traffic island at the intersection of Comly St and Bustleton Ave, but that is likely infeasible based on property ownership. Fuel dispensers could be located in existing fuel lanes.

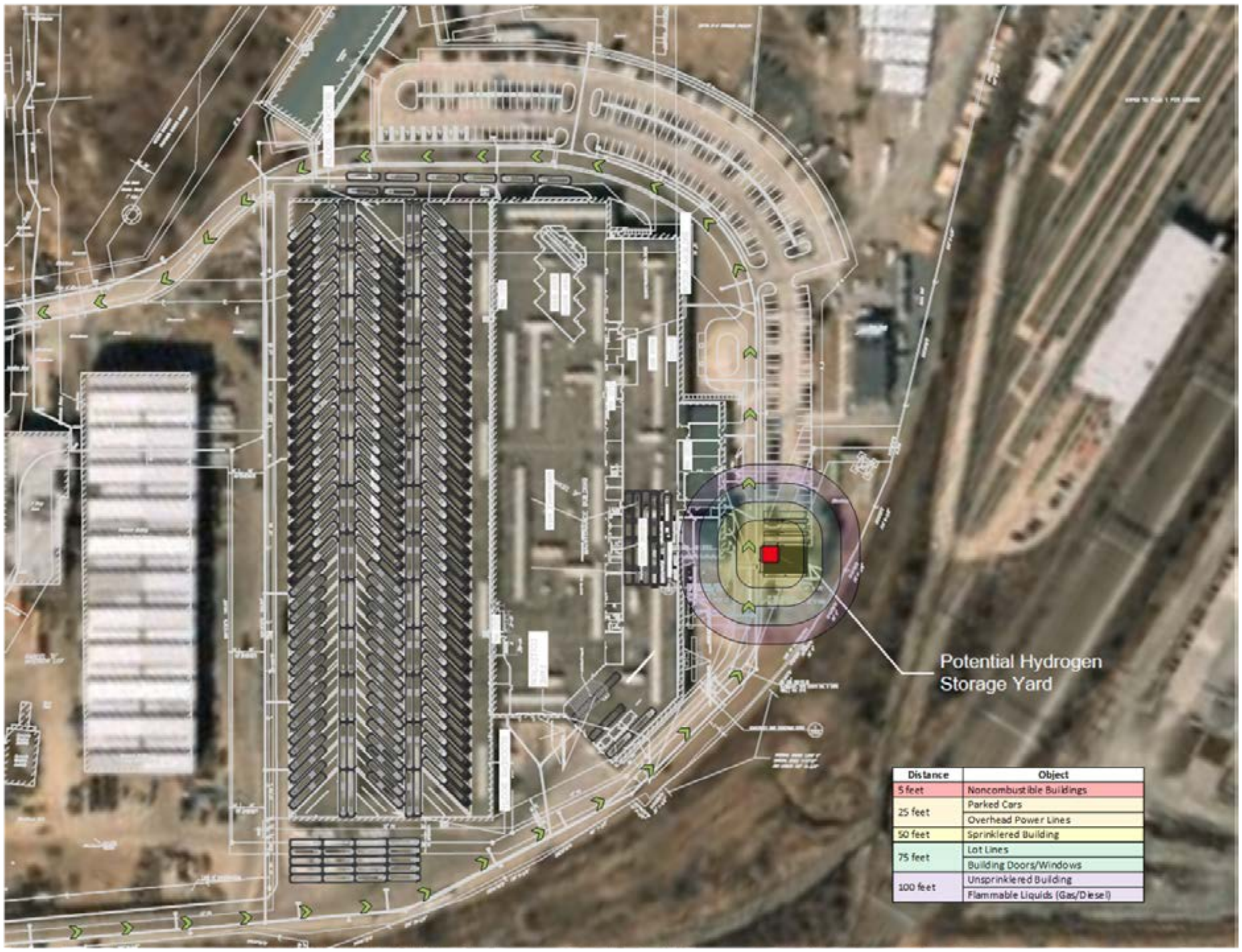


Frankford was rated as "Maybe" with regard to having space to support FCEB fueling infrastructure. The most likely location for fuel tanks would be aboveground next to the building; this would require firewalls for reduced setbacks dependent on the local authority having jurisdiction. Fuel dispensers could be located in existing fuel lanes. A potential challenge at this location is that hydrogen fueling could interfere with existing trackless trolley operations.



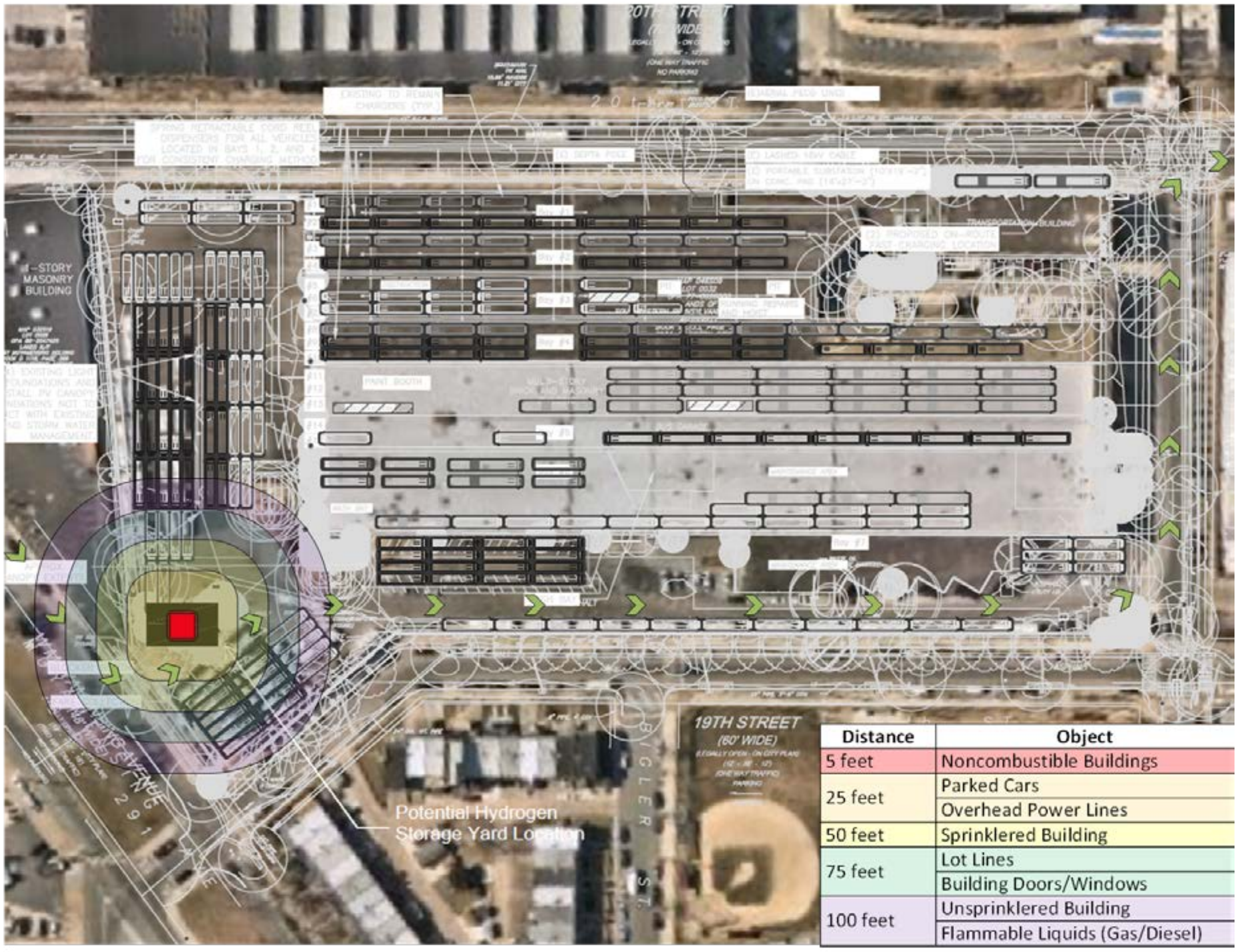
Distance	Object
5 feet	Noncombustible Buildings
25 feet	Parked Cars
	Overhead Power Lines
50 feet	Sprinklered Building
75 feet	Lot Lines
	Building Doors/Windows
100 feet	Unsprinklered Building
	Flammable Liquids (Gas/Diesel)

Frontier was rated as "Yes" with regard to having space to support FCEB fueling infrastructure. The figure below shows a hydrogen fuel yard potentially placed in the existing outdoor bus parking area; this would require reconfiguring the parking. Fuel dispensers could be placed in a new outdoor location. The setbacks related to the fueling infrastructure could potentially be reduced through use of firewalls, dependent on the local authority having jurisdiction.

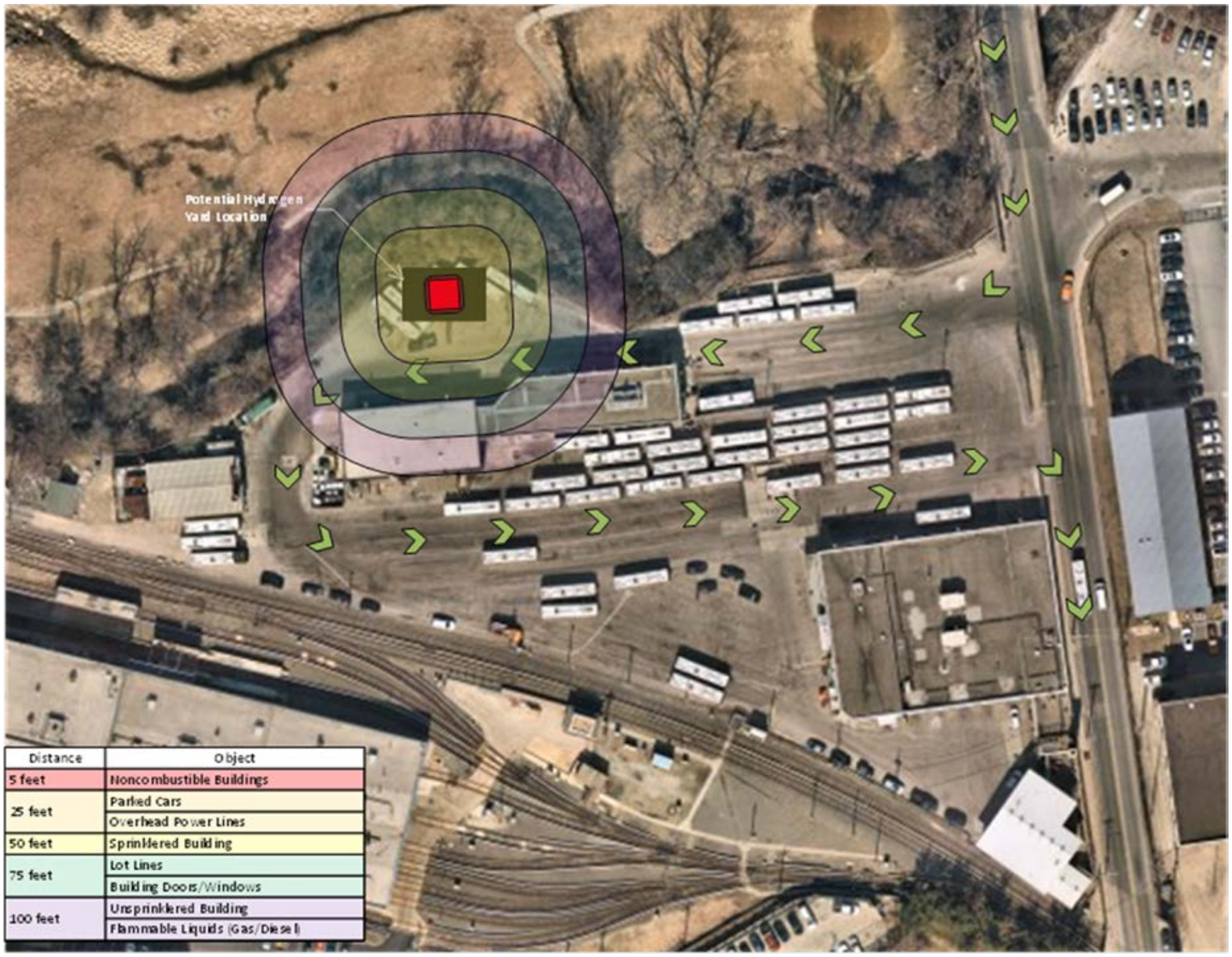


Distance	Object
5 feet	Noncombustible Buildings
25 feet	Parked Cars
	Overhead Power Lines
50 feet	Sprinklered Building
75 feet	Lot Lines
	Building Doors/Windows
100 feet	Unsprinklered Building
	Flammable Liquids (Gas/Diesel)

Midvale was rated as “Yes” with regard to having space to support FCEB fueling infrastructure. The figure below shows a hydrogen storage yard placed aboveground in an existing auto parking lot. The setbacks from property lines would need to be confirmed and may benefit from firewalls that allow reduced setbacks, dependent on the local authority having jurisdiction. Fuel dispensers could be located in existing fueling lanes. A potential challenge for further investigation here may be interference with an existing sewer easement.



Southern was rated as “Maybe” with regard to having space to support FCEB fueling infrastructure. The figure below shows hydrogen fuel storage placed in an existing outdoor bus parking area; this would require reconfiguring the parking. Fuel dispensers could be placed in a new outdoor location. The fuel storage location would need to be confirmed to meet property line setbacks and would depend upon the use of firewalls to reduce setbacks, dependent on the local authority having jurisdiction.



Victory was rated as "Maybe" with regard to having space to support FCEB fueling infrastructure. The figure below shows hydrogen fuel storage placed in an existing outdoor bus parking area; this may require reconfiguring the parking. Fuel dispensers could be placed in existing fueling lanes. The precise fuel tank location would need to be confirmed to meet property line setbacks, and it may need to shift away from Cobbs Creek. The use of firewalls could reduce setbacks, dependent on the local authority having jurisdiction.

Please note that these findings represent a preliminary assessment, and further study will be needed to confirm the feasibility of accommodating FCEB fueling infrastructure at SEPTA bus depots. Specifically, SEPTA should pursue the following next steps:

- → Further explore feasibility of facilities rated as "maybe" based on use of firewalls, existing fireproof building characteristics and local requirements of the authority having jurisdiction.
- → Investigate acquiring additional property for fueling operations for Allegheny and Callowhill.
- → Evaluate the full range of building upgrades that would be required by the authority having jurisdiction.

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The range of potential infrastructure costs for facility upgrades to accommodate FCEBs were estimated using the spreadsheet below:

Tank Size	18000	gallons
Days Storage	1.9	days
Buses/hr	6	Dispenser throughput
Window	8	hours for fueling
Spares	20%	Unused buses
Bay Capacity	20	buses/bay

Stout, Thomas: Estimated total daily quantity of hydrogen required for the active fleet.

Stout, Thomas: Number of maintenance bays that need upgraded to support this fleet size.

Stout, Thomas: Number of sets of tanks, pumps, and vaporizers required. Cost includes all these components that are needed per tank.

Stout, Thomas: Number of dispensers needed to support the active fleet per day.

Stout, Thomas: Number of station modules required to support the required dispensers.

Adjusted kg to reflect actual milege per district; only tank numbers and respective costs impacted

District	Space	40' Buses	60' Buses	Total kg	Bays	Low$	High$	Tanks	Low$	High$	Dispensers	Low$	High$	Stations	Low$	High$	Low$	High$	Days H2
					$/each	$1,000,000	$1,500,000		$7,000,000	$10,000,000		$75,000	$100,000		$150,000	$200,000			
Allegheny	No	42	81	1433	7	$7,000,000	$10,500,000	1	$7,000,000	$10,000,000	3	$225,000	$300,000	1	$150,000	$200,000	$14,375,000	$21,000,000	3.37
Callowhill	No	181	0	1727	10	$10,000,000	$15,000,000	1	$7,000,000	$10,000,000	4	$300,000	$400,000	2	$300,000	$400,000	$17,600,000	$25,800,000	2.79
Comly	Maybe	165	20	2177	10	$10,000,000	$15,000,000	1	$7,000,000	$10,000,000	4	$300,000	$400,000	2	$300,000	$400,000	$17,600,000	$25,800,000	2.22
Frankford	Maybe	146	0	1410	8	$8,000,000	$12,000,000	1	$7,000,000	$10,000,000	3	$225,000	$300,000	1	$150,000	$200,000	$15,375,000	$22,500,000	3.42
Frontier	Yes	102	0	2037	6	$6,000,000	$9,000,000	1	$7,000,000	$10,000,000	2	$150,000	$200,000	1	$150,000	$200,000	$13,300,000	$19,400,000	2.37
Midvale	Yes	229	83	3414	16	$16,000,000	$24,000,000	2	$14,000,000	$20,000,000	6	$450,000	$600,000	2	$300,000	$400,000	$30,750,000	$45,000,000	2.83
Southern	Maybe	207	21	2250	12	$12,000,000	$18,000,000	1	$7,000,000	$10,000,000	4	$300,000	$400,000	2	$300,000	$400,000	$19,600,000	$28,800,000	2.14
Victory	Maybe	176	0	2439	9	$9,000,000	$13,500,000	1	$7,000,000	$10,000,000	3	$225,000	$300,000	1	$150,000	$200,000	$16,375,000	$24,000,000	1.98

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Appendix I: Environmental Benefits

Emissions impacts associated with our ZEB transition scenarios were modeled using a similar approach to the cost modeling described in Appendix E. The specific pollutants included in our analysis are described below.

Emissions Inputs

CO_2 Emissions

Emissions of CO_2 were calculated annually for each bus. Hybrid buses generate 10.21 kg CO_2 per gallon of diesel fuel.[37] The power used by BEBs, provided by the regional transmission organization PJM, produces 791 lbs CO_2 per MWh, and we assume this emissions rate continues declining at a rate of 2.6% annually.[38] Hydrogen fuel produced via SMR generates 9.0 kg CO_2 per kg hydrogen.[39] Emissions from fuel delivery were also estimated using trucking emissions rates published by USEPA. Delivery distances were assumed to be 30 miles for diesel and 712 mi for hydrogen (the median of suppliers after values over 1,000 miles were removed.)

NO_x Emissions

Emissions of NO_x were calculated annually for each bus. Hybrid buses generate 10.4 g NO_x per gallon of diesel fuel.[40] The power used by BEBs produces 0.36 lbs NO_x per kWh, and we assume this emissions rate continues declining at a rate of 5.7% annually.[41] Hydrogen fuel produced via SMR generates 0.839 g NO_x per kg hydrogen.[42] Emissions from fuel delivery were also estimated using trucking emissions rates published by USEPA.

$PM_{2.5}$ Emissions

Emissions of $PM_{2.5}$ were also calculated annually for each bus. Hybrid buses generate 0.119 g $PM_{2.5}$ per mile,[43] while the power used by BEBs produces 0.0481 lbs $PM_{2.5}$ per kWh.[44] A source for projected $PM_{2.5}$ over time was not available. Hydrogen fuel produced via SMR generates 0.329 g

37 2018 USEPA Emission Factors for Greenhouse Gas Inventories

38 2020 PJM Emissions Rate Report

39 Hydrogen SMR emissions rates from Argonne National Laboratory. Updates of Hydrogen Production from SMR Process in GREET, 2019.

40 California Air Resources Board, Emission Factor Tables September 2019.

41 2020 PJM Emissions Rate Report

42 EPA Estimated U.S. Average Vehicle Emissions Rates per Vehicle by Vehicle Type Using Gasoline and Diesel, 2020

43 Hydrogen SMR emissions rates from Argonne National Laboratory. Updates of Hydrogen Production from SMR Process in GREET, 2019.

44 2020 Estimating Particulate Matter Emissions for eGRID

$PM_{2.5}$ per kg hydrogen.[45] Emissions from fuel delivery were also estimated using trucking emissions rates published by USEPA.

Environmental Benefits

Finally, our modeling demonstrates that converting to a ZEB fleet will yield significant environmental benefits to SEPTA's service area. The projected emissions reductions consider not only tailpipe emissions, but also upstream emissions related to power generation, fuel production, and delivery. At the end of a transition to an all BEB scenario, annual CO_2 emissions would be 74% less, NO_x emissions would be 94% less, $PM_{2.5}$ emissions would be 45% less, and noise impacts would be 37% less compared to pre-transition figures.

At the end of a transition to the FCEB scenario, annual CO_2 emissions would be 53%-91% less, NO_x emissions would be 91%-95% less, $PM_{2.5}$ emissions would be 58%-86% less. (The range of values depends on whether SEPTA uses "gray" hydrogen produced from fossil fuels via the SMR process, or "green" hydrogen produced using electricity generated from renewable energy sources. As noted earlier, SEPTA's choice of hydrogen fuel type will prioritize more sustainable options to the extent they are available; more detail about the types of hydrogen is presented in ***Chapter 4***.). Note that these projections include both emissions from energy/fuel and from daily fuel delivery to each depot. Fuel delivery can be a substantial source of emissions, given that the nearest hydrogen supplier to SEPTA is over 300 miles away.

The detailed comparison of projected emissions under diesel hybrid, BEB, and FCEB scenarios are shown in ***Figure 28***. These include emissions from tailpipe emissions, power generation, fuel production, and fuel delivery. The emissions reductions will benefit local public health as well as global climate sustainability.

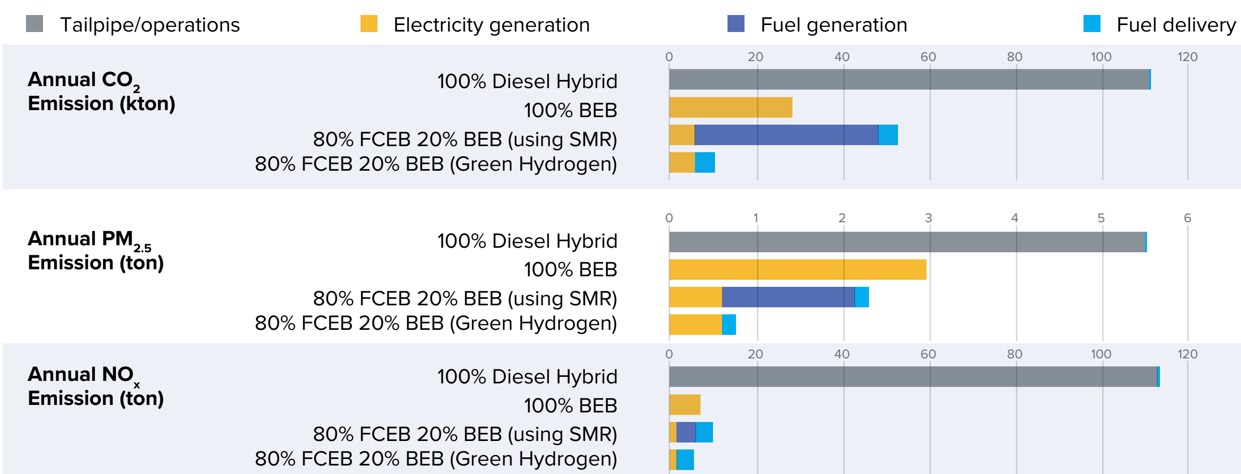

Figure 28 *– Graphs comparing environmental impacts before a fleet transition and at the end of a fleet transition*

45 Hydrogen SMR emissions rates from Argonne National Laboratory. Updates of Hydrogen Production from SMR Process in GREET, 2019.

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LA Metro
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Champaign–Urbana Mass Transit District
Alameda-Contra Costa Transit District
Stark Area Regional Transit Authority
SunLine Transit Agency

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