LIVERMORE AMADOR VALLEY TRANSIT AUTHORITY

STAFF REPORT

SUBJECT: Zero-Emission Bus Study Update

FROM: Toan Tran, Director of Operations and Innovation

DATE: September 13, 2021

Action Requested
No action required.

Background
Under the California Air Resources Board's (CARB) Innovative Clean Transit Rule, LAVTA's new bus purchases are required to be a minimum of 25% ZEBs beginning in 2026 and ramping up to 100% in 2029, with the goal of transitioning the state's entire transit fleet to 100% ZEBs by 2040.

LAVTA has been working with the Center for Transportation and the Environment (CTE) to perform a ZEB study. The goal of the study is to develop a board-approved transition plan outlining the capital projects required to fully electrify the fleet in accordance with the CARB Innovative Clean Transit Rule and LAVTA's local priorities by July 1, 2023.

Discussion
The study analyzed several different zero-emission fleet scenarios and the resources and costs required, and compared them to a baseline. The scenarios were:

1. Battery electric fleet only;
2. Battery electric and fuel cell electric mixed fleet;
3. Fuel cell electric only fleet,

In each scenario, CTE assessed the assumptions and requirements for LAVTA's routes, service and operations, fleet replacement plan timeline, fuel and charging, facilities and infrastructure, maintenance, associated capital costs, and total cost of ownership.

CTE will provide a presentation to the Board of Directors on the overview and findings of the study. Attachment 2 is a draft of the Master Transit Plan for your review in the next few weeks.

Recommendation
None – information only.

Attachments:
1. ZEB Transition Study Update presentation
2. ZEB Master Transition Plan Draft

Approved: ________________________

Attachment 1

LAVTA ZEB Transition Study Update

September 14, 2021

Steve Clermont, Director of Planning & Deployment
Savannah Gupton, Lead Managing Consultant
Niki Rinaldi El-Abd, Lead Associate

About CTE

WHO WE ARE

501(c)(3) nonprofit engineering and planning firm

OUR MISSION

Improve the health of our climate and communities by bringing people together to develop and commercialize clean, efficient, and sustainable transportation technologies

PORTFOLIO

$600+ million

- *Research, demonstration, deployment*
- *118 Active Projects totaling over $316 million*

OUR FOCUS

Zero-Emission Transportation Technologies

NATIONAL PRESENCE

Atlanta, Berkeley, Los Angeles, St. Paul

CTE Service Areas

Prototype Development & Demonstration

We support technology providers' cutting edge pilots.

Smart Deployment

We support early adopters with technical solutions.

Fleet Transition

We help fleet operators implement strategic plans.

Education & Outreach

We help organizations of all shapes and sizes stay ahead of the technology curve.

CARB Innovative Clean Transit Regulation

100% ZEB Fleet by 2040 is not a mandate, but a goal

There is only a *purchasing* mandate:

ZEB Purchase Requirements

Starting January 1	ZEB Percentage of Total New Bus Purchases
2026	25%
2027	25%
2028	25%
2029	100%

- Small CA Transit Agencies (<100 buses) are required to submit a board-approved ZEB Rollout Plan by **July 1, 2023.**
- **If the available depot-charged battery electric buses cannot meet a transit agency's daily mileage needs, the agency may request an exemption**

Battery Electric Buses & Fuel Cell Electric Buses

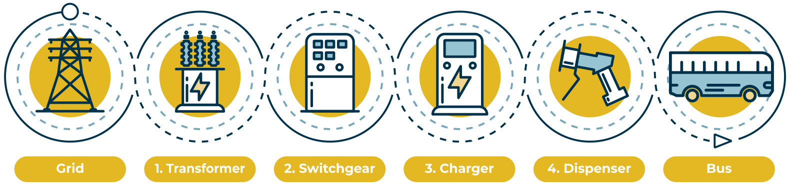
Battery Electric Buses (BEBs)

- May need to increase fleet size
- Fueling time longer than ICE bus
- Fuel cost highly variable could be higher or lower than fossil fuels
- BEB bus cost approximately 50% higher than ICE bus
- Infrastructure costs increases per bus when scaled up

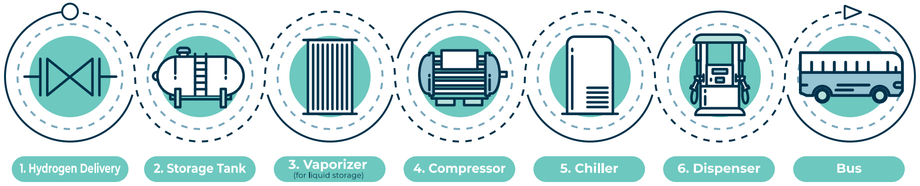
Fuel Cell Electric Buses (FCEB)

- Comparable range to ICE bus – 1:1 replacement ratio
- Fueling time comparable to ICE bus
- Fuel cost significantly higher than fossil fuel
- Bus cost significantly higher than ICE bus
- Infrastructure costs reduce per bus when scaled up
- Greater resilience

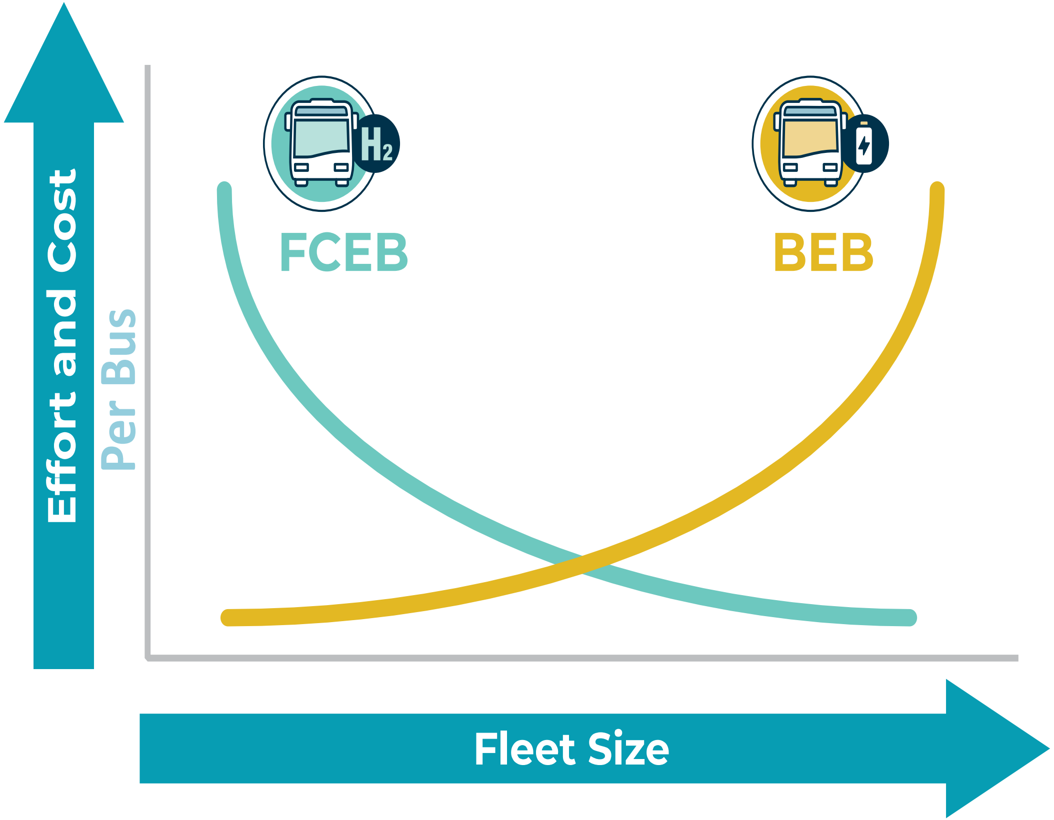
BEB Fuel Delivery Pathway



FCEB Fuel Delivery Pathway

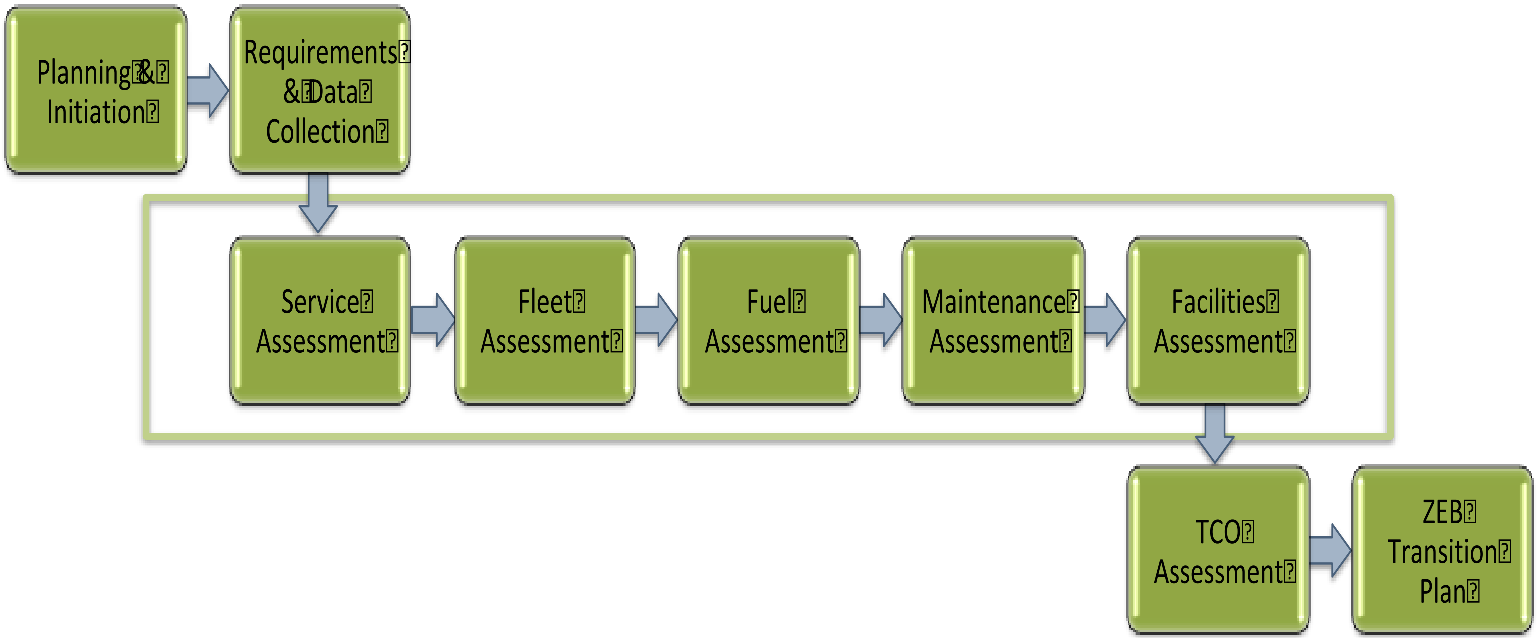


ZEB Infrastructure Scalability

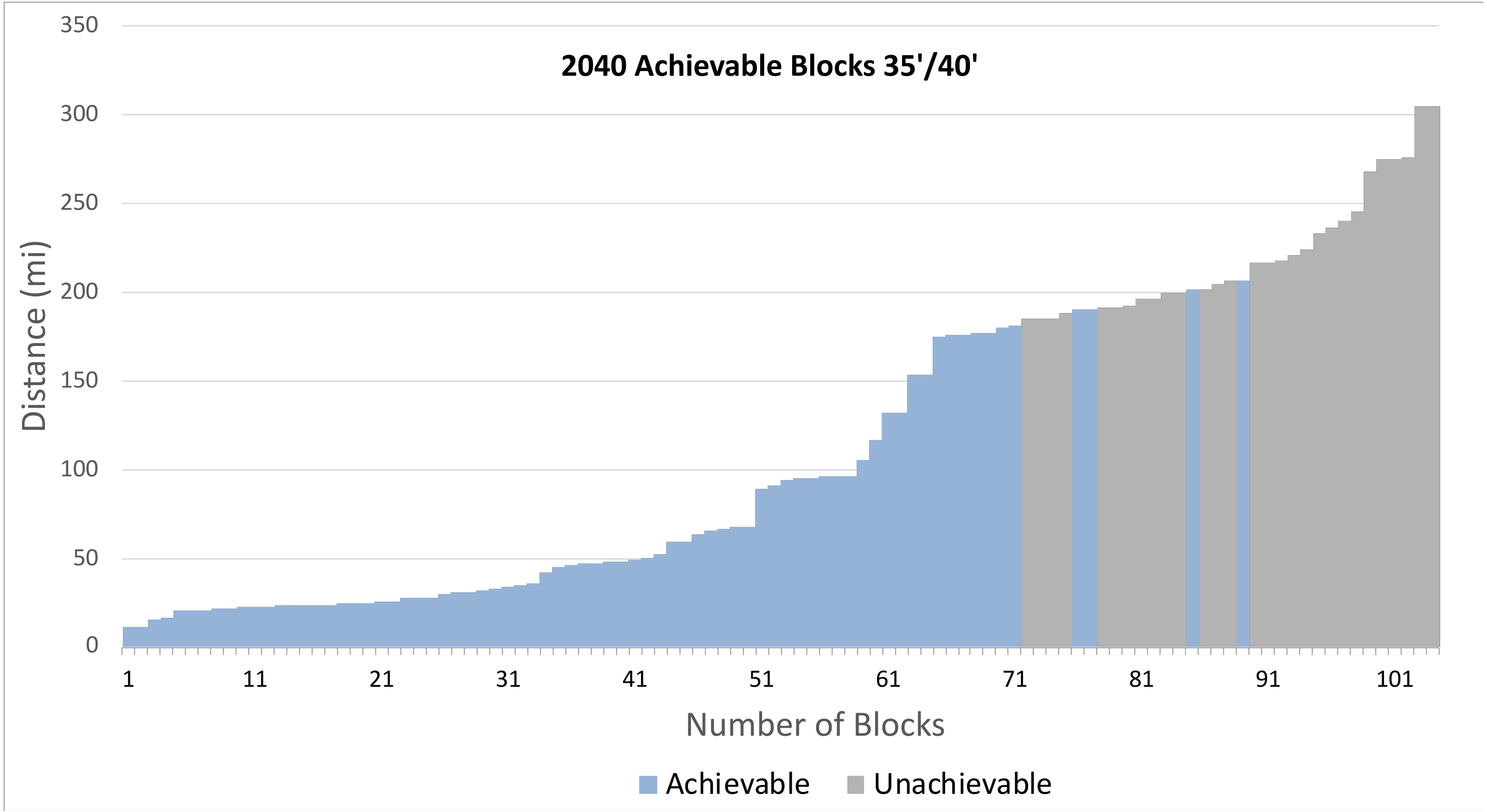


- FCEB: High initial cost for H2 fueling stations can be leveraged over many buses in larger fleets
- BEB: More equipment and infrastructure is needed to support larger fleets

ZEB Transition Methodology



Overnight Depot- Charged Battery-Electric Bus Service



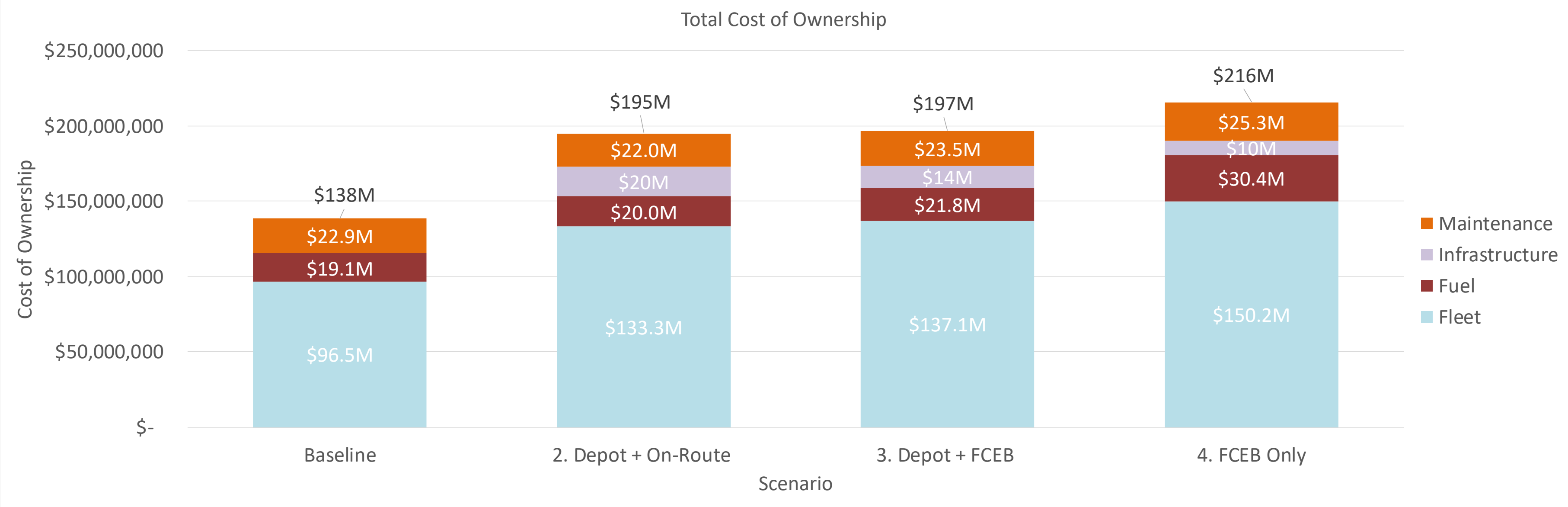
ZEB Technology Fleet Transition Scenarios

ZEB technology solutions required to achieve a 100% zero-emission fleet transition

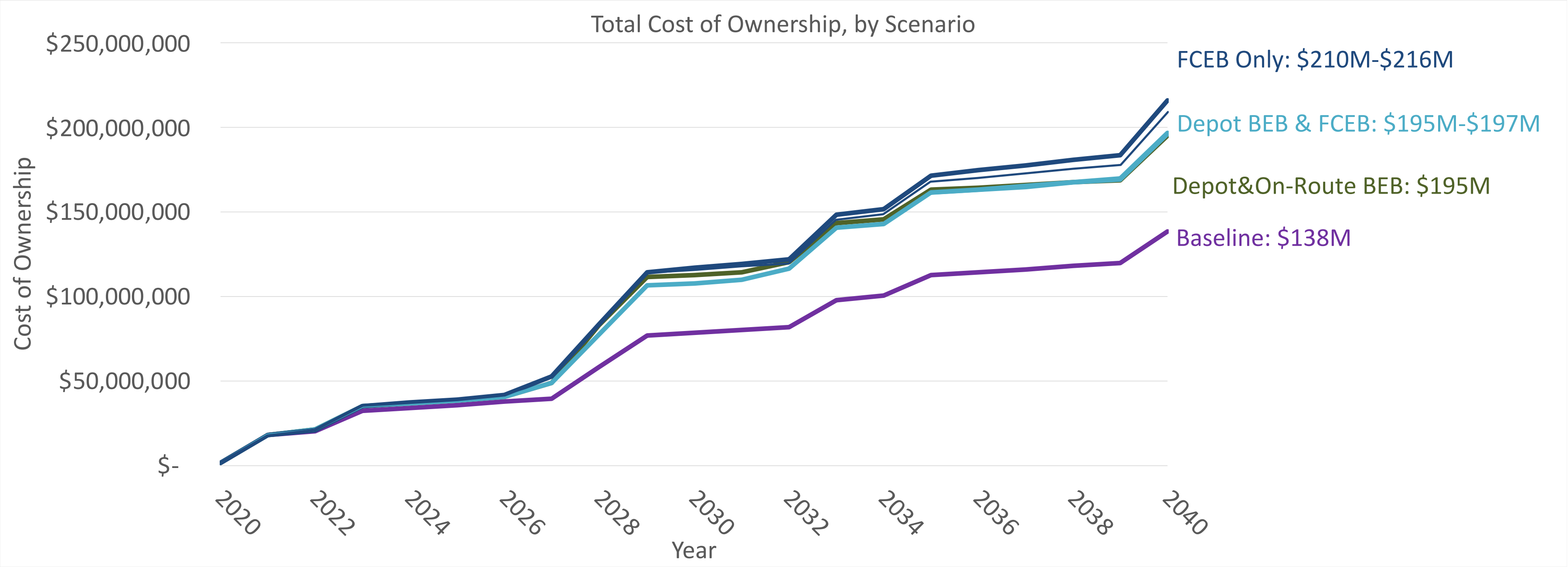
1. Depot & on-route charged battery-electric buses (BEBs)
2. Depot charged battery-electric buses (BEBs) & fuel cell electric buses (FCEBs)
3. Fuel cell electric buses (FCEBs) only

Total Cumulative Capital & Operating Costs

All Scenarios, 2020-2040



Cumulative Total Cost of Ownership Summary



*Includes fuel sensitivity analysis for future lower cost H_2

Considerations for ZEB Transition Selection

1. BEB Fleet, Depot & On-Route Charge	2. Mixed Fleet, Depot Charged BEBs & FCEBs	3. FCEB Only Fleet
- Operationally challenging, may require schedule and/or service changes due to on-route charging requirement	+ Two technologies provide greater redundancy and resilience benefits; less reliant on the grid	+ Operationally similar to current fleet. No service or schedule changes are required due to the technology
- Acquisition costs for on-route charger location is unaccounted for in scenario costs	- Operationally challenging due to the creation of sub fleets by technology	+ Anticipated fuel price reduction due to regional renewable H_2 supply developments
- Requires major infrastructure and operations restructuring in the depot	- Two different fueling infrastructures will be required at depot	+ Potential to leverage local station development and fueling access to significantly reduce initial capital infrastructure investment for LAVTA for early FCEB adoption

Next Steps

- Seek input and approval of ZEB Master Transition Plan at the September P&S and October BOD meetings
- Seek approval ZEB Rollout Plan at the November BOD meeting

Questions?

Attachment 2

Livermore-Amador Valley Transit Authority Zero-Emission Bus Fleet Transition Study

Presented by: The Center for Transportation and the Environment

Date: August 11, 2021

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Executive Summary

Livermore-Amador Valley Transit Authority (LAVTA) engaged the Center for Transportation and the Environment (CTE) to perform a zero-emission bus (ZEB) transition study in May 2020. The study's goal is to create a plan for a 100% zero-emission fleet by 2040 to comply with the Innovative Clean Transit (ICT) regulation enacted by the California Air Resources Board (CARB). The results of the study will inform LAVTA Board members and LAVTA staff of the estimated costs, benefits, constraints, and risks of the transition to a zero-emission fleet and will guide future planning and decision-making.

On December 14, 2018, CARB enacted the ICT regulation, setting a goal for California public transit agencies to have 100% zero-emission fleets by 2040. The ruling specifies the percentage of new bus procurements that must be zero-emission for each year of the transition period (2023 – 2040). Those annual percentages are outlined in **Table 1** below.

Table 1 - ICT ZEB Percentage Requirements

Starting January 1	ZEB Percentage of Total New Bus Purchases
2026	25%
2027	25%
2028	25%
2029	100%

This schedule lays out a pathway to reaching 100% zero-emission fleets in 2040 based on a 12-year projected lifespan for a transit bus. There is the opportunity to request waivers, however, that allow purchase deferrals in the event of economic hardship or if zero-emission technology has not matured enough to meet the service requirements of a given route. These concessions recognize that zero-emission technologies may cost more than current internal combustion engine (ICE) technologies on a lifecycle basis and that zero-emission technology may not currently be able to meet all service requirements.

Zero-emission technologies considered in this study include battery-electric buses (BEB) and hydrogen fuel cell electric buses (FCEB). BEBs and FCEBs have similar electric drive systems that feature a traction motor powered by a battery. The primary differences between BEBs and FCEBs are the respective amount of battery storage and the method by which the batteries are recharged. The energy supply in a BEB comes from electricity provided by an external source, typically the local utility's electrical grid, which is used to recharge the batteries. The energy supply for an FCEB is on-board the bus, where hydrogen, stored in tanks, is converted to electricity using a fuel cell. The electricity from the fuel cell is used to recharge the batteries. The electric drive components and energy source for a BEB and FCEB are illustrated in **Figure 1.**

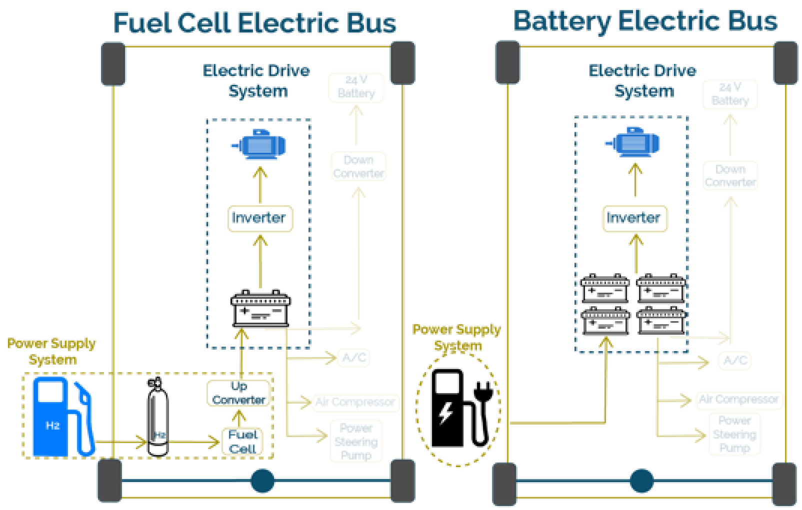

Figure 1 – Battery and Fuel Cell Bus Schematic

CTE worked closely with LAVTA staff throughout the project to develop an approach, define assumptions, and confirm the results. The approach for the study is based on analysis of three ZEB technology scenarios compared to a baseline scenario:

1. Baseline
2. BEB Only
3. Mixed Fleet: BEB and FCEB
4. FCEB Only

To accurately project service feasibility for each of these zero-emission technologies, CTE then assessed the block achievability of LAVTA's current service schedules. Block achievability is determined by comparing the estimated energy required to operate a BEB on a given block to the usable onboard energy storage capacity of the bus. If the block energy requirement exceeds the onboard storage capacity, the block is considered unachievable. If the block energy requirement does not exceed the usable onboard storage capacity, the block is considered to be achievable. Although not a zero-emission scenario, this study also includes a baseline scenario that is used to compare the cost of a ZEB transition to a "business-as-usual" case (i.e., without the need to meet ICT requirements).

The BEB Only scenario was developed to model a fleet option with a fleet consisting entirely of battery electric buses that can meet existing service range requirements. Fleets consisting of BEBs that only charge at a depot may not be able to meet the range requirements of many routes and require additional time returning to the depot to charge. These constraints would necessitate additional bus purchases to cover the charging times. On-route charging mitigates the possible need for additional bus purchases by extending the range of in-service buses and reducing the depot time necessary for charging. A uniform technology throughout the fleet allows for the installation of a single fueling technology at the depot. The challenges of on-route charging are finding space along the routes for chargers and the additional costs of land acquisition, equipment, and infrastructure installation.

A Mixed Fleet: BEB and FCEB scenario was developed with the assumption that all of the blocks that could be achieved with depot only charged BEBs. Because the range of FCEBs exceeds that of BEBs, FCEBs are capable of completing blocks that BEBs cannot and are modeled therefore to replace ICE buses at a 1:1 ratio. FCEBs and hydrogen, however, are more expensive than BEBs and electricity, so a mixed fleet allows an agency to use the less expensive BEB technology where possible and cover service needs with FCEBs as needed. A mixed fleet is also more resilient to service interruptions if either fuel becomes temporarily unavailable. For agencies such as LAVTA that operate only one depot, however, mixed fleets present the spatial challenge of hosting both infrastructure types in one depot.

The FCEB scenario was developed to help identify benefits and mitigate challenges associated with switching the entire fleet to fuel cell technology. An FCEB fleet could replace ICE buses on a 1:1 ratio and avoids the need to install two types of fueling infrastructure or purchase additional land for on-route charging. A FCEB fleet, however, lacks the redundancy provided by diverse fuels that a mixed fleet utilizes. Additionally, the cost of the buses and fuel for this scenario make an FCEB fleet the most expensive option despite the savings in infrastructure costs compared to a large-scale fleet transition to BEBs.

Improvements in technology are expected, but there is no indication of when BEB technology may improve to the point of one-for-one replacement of internal combustion engine buses or when the cost of FCEBs and hydrogen fuel will decrease to cost-competitive levels. Given these unknowns and the possible rapid changes in zero-emission technologies as interest in the field grows, this study presents a range of estimated costs that can be expected for LAVTA's ZEB fleet transition.

The underlying basis for the assessment is CTE's ZEB Transition Planning Methodology, a complete set of analyses used to inform agencies planning the conversion of their fleets to zero-emission technologies. The methodology consists of data collection, analysis, and evaluation stages; these stages are sequential and build upon findings in previous steps. In the evaluation stage, CTE assesses energy efficiency and energy use by the buses to calculate the distance that a bus will be able to travel on a single charge or hydrogen fill. CTE collected sample data from eight of LAVTA's routes. Then, using generic ZEB battery capacity specifications for given bus lengths, CTE estimated range and energy consumption on all LAVTA routes and blocks under varying environmental and passenger load conditions. Once this information was established, CTE completed the following assessments to develop cost estimates for each of the three scenarios:

The **Fleet Assessment** develops a projected timeline for replacement of current buses with ZEBs that is consistent with the agency's fleet replacement plan. This assessment also includes a projection of fleet capital cost over the transition lifetime and it can be optimized with regard to any state mandates, like CARB's ICT regulation, or to meet agency goals, such as minimizing cost or maximizing service levels.

The **Fuel Assessment** merges the results of the Service Assessment and Fleet Assessment to determine annual fuel requirements and associated costs. The Fuel Assessment calculates energy costs through the full life of the transition, including the agency's current fossil fuel buses. As current technologies are phased out in later years of the transition, the Fuel Assessment calculates the increasing energy requirements for ZEBs. The Fuel Assessment also provides a total energy cost over the transition lifetime.

The **Facilities Assessment** determines the necessary infrastructure to support the projected zero-emission fleet based on results from the Fleet Assessment and Fuel Assessment. The Facilities Assessment is calculated to meet the fleet procurement schedules defined in the Fleet Assessment and the and fueling capacity required based on the Fuel Assessments. The result shows quantities of hydrogen and battery electric infrastructure and calculates associated costs.

The **Maintenance Assessment** calculates all projected fleet maintenance costs over the life of the project. This includes costs related to existing fossil fuel buses remaining in the fleet, as well as new BEBs.

The **Total Cost of Ownership Assessment** compiles results from the previous assessment stages and provides a comprehensive view of all associated costs, over the transition lifetime. The table and figure below provide a side-by-side comparison of the cumulative transition costs for each scenario.

Table 2 - Total Cost of Ownership, by Scenario

Assessment Type	Baseline	BEB Only	Mixed Fleet: BEB and FCEB	FCEB Only
Fleet	$ 96,507,000	$ 133,274,000	$ 137,106,000	$ 150,188,000
Fuel*	$ 19,050,000	$ 19,965,000	$ 21,833,000	$ 30,399,000
Infrastructure	$ 0	$ 19,955,000	$ 14,427,000	$ 9,752,000
Maintenance	$ 22,902,000	$ 21,961,000	$ 23,536,000	$ 25,303,000
Total	**$ 138,459,000**	**$ 195,155,000**	**$ 196,902,000**	**$ 215,642,000**
% ZEB in 2040	**0%**	**100%**	**100%**	**100%**

*Excludes any potential LCFS credit revenue

Battery Electric Bus Only Scenario

As seen in **Table 2**, in an all BEB strategy, ZEB transition costs are likely to be $195 million for the BEB Only scenario (100% of LAVTA's fleet is replaced with BEBs by 2035 without adding additional buses). The costs shown in this graph increase over time because they are cumulative. The capital and maintenance costs for FCEBs exceed the additional costs from on-route charging infrastructure and utility costs in the BEB scenario. The difference in cost between the Baseline and BEB scenario is largely the result of higher capital costs for BEBs compared to diesel-hybrid buses and the fact that infrastructure is already in place for diesel fueling. It should be noted that only 40-foot buses were considered in all ZEB transition scenarios. These parameters were based on LAVTA's current fleet structure and planned procurements, which include replacing 30-foot buses that are currently in their fleet with 40-foot buses going forward. Also, these bus lengths have passed Altoona testing and are thus allowable under the CARB ICT regulation.

Mixed Fleet: BEB and FCEB Scenario

The Mixed Fleet: BEB and FCEB scenario resulted in a total cost of approximately $197 million. Though the costs are less for a mixed fleet deployment than for the FCEB Only deployment, there is the added complexity of installing infrastructure for both fuel types. Since LAVTA has only one depot, the space constraint of installing both infrastructure types may be a challenge. Compared to ICE buses, ZEBs may require significantly less maintenance since their engines require no fluids and have fewer components to maintain.[1] It is possible then that a ZEB fleet would require fewer maintenance bays than an ICE fleet, possibly further reducing space constraints.

Fuel Cell Electric Bus Only Scenario

In the FCEB Only scenario, ZEB transition costs are estimated at $216 million for replacement of 100% of the fleet with FCEBs by 2035. A primary assumption for the FCEB Only scenario is that 40-foot fuel cell electric buses will be available during the entire transition period. It is expected that, due to the limited deployment of FCEBs in service in the United States, capital costs for these buses and hydrogen fuel costs will remain high in the near-term due to low market competition which is expected to change; however, more data is needed to adequately project these cost decreases. As such, this study uses current FCEB and infrastructure pricing for the entirety of the ZEB transition period.

For estimates of FCEB maintenance costs, CTE used data reported from Orange County Transit Authority's (OCTA) FCEB fleet of 10 New Flyer buses in their first year of operation. Fuel cell technology was new to OCTA and, as a result, the maintenance costs were higher than expected. OCTA does expect reductions in the long run. Given the necessary reliance on this early-adoption maintenance data, FCEB maintenance cost data has a wider error margin than BEB cost estimates. More concrete data will become available, and costs will likely fall as a larger number of fuel cell electric buses and hydrogen infrastructure are deployed. Significant investments in hydrogen infrastructure may take years to materialize, however.

[1] Eudy, Leslie and Matthew Jeffers. 2018. Zero-Emission Bus Evaluation Results: County Connection Battery Electric Buses. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-72864. https://www.nrel.gov/docs/fy19osti/72864.pdf.

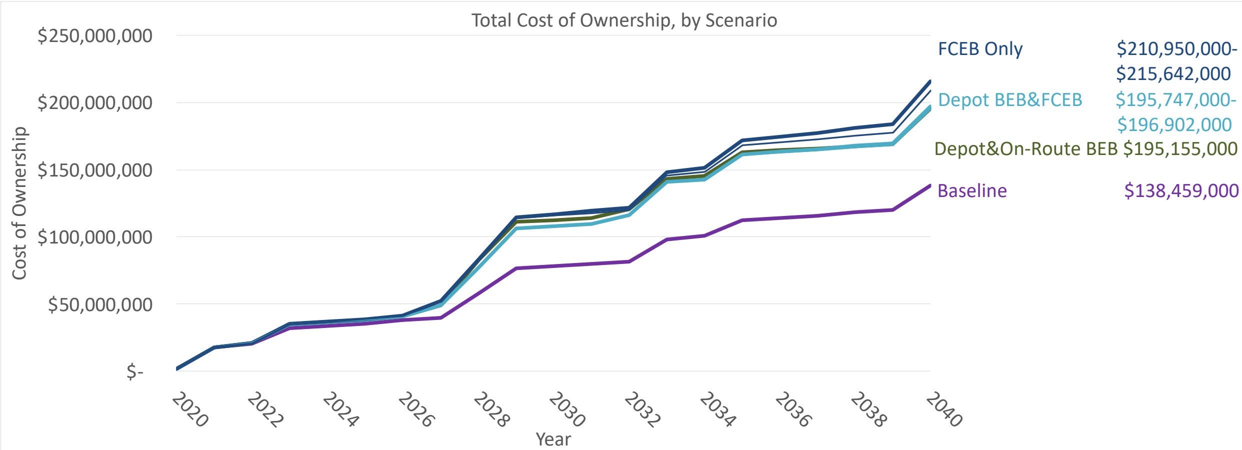

Figure 2 - Total Cost of Ownership, by Scenario

Recommendations

In addition to the uncertainty of technology improvements, there are other risks in trying to estimate costs over the 20-year transition period to consider. Although current BEB range limitations may be improved over time as a result of advancements in battery energy density and more efficient components, battery degradation may re-introduce range limitations, which is a cost and performance risk to an all-BEB fleet over time. In emergency scenarios that require use of BEBs, agencies may face challenges supporting long-range evacuations and providing temporary shelters in support of fire and police operations. Furthermore, fleetwide energy service requirements, power redundancy, and resilience may be difficult to achieve at any given depot in an all-BEB scenario. Although FCEBs may not be subject to these same limitations, higher capital equipment costs and availability of hydrogen may constrain FCEB solutions.

Given these considerations, the recommendations for LAVTA are as follows:

1. **Remain proactive with ZEB deployments:** LAVTA has been proactive in the purchase and deployment of BEBs through their ZEB Program. For successful fleetwide deployment, BEBs will require charge management software, hardware, and standards to manage the fleetwide transition. For FCEB deployment to be competitive, lower fuel costs that will evolve over time with the production of hydrogen at scale will be required. LAVTA should move forward thoughtfully, taking advantage of various grant and incentive programs to offset the incremental cost for ZEB deployment. Incentive programs may be eliminated in future years as ZEB procurements are required instead of being optional.
2. **Target specific routes and blocks for early ZEB deployments:** LAVTA should consider the strengths of given ZEB technologies and focus those technologies on routes and blocks that take advantage of their efficiencies and minimize the impact of the constraints related to the respective technologies. These technologies cannot follow a one-size-fits-all approach from either a performance or cost perspective. Matching the technology to the service will be a critical best practice. Results from early LAVTA ZEB deployment will help to inform these decisions.

The transition to ZEB technologies represents a paradigm shift in bus procurement, operation, maintenance, and infrastructure. It is only through a continual process of deployment with specific goals for advancement that the industry can achieve the goal of economically sustainable, zero-emission transportation sector.

1 Introduction

Beginning operation in 1986, LAVTA provides bus services to communities in the cities of Dublin, Livermore, Pleasanton and Alameda County. LAVTA's mission is "to provide equal access to a variety of safe, affordable and reliable public transportation choices, increasing the mobility and improving the quality of life of those who live or work in and visit the Tri-Valley area." LAVTA currently has one facility, located on Rutan Court, but will be moving to Atlantis Court by 2028:

1. LAVTA Current Facility: 1362 Rutan Court, Livermore, CA 94551
2. LAVTA Future Facility: 875 Atlantis Court, Livermore, CA 94551

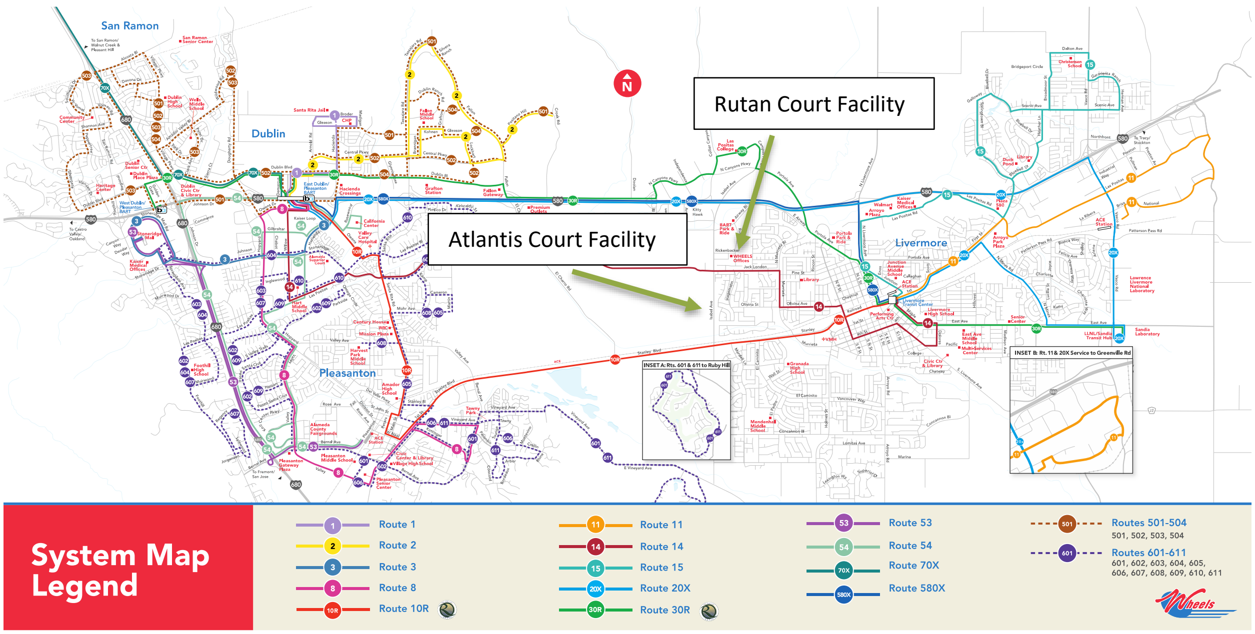

Figure 3 - LAVTA System Map Highlighting Facility Locations

LAVTA engaged CTE to perform a ZEB transition study in May 2020. The study's goal is to create a plan for a 100% zero-emission fleet by 2040 to comply with the Innovative Clean Transit (ICT) regulation enacted by California Air Resources Board (CARB). The results of the study will inform LAVTA Board members and LAVTA staff of the estimated costs, benefits, constraints, and risks of the transition to a zero-emission fleet and will guide future planning and decision-making.

Zero-emission technologies considered in this study include battery electric buses (BEBs) and hydrogen fuel cell electric buses (FCEBs). BEBs and FCEBs have similar electric drive systems that feature a traction motor powered by a battery. The primary differences between BEBs and FCEBs are the respective amount of battery storage and the method by which the batteries are recharged. The energy supply in a BEB comes from electricity provided by an external source, typically the local utility's electric grid, which is used to recharge the batteries. The energy supply for an FCEB is completely on-board, where hydrogen is converted to electricity within a fuel cell. The electricity from the fuel cell is used to recharge the batteries. The electric drive components and energy source for a BEB and FCEB are illustrated in

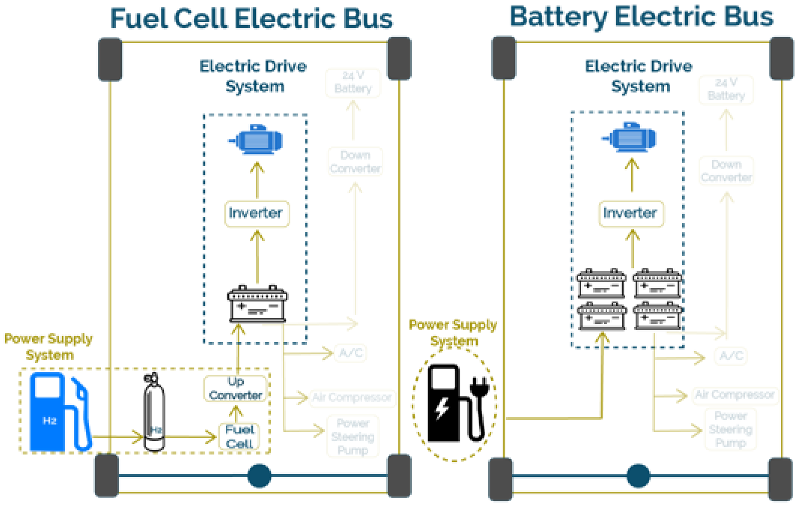

Figure 4 - Battery and Fuel Cell Electric Bus Schematic

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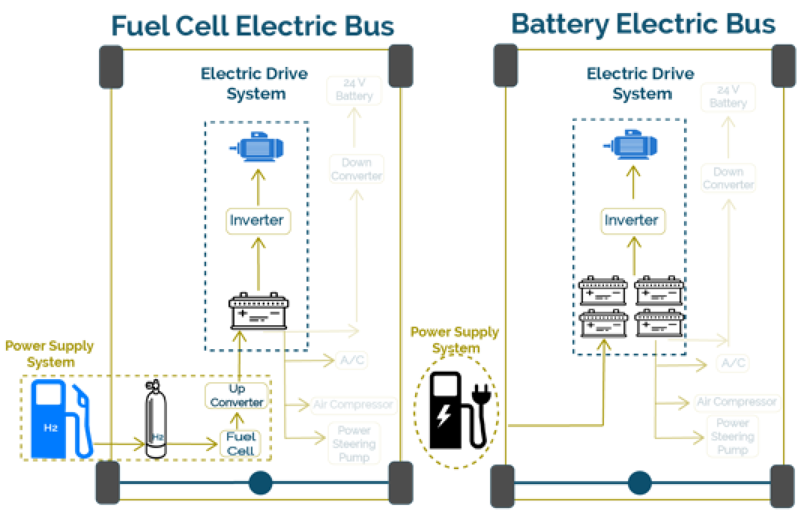

Figure 4 - Battery and Fuel Cell Electric Bus Schematic

CARB's Innovative Clean Transit Regulation

On December 14, 2018, CARB enacted the ICT regulation, requiring all California public transit agencies to purchase only ZEBs from 2029 onward, with partial ZEB purchasing requirements beginning in 2023 for large agencies, and 2026 for small agencies, with the goal of transitioning agencies to ZEB fleets. This section summarizes key elements of the ICT.

ZEB Purchase Requirements

LAVTA's fleet is designated as a small fleet by the California Air Resources Board (CARB) because the fleet does not exceed 100 vehicles at pullout. The ICT regulation requires that all new bus purchases include a specified percentage of ZEBs in accordance with the following schedule:

Table 3 – CARB Innovative Clean Transit (ICT) ZEB Transition Timeline for Small Agencies

Starting January 1	Percent of New Bus Purchases	Purchase Discharge Criteria
2023		If 850 ZEBs by 12/31/2020
2024		If 1250 ZEBs by 12/31/2020
2025		-
2026	25%	-
2027	25%	-
2028	25%	-
2029	100%	-

New bus purchase requirements may be eliminated in 2023 and 2024 if a minimum number of buses are purchased by a specified date across all transit agencies in California. ZEB bonus credits do not count toward these milestones. Purchase of a cutaway bus, over-the-road bus, double-decker bus, or articulated bus may be deferred until either January 1, 2026 or until a model of a given type has passed the Altoona bus testing procedure and obtained a Bus Testing Report, regardless of if purchasing milestones are met or not.

ZEB Bonus Credits

Agencies may earn bonus credits for early acquisition of ZEBs, which may be used against future compliance requirements. To earn bonus credits, ZEBs must be placed into service according to the following schedule. Bonus credits expire on December 31, 2028.

Table 4 - ZEB Bonus Credits Applied to CARB ICT Transition Schedule

Technology	Placed in Service	ZEB Bonus Credit
BEB	Before January 1, 2018	1
FCEB	Before January 1, 2018	2
FCEB	January 1, 2018 to December 31, 2022	1

Since LAVTA does not plan to purchase any ZEBs until 2023, it will not be eligible to receive these credits for their purchases.

ZEB Rollout Plan

LAVTA is required to submit a ZEB Rollout Plan to CARB that has been approved by their governing board by July 1, 2023. ZEB Rollout Plans must include all of the following components:

- A goal of full transition to ZEBs by 2040 with careful planning that avoids early retirement of conventional internal combustion engine (ICE) buses;

- Identification of the types of ZEB technologies a transit agency is planning to deploy, such as battery-electric or fuel cell electric buses;
- A schedule for construction of facilities, infrastructure modifications, or upgrades including charging, fueling, and maintenance facilities to deploy and maintain ZEBs. This schedule must specify the general location of each facility, type of infrastructure, service capacity of an infrastructure, and a timeline for construction;
- A schedule for zero-emission and conventional ICE bus purchases and lease options. This schedule for bus purchases replacements must identify the bus types, fuel types, and number of buses;
- A schedule for conversion of conventional ICE buses to ZEBs, if any. This schedule for bus conversion must identify number of buses, bus types, the propulsion systems being removed and converted to;
- A description on how a transit agency plans to deploy ZEBs in disadvantaged communities as listed in the latest version of CalEnviroScreen at the time the Rollout Plan is submitted;
- A training plan and schedule for ZEB operators and maintenance and repair staff; and
- The identification of potential funding sources.

Exemptions

Agencies may request exemptions from ZEB purchase requirements in a given year due to circumstances beyond the transit agency's control. Acceptable circumstances include:

- Delay in bus delivery caused by setback of construction schedule of infrastructure needed for the ZEB;
- Available depot-charged BEBs cannot meet a transit agency's daily mileage needs;
- Available ZEBs do not have adequate gradeability performance to meet the transit agency's daily needs;
- When a required ZEB type for the applicable weight class [based on gross vehicle weight rating (GVWR)] is unavailable for purchase because the ZEB has not passed Altoona, cannot meet ADA requirements, or would violate any federal, state, or local regulations or ordinances;
- When a required ZEB type cannot be purchased by a transit agency due to financial hardship.

Reporting Requirements

Starting March 31, 2021 and continuing every year thereafter through March 31, 2050, each transit agency must submit an annual ICT ZEB compliance report by March 31 for the prior calendar year. The initial report must be submitted by March 31, 2021 and must include the number and information of active buses in the transit agency's fleet as of December 31, 2018.

2 ZEB Transition Planning

Methodology

This study uses CTE's ZEB Transition Planning Methodology, which is a complete set of analyses, used to inform agencies converting their fleets to zero-emission technology. The methodology consists of data collection and analysis and assessment stages; these stages are sequential and build upon findings in previous steps. The work steps specific to this study are outlined below:

1. Planning and Initiation
2. Requirements & Data Collection
3. Service Assessment
4. Fleet Assessment
5. Fuel Assessment
6. Facilities Assessment
7. Maintenance Assessment
8. Total Cost of Ownership Assessment

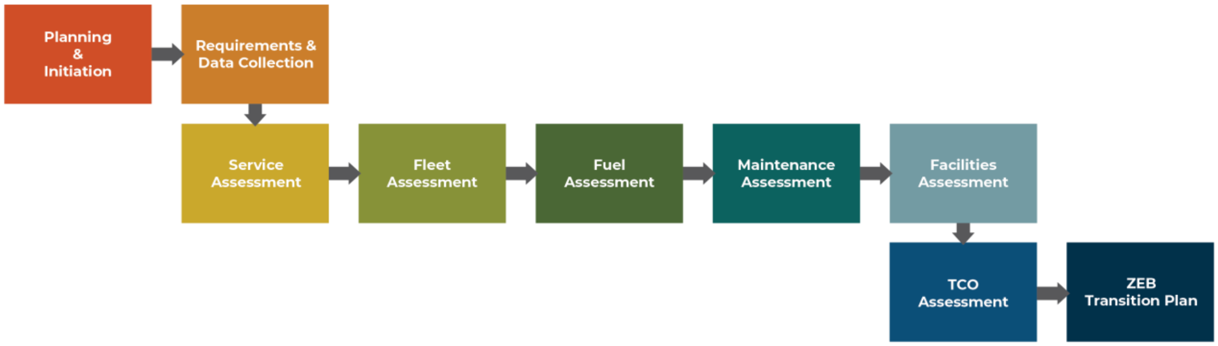

Figure 5 - CTE's ZEB Transition Study Methodology

The **Planning and Initiation** phase builds the administrative framework for the transition study. During this phase, the project team drafted the scope, approach, tasks, assignments and timeline for the project. CTE worked with LAVTA staff to plan the overall project scope and all deliverables throughout the full life of the study.

For the **Requirements & Data Collection,** CTE collected GPS data on selected LAVTA routes and used software models to estimate ZEB performance. The outputs from this modeling were used to estimate the achievability of serving every block in LAVTA's network using BEBs and FCEBs.

The **Service Assessment** phase initiated the data collection and technical analysis of the study. CTE met with LAVTA to define assumptions and requirements used throughout the study and to collect operational data. The results from the Service Assessment were used to guide ZEB procurement analysis in the Fleet Assessment and to determine energy requirements (depot charging, on-route charging, and/or hydrogen) in the Fuel Assessment.

The **Fleet Assessment** develops a projected timeline for replacing current buses with ZEBs that is consistent with the agency's fleet replacement plan. Multiple projection scenarios with different combinations of ZEB technologies are created. This assessment also includes a projection of fleet capital costs over the transition timeline, and it can be optimized for any state mandates like CARB's ICT regulation or agency goals such as minimizing cost or maximizing service levels.

The **Fuel Assessment** merges the results of the Service Assessment and Fleet Assessment to determine annual fuel requirements and associated costs. The Fuel Assessment calculates energy costs through the full transition timeline for each scenario, including the agency's current fossil-fuel buses. To more accurately estimate BEB charging costs, a focused Charging Analysis is performed to simulate daily system-wide charging use. As current technologies are phased out in later years of the transition, the Fuel Assessment calculates the increasing energy requirements for ZEBs. The Fuel Assessment also provides a total energy cost over the transition lifetime.

The **Facilities Assessment** determines the necessary infrastructure to support the projected zero-emission fleet based on results from the Fleet Assessment and Fuel Assessment. The Facilities Assessment is calculated for each scenario used in the Fleet and Fuel Assessments. The result shows quantities of hydrogen and battery-electric infrastructure and calculates associated costs.

The **Maintenance Assessment** calculates all projected fleet maintenance costs over the life of the project. This includes costs related to existing fossil-fuel buses remaining in the fleet, as well as new BEBs and FCEBs, calculated for each scenario.

The **Total Cost of Ownership Assessment** compiles results from the previous assessment stages and provides a comprehensive view of all associated costs, organized by scenario, over the transition lifetime.

Assessment Scenarios

The approach for this ZEB transition study is based on the creation and analysis of three scenarios, as well as a baseline:

0. Baseline
1. BEB Only
2. Mixed Fleet: BEB and FCEB
3. FCEB Only

Current battery electric bus technologies do not have the range to allow for a one-for-one replacement of all types of fossil-fuel buses. Technology and range improvements are expected; however, there are significant challenges to overcome, and the timeline to achieve the goal is uncertain. In many cases, if a transit agency were to maintain service levels after transitioning to a fleet of BEBs charged only at a depot, it would be necessary to replace conventional ICE buses at a 2:1 ratio to cover the range limitations and charging times of the new BEB fleet. Naturally, increasing fleet size to accommodate the 2:1 replacement ratio would result in increased costs for purchasing, fueling, and maintaining additional buses and the additional infrastructure required to charge them. On-route charging provides an alternative to the larger fleet approach and, as such, the BEB Only scenario was developed to explore this alternative solution for deploying a ZEB fleet. In this scenario, BEBs are charged at the depots when not in-service and are charged on-route when necessary to complete service requirements.

The Mixed Fleet: BEB and FCEB scenario utilizes both battery electric and fuel cell electric technologies. The underlying assumption for the mixed scenario is that neither technology is suitable for 100% of the fleet replacement due to inherent constraints and that including both technologies allows for more flexibility. Additionally, using a mixed fleet of BEBs and FCEBs achieves a 100% zero-emission fleet without the need to add buses.

Finally, the FCEB Only scenario is based on the outputs of the Requirements Analysis, which found that FCEBs can meet all LAVTA's daily service requirements by block. This scenario examines the costs incurred by hydrogen fueling and transitioning to a 100% FCEB fleet.

Assessment Assumptions

Due to varying conditions over the course of a long-term fleet transition, it is necessary to establish a number of simplifying assumptions. These assumptions were developed based on discussions between CTE and LAVTA:

- Transition period is defined as achieving 100% ZEB fleet purchasing by 2040 to comply with the CARB ICT regulation;
- No change in fleet size will occur during the transition period except where necessary to maintain route achievability;
- Agency's planned procurements are included;
- A 12-year bus lifespan is assumed for future heavy-duty transit buses (i.e. buses are retired after 12 years of service);
- Costs are expressed in 2021 dollars with no escalation, and prices remain constant for the entire transition period;
- Current battery sizes for BEBs and fuel tank sizes for FCEBs are based on existing specifications for buses that have completed Altoona testing;
- A 5% improvement in battery capacity (for BEB) and efficiency (for FCEB) occurs every two years;
- A battery replacement will occur at the midlife of each heavy-duty transit BEB (six years), but the cost of this maintenance is included in the extended warranty cost; and
- A battery replacement and fuel-cell overhaul will occur at the midlife of each heavy-duty transit FCEB (six years) and the cost of this battery maintenance will also be included in the extended warranty. This cost is factored into the estimated maintenance costs as a sum expended in the year of vehicle purchase.

BEB-Specific Assumptions

Research by the US Department of Energy (DOE) suggests that battery density for electric vehicles has improved by an average of 5% each year.[2] For this study, considering the extended period of a complete fleet transition through 2040, CTE assumes a more conservative 5% improvement of battery density every two years. If the trend continues, buses will continue to increase the amount of energy they carry without incurring a weight penalty or reduction in passenger capacity.

Initially, as more BEBs entered the market, many believed that the costs of BEBs would continue to decrease due to higher production volumes and competition from new vendors. While cost decreases did occur for a time, costs appear to have leveled out in recent years. However, it should be also noted that vendors have added more battery storage over the same time period without increasing base costs.

The terms “fuel” and “energy” are used interchangeably in this assessment, as ZEB technologies do not always require traditional liquid fuel. In the case of BEBs, “fuel” is electricity and costs include energy, demand and other utility charges.

BEB labor and maintenance costs come from an analysis completed by the U.S. DOE National Renewable Laboratory (NREL).[3]

For infrastructure cost estimates, CTE and AECOM developed estimates for components of each project type to build up a total cost estimate by project type. Assumptions used for BEB infrastructure are shown in **Table 26**. Conceptual BEB Scenario layouts, prepared by AECOM, are provided in **Appendix A1** – LAVTA Depot Site Plans, **.**

FCEB-Specific Assumptions

FCEBs do not have the same range constraints as BEBs. Alameda-Contra Costa Transit District (AC Transit) and Orange County Transportation Authority (OCTA) have reported operational ranges for FCEBs up to 350 miles. Typically, FCEBs can more readily serve an agency’s current blocks on a one-to-one basis with fossil fuel buses; however, costs of hydrogen fuel and bus capital costs create financial barriers to entry. This study assumes 5% bi-annual improvement in hydrogen tank size as a proxy for other component improvements such as battery capacity, motor efficiency, and fuel cell efficiency.

FCEB prices are expected to decrease over time as bus orders increase; however, CTE does not currently have an adequate basis to assume reduced costs for future FCEB purchases.

FCEBs are similar to fossil fuel buses in that they are fueled by a gaseous fuel— hydrogen—at a dispenser. In addition to the cost of the fuel itself, however, there are additional operational

[2] U.S. Department of Energy; LONG-RANGE, LOW-COST ELECTRIC VEHICLES ENABLED BY ROBUST ENERGY STORAGE, MRS Energy & Sustainability, Volume 2, Wednesday, September 9, 2015; https://arpa-e.energy.gov/?q=publications/long-range-low-cost-electric-vehicles-enabled-robust-energy-storage

[3] Eudy, Leslie and Matthew Jeffers. 2019. Foothill Transit Agency Battery Electric Bus Progress Report: Data Period Focus: Jul.2018 through Dec. 2018. Golden, CO: National Renewable Energy Laboratory. NREL/PR-5400-72209. https://afdc.energy.gov/files/u/publication/foothill_transit_beb_progress_rpt_5-2019.pdf.

costs for a hydrogen fueling station that must be considered. The fuel prices used in CTE's assessment were based on current prices at OCTA. These prices include fueling infrastructure maintenance, and delivery fees. CARB funded projects are also subject to a 33% renewables requirement, which mandates that 33% of the hydrogen delivered to OCTA must be produced with renewable energy, which further increases this price.

There is limited information on maintenance costs for FCEBs due to the limited number of buses in operation in the United States. Much of the information currently available comes from AC Transit, which has the largest FCEB fleet in the country. Unfortunately, many of these buses are older models that are past their warranty period and require expensive maintenance service from their European manufacturer, thus skewing the available dataset toward more expensive cases. CTE decided to model FCEB maintenance costs based on OCTA's FCEB fleet of 10 New Flyer buses during their first year of operation.

3 Requirements Analysis

Baseline Data Collection

Understanding the key elements of LAVTA's service is essential to evaluating the costs of a complete transition to a zero-emission fleet. LAVTA staff provided key data on current LAVTA service including the following:

- Fleet composition: vehicle propulsion types and lengths currently in operation
- Route and block information including distances and trip frequency
- Mileage and fuel consumption
- Maintenance costs

Fleet Composition

In 2020, the LAVTA bus fleet totaled 60 diesel hybrid buses including a six-bus contingency fleet. The fleet provided service on 31 fixed routes. A breakdown of the fleet by size is shown in **Table 5**. Bus services operate out of one depot, but since that depot will be moving, it is referred to as "Rutan" while the buses operate out of the Rutan Court depot and "Atlantis" when the ZEBs will operate out of the new facility at Atlantis Court. For the purposes of this document, that is assumed to be by 2028. Operations, maintenance, and fueling functions are performed at the depot.

Table 5 - Fleet Breakdown by Depot and Length

Depot	Bus Length (ft)			Total
	30'	35'	40'	
Rutan	17	10	33	60
Total	17	10	33	60

Routes and Blocks

LAVTA's current service consists of 31 routes run on 102 blocks, as detailed in

Table 6.

Table 6 – Count of Blocks by Depot and Bus Length

Depot	Bus Length (ft)			Total
	30'	35'	40'	
Rutan	18	17	67	102
Total	18	17	67	102

Miles and Fuel Consumption

Data on LAVTA's current fuel use was collected and used to estimate energy costs throughout the transition period. This study assumes that no cost escalation for fuel occurs throughout the transition period. Annual fleet mileage and fuel use are shown in **Table 7** and **Table 8**.

Table 7 – Annual Service Miles by Depot and Bus Length

Depot	Bus Length (ft)			Total
	30'	35'	40'	
Rutan	583,020	523,565	983,851	2,090,436
Total	583,020	523,565	983,851	2,090,436

Table 8 – Annual Diesel Consumption by Depot and Bus Length [Diesel Gas Equivalence (DGE)]

Depot	Bus Length (ft)			Total (DGE)
	30'	35'	40'	
Rutan	111,029	113,724	192,186	416,938
Total	111,029	113,724	192,186	416,938

4 Service Assessment

The Service Assessment analyzes the feasibility of maintaining LAVTA's current level of service using BEB and FCEB buses. This assessment does not incorporate any plans for expansions except where necessary to maintain block achievability. The main focus of the Service

Assessment is the Block Analysis, which analyzes bus range limitations to determine if ZEBs could meet the service requirements of the blocks within the transition period. The energy needed to complete a block is compared to the available energy for the prospective bus type that is planned for the block. If the prospective bus's available energy exceeds the block's required energy, then that block is considered achievable for that ZEB type. The Service Assessment also outputs a timeline for when blocks become achievable for zero-emission buses as technology improves. This information is used to then inform ZEB procurements in the Fleet Assessment.

Bus efficiency and range are primarily driven by bus specifications; however, both metrics can be impacted by a number of variables including the route profile (i.e., distance, dwell time, acceleration, sustained top speed over distance, average speed, traffic conditions), topography (i.e. grades), climate (i.e. temperature), driver behavior, and operational conditions (e.g. passenger loads and auxiliary loads). As such, efficiency and range of a given BEB model can vary dramatically from one agency to another. Therefore, it is critical to determine efficiency and range estimates that are based on an accurate representation of LAVTA's operating conditions.

The first task in the Service Assessment is to develop route and bus models to run operating simulations for representative LAVTA routes. Rather than collecting data from all of LAVTA's routes, CTE used a sampling approach in which representative sample routes were identified based on topography and average speed characteristics. CTE then collected GPS data from 8 LAVTA routes that were identified for sampling. GPS data includes time, distance, bus speed, bus acceleration, GPS coordinates, and roadway grade. These variables were used to develop the route model. CTE used component-level specifications and the collected route data to develop a baseline performance model by simulating the operation of an electric bus on each route. Collecting data on and modeling every route in LAVTA's network would be ideal; however, this is impractical due to the amount of time and labor this approach would require.

The modeling outputs of the sample routes were then applied to all routes and blocks that share the same characteristics. Routes selected for the analysis are included in **Table 9** below. CTE uses Autonomie, a powertrain simulation software program developed by Argonne National Labs for the heavy-duty trucking and automotive industry. Within Autonomie, CTE modified software parameters to assess energy efficiencies, energy consumption, and range projections for electric buses specifically.

Table 9 – Selected Routes for Modeling

Depot	Hills/ Low Speed	Hills/High Speed	Flat/Low Speed	Flat/High Speed	Count
Rutan	503, 611		2, 8, 14, 30	70, 580	8
Count	**2**	**0**	4	2	8

The route modeling includes analysis of varying passenger load, accessory load, and battery degradation to estimate real-world bus performance, fuel efficiency, and range. The GPS data from routes and the specifications for each of the bus models are used to simulate operation on each type of route. The models were run with varying loads to represent “nominal” and “strenuous” loading conditions. Nominal loading conditions assume average passenger loads and moderate temperature over the course of the day, which places marginal demands on the motor and heating, ventilation, and air conditioning (HVAC) system. Strenuous loading conditions assume high or maximum passenger loading and near-maximum output of the HVAC system. This nominal/strenuous approach offers a range of operating efficiencies to use for estimating average annual energy use (nominal) or planning minimum service demands (strenuous).

Route modeling ultimately provides an average energy use per mile (kilowatt-hour/mile [kWh/mi]) for each combination of route, bus size, and load case. System-wide energy use is estimated in subsequent assessments, using the results shown in

Table 10.

Table 10 – Modeling Results Summary

Bus Length [ft]	Route	Nominal Efficiency [kWh/mi]	Strenuous Efficiency [kWh/mi]
40	2	2.05	2.70
	8	2.02	2.78
	14	1.90	2.52
	30X	2.16	2.91
	70X	2.24	2.58
	503	2.14	2.86
	580X	2.14	2.59
	611	1.61	2.28

The Block Analysis, using the assumed 5% improvement in battery capacity or hydrogen storage capacity every other year, determines the timeline for when routes and blocks become achievable for BEBs and FCEBs. This information is then used to inform ZEB procurement decisions in the Fleet Assessment. Overall, the block analysis helps to determine when, or if, a full transition to BEBs or FCEBs may be feasible. Results from this analysis are also used to determine the specific energy requirements and develop the estimated costs to operate the ZEBs in the Fuel Assessment.

Results from the block analysis are included in **Figure 6** below.

The BEB achievability in **Figure 6** shows that, by 2040, 72% of LAVTA’s blocks can be completed by 40-foot BEBs and that all blocks are achievable with FCEBs throughout the transition period. This analysis assumes that FCEBs can already complete any block under 350 total miles.

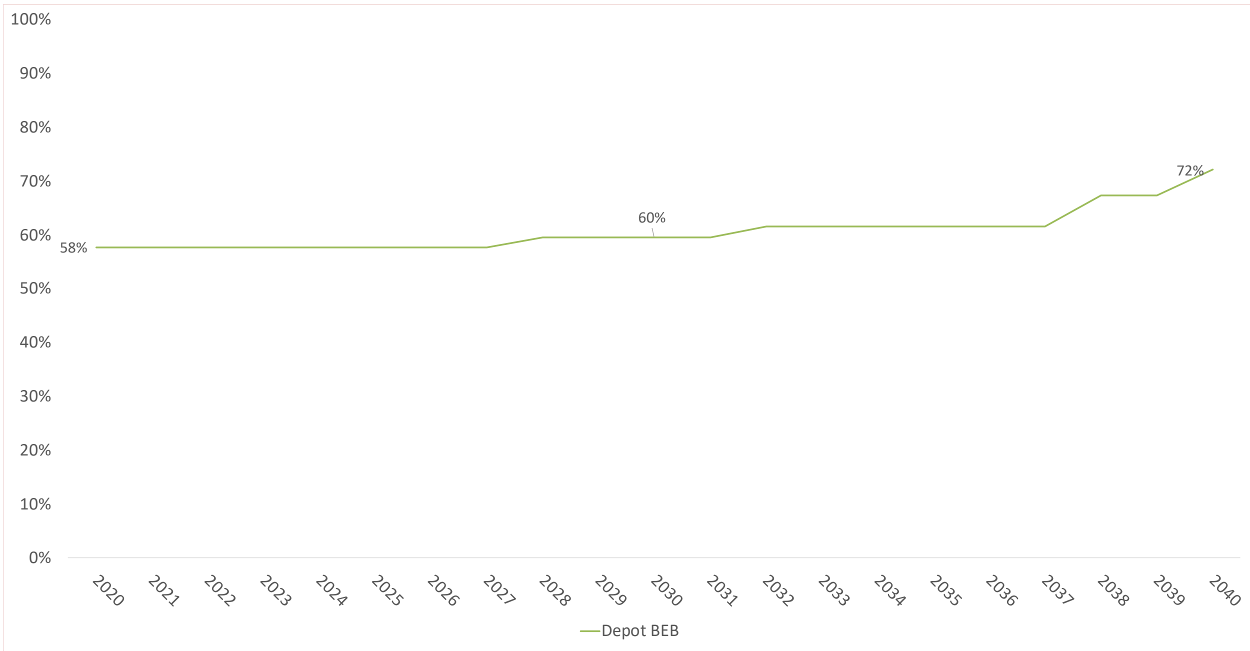

Figure 6 - 40' BEB Block Achievability Percentage by Year

While routes and block schedules are unlikely to remain the same over the course of the transition period, these projections assume the blocks maintain a similar distribution of distance, relative speeds, and elevation changes because LAVTA maintains service to similar destinations within the city. This core assumption affects energy use estimates and block achievability in each year.

Another factor affecting block achievability is battery degradation. BEB range is negatively impacted by battery degradation over time. A BEB may be placed in service on a given block with beginning-of-life batteries; however, it may not be able to complete the entire block at some point in the future before the batteries reach end-of-life. End-of-life is typically defined as when batteries reach 80% of available service energy. Conceptually, older buses can be moved to shorter, less demanding blocks and newer buses can be assigned to longer, more demanding blocks. LAVTA can rotate the fleet to meet demand, assuming there is a steady procurement of BEBs each year to match service requirements.

5 Fleet Assessment

The goal of the Fleet Assessment is to determine the technology type and quantity of zero-emission buses, as well as the schedule and cost to transition the entire fleet to zero emissions. Results from the Service Assessment are integrated with LAVTA's current fleet replacement plan and purchase schedule to produce two main outputs: a projected bus replacement timeline through the end of the transition period and the total capital costs of those replacements.

Cost Assumptions

CTE and LAVTA developed cost assumptions for each bus length and technology type (e.g. CNG, gasoline hybrid, BEB, FCEB). Key assumptions for bus costs for the LAVTA ZEB Transition Study are as follows:

- Bus costs are based on LAVTA's most recent procurement price and the Metropolitan Transit Commission (MTC) Pricelist
- Bus costs are inclusive of estimates for configurable options and taxes
- Future bus costs are based on year 2020 prices

Table 11 provides estimated bus costs used in the analysis.

Table 11 – Fleet Assessment Cost Assumptions

Length [ft]	BEB	FCEB
40'	$1,270,577	$1,412,602

Note: Based on MTC Pricelist

Baseline

In the Baseline Scenario, LAVTA continues to replace retired buses with diesel-hybrid buses on a 12-year replacement cycle. This scenario illustrates the costs LAVTA would expect over the 20-year period if it purchased no ZEBs. **Figure 7** shows the number of diesel-hybrid buses that would be purchased each year through 2040 in this scenario.

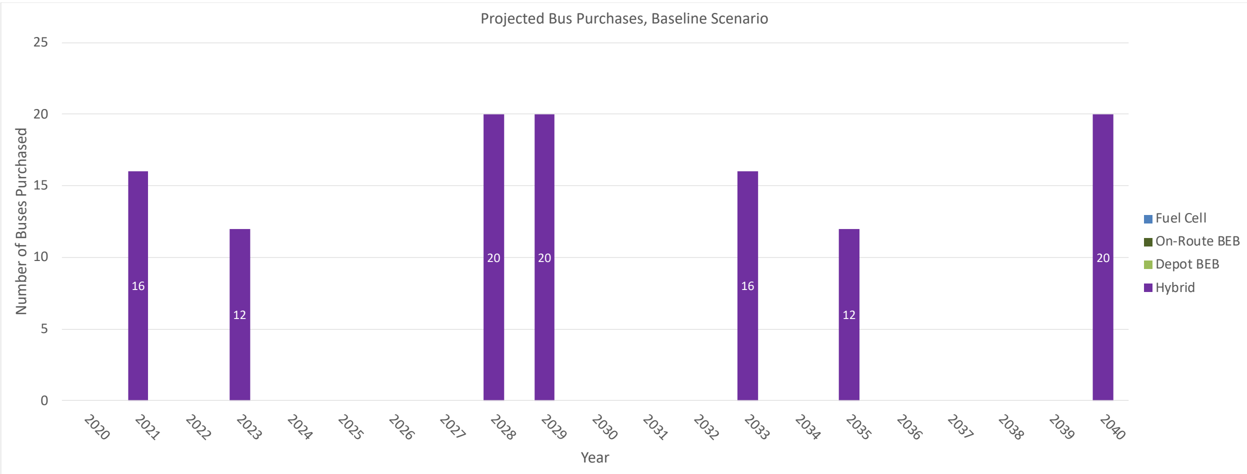

Figure 7 - Projected Bus Purchases, Baseline Scenario

Figure 8 depicts the annual fleet composition through 2040 for the Baseline scenario; the fleet remains composed of diesel-hybrids over the 20-year period.

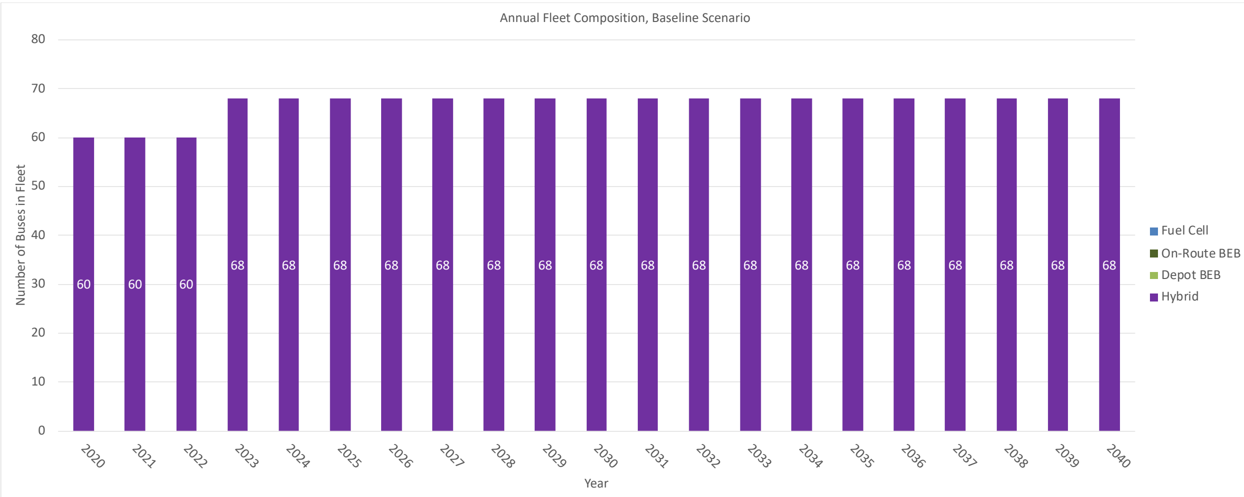

Figure 8 - Annual Fleet Composition, Baseline Scenario

Figure 9 shows the annual total bus capital costs for the diesel-hybrid buses purchased in each year in the Baseline Scenario.

Figure 9 - Annual Capital Costs, Baseline Scenario

BEB Only

On-route charging allows an agency to add energy to buses while the bus is in service, complementing depot charging and improving block achievability for BEBs. On-route charging removes the need to travel extra distance and take extra time to charge at a depot. Based on LAVTA's Service Assessment, on-route charging would be required to accommodate an all-BEB fleet without increasing fleet size by extending the range of on-route charged buses indefinitely.

The figures below show projected purchases, annual fleet composition, and annual total capital costs for the BEB Only scenario. By 2035, the addition of on-route charging allows LAVTA to replace 100% of the fleet with BEBs without needing any additional buses.

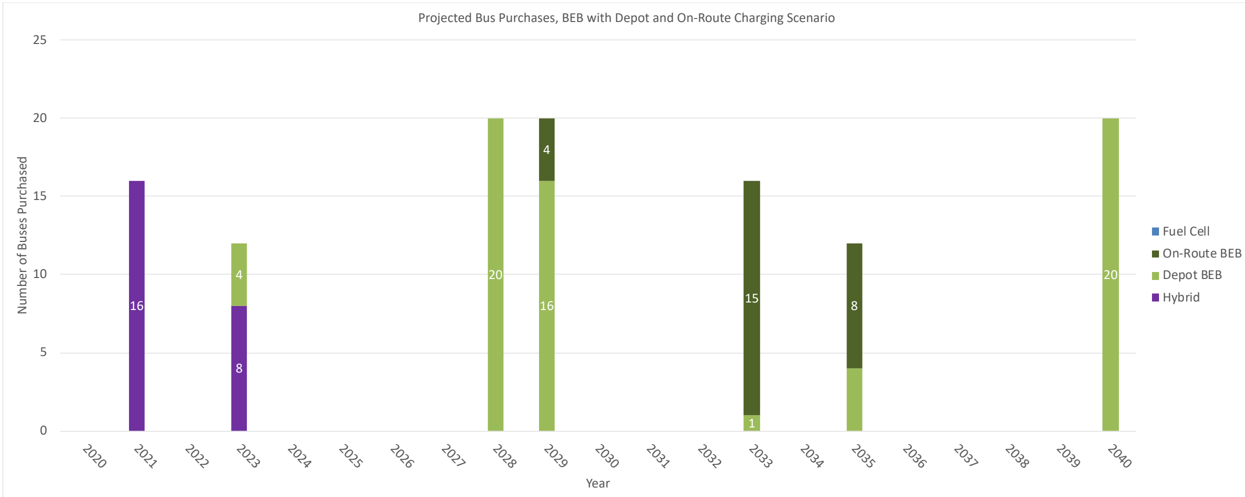

Figure 10 – Projected Bus Purchases, BEB Only Scenario

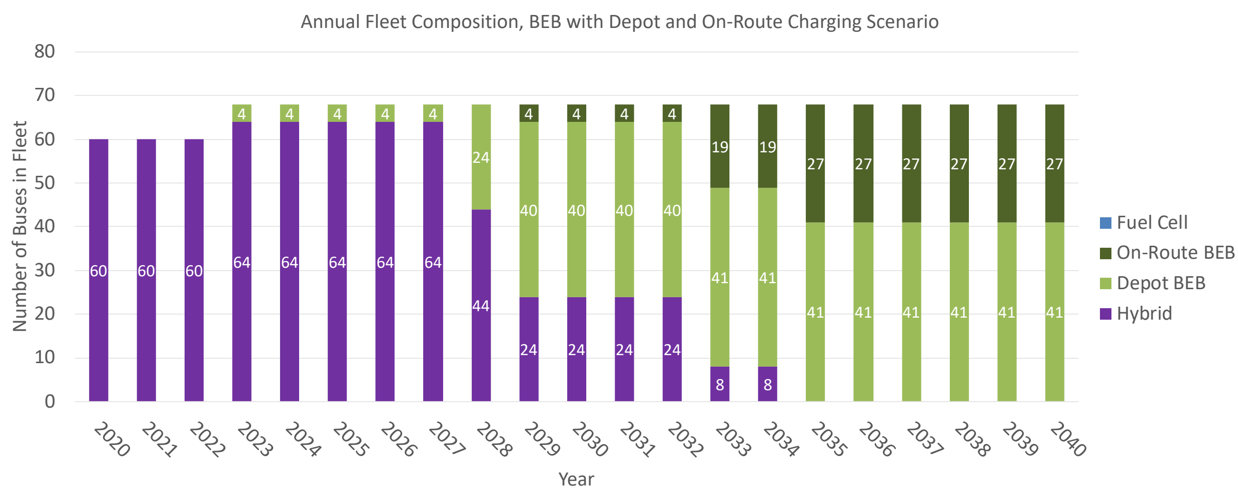

Figure 11 – Annual Fleet Composition, BEB Only Scenario

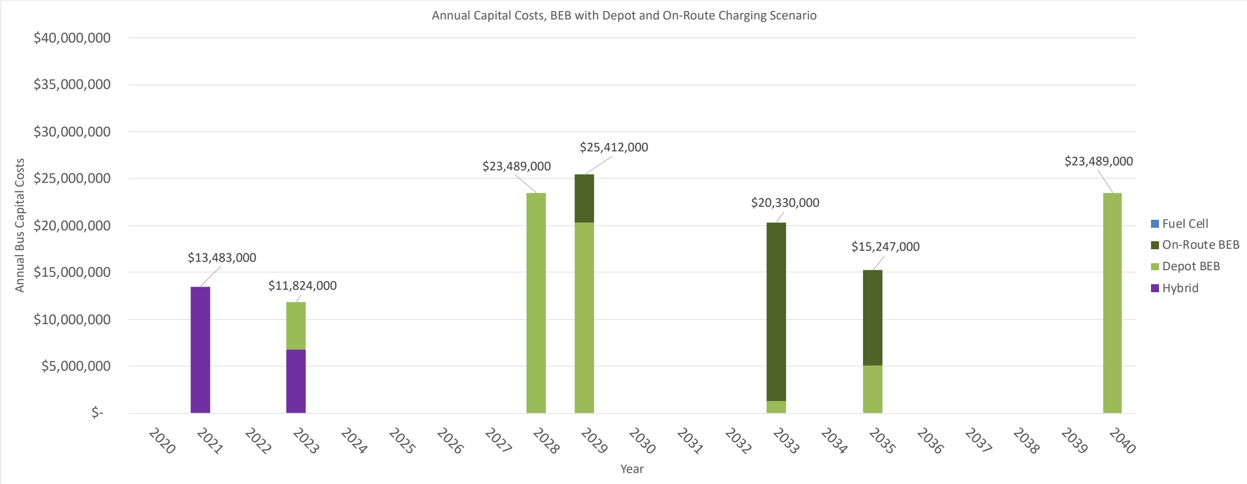

Figure 12 – Annual Capital Costs, BEB Only Scenario

Mixed Fleet: BEB and FCEB

In the Mixed Fleet: BEB and FCEB scenario, LAVTA operates a mixed-technology depot and fleet. The longest blocks are run by FCEBs, allowing LAVTA to take advantage of the greater range of FCEBs. BEBs are then able to run the less demanding routes. Under this approach, LAVTA only incurs the higher costs of FCEBs where necessary to maintain block achievability.

The figures below show projected purchases, annual fleet composition, and annual total capital costs for the Mixed Fleet: BEB and FCEB fleet.

By 2035, LAVTA would be able to replace 100% of its fleet with BEB and FCEBs.

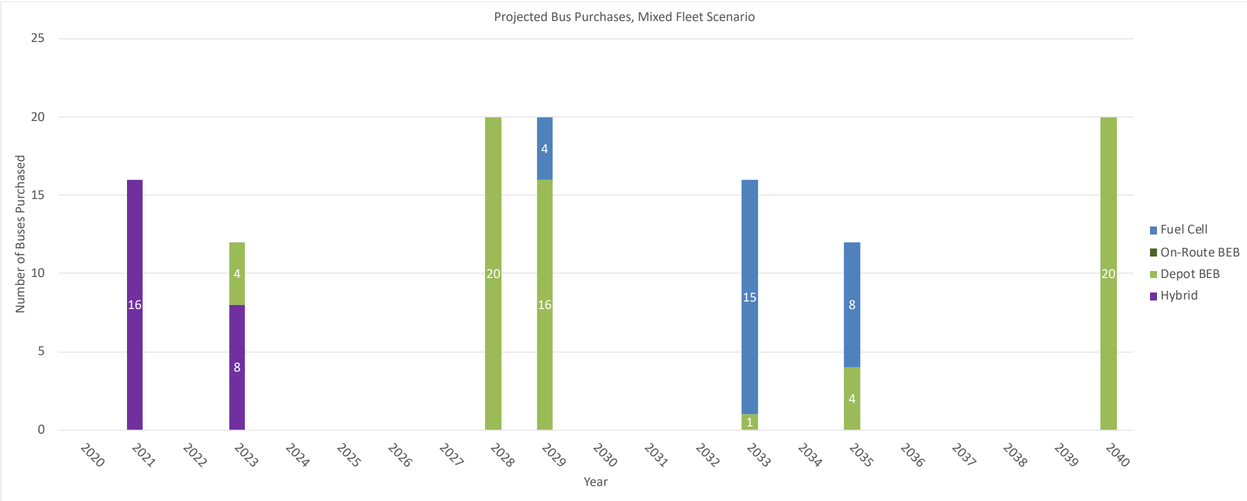

Figure 13 – Projected Bus Purchases, Mixed Fleet Scenario

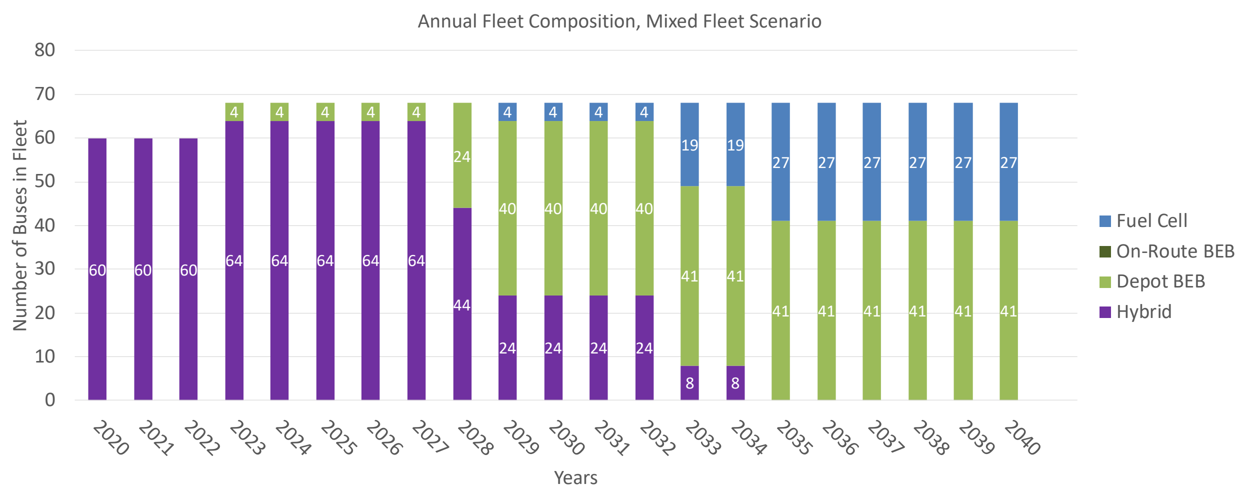

Figure 14 – Annual Fleet Composition, Mixed Fleet Scenario

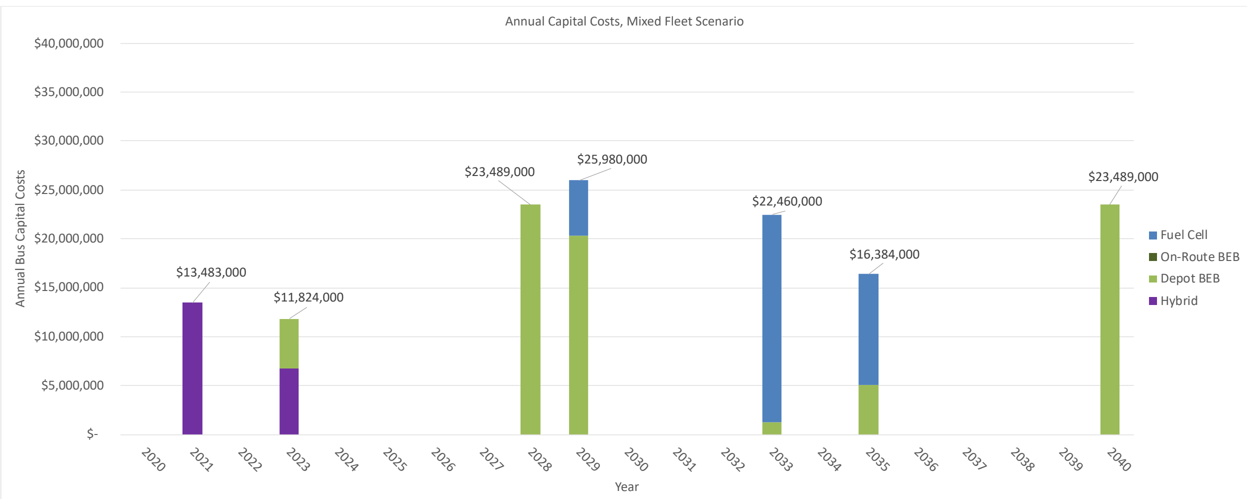

Figure 15 – Annual Capital Costs, Mixed Fleet Scenario

FCEB Only

FCEBs do not have the same range constraints as BEBs. FCEBs are assumed to be able to achieve any block that is up to 350 miles long. Analysis results show that all of LAVTA's blocks can be served by an FCEB on a one-for-one replacement basis to diesel-hybrids by the end of the transition period.

The figures below show projected purchases, annual fleet composition, and annual total capital costs for the FCEB Only scenario.

By 2035, LAVTA is able to replace 100% of its fleet with FCEBs. An accelerated purchasing schedule that illustrates purchasing only FCEBs in 2023 and the additional costs incurred can be found in **Addenda –** Accelerated FCEB Purchase Cost Information.

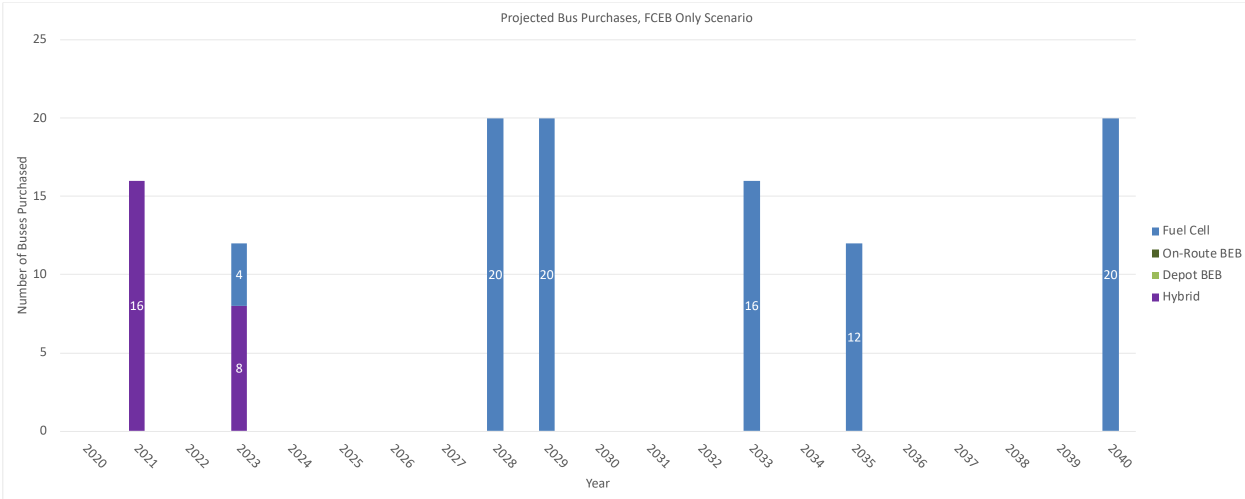

Figure 16 – Projected Bus Purchases, FCEB Only Scenario

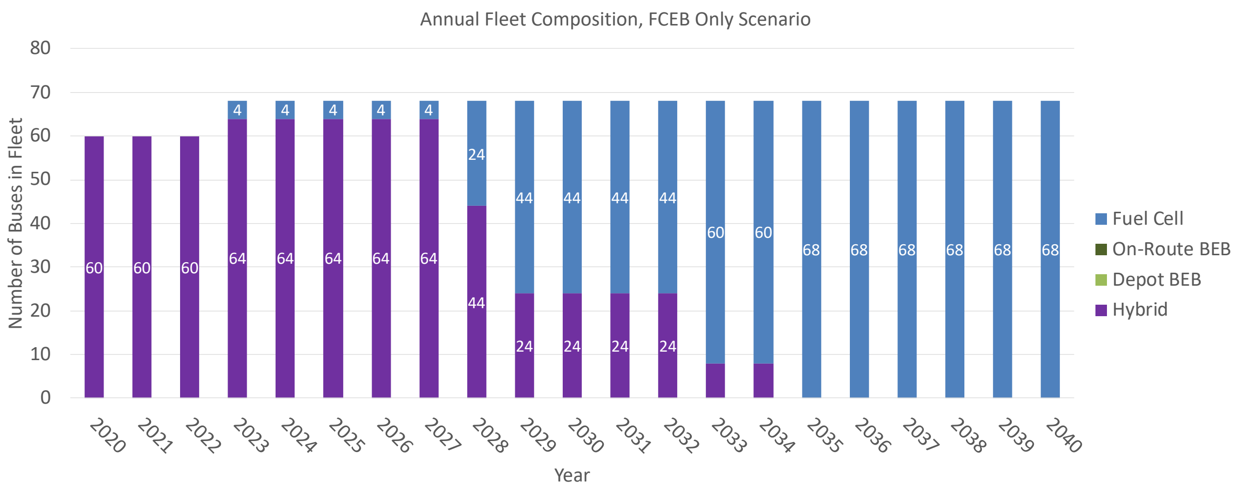

Figure 17 – Annual Fleet Composition, FCEB Only Scenario

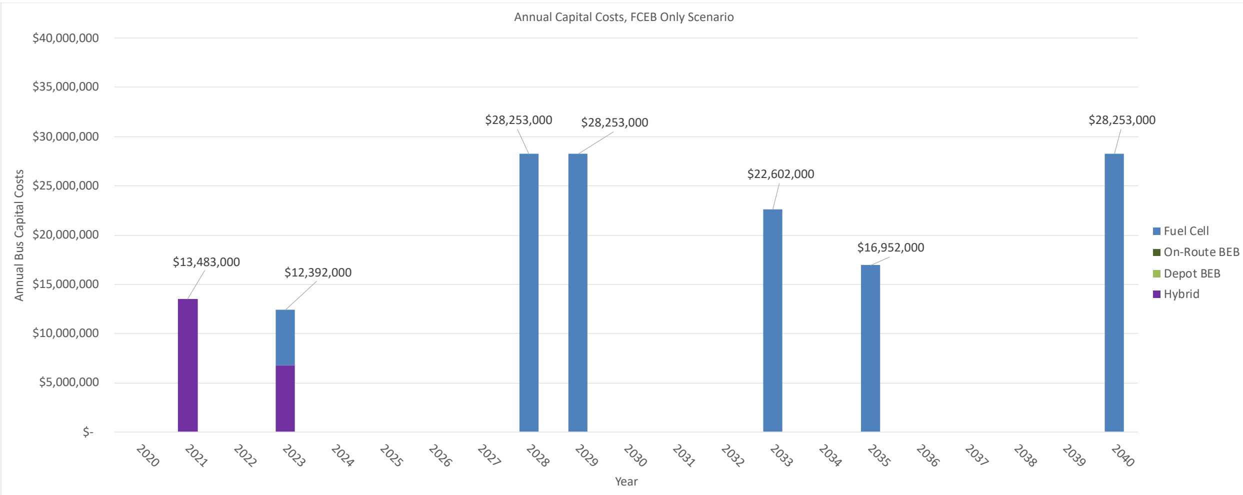

Figure 18 - Annual Capital Costs, FCEB Only Scenario

Fleet Assessment Cost Comparison

The transition and fleet composition schedules were used to develop the total capital cost for bus purchases through the transition period. **Figure 19** shows the cumulative bus purchase costs for each scenario.

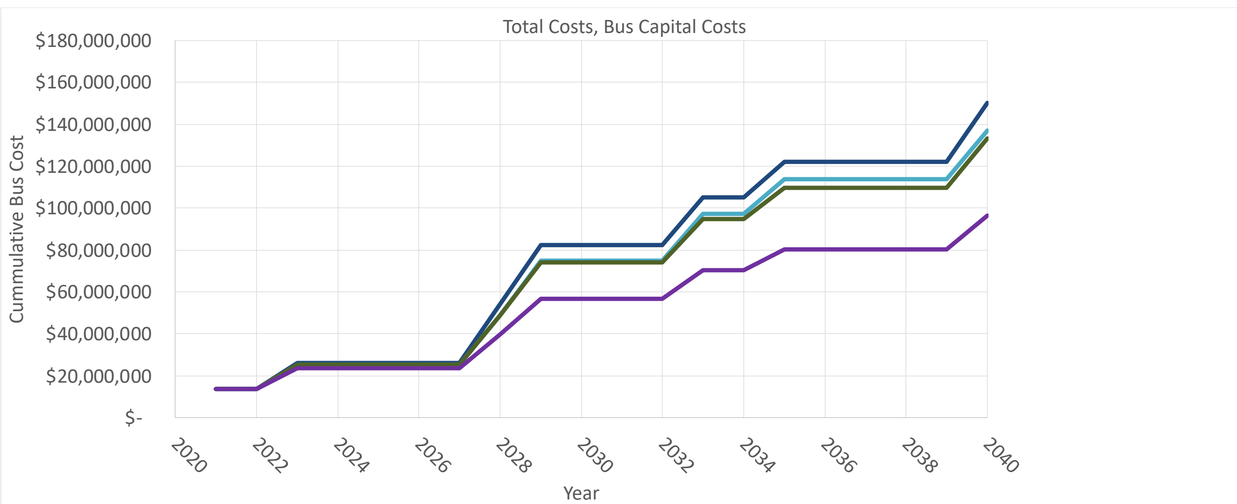

Figure 19 - Cumulative Bus Capital Costs, Fleet Assessment

By the end of the transition period, the cumulative bus costs vary substantially according to the technology selected, although all scenarios result in 100% of the fleet transitioning to zero-emission by 2040. **Table 12** provides the combined total costs for each transition scenario and the percentage of ZEBs present in the fleet in 2040 for the scenario.

Table 12 - Total Bus Capital Costs, Fleet Assessment

Scenario	Cost	% ZEB in 2040
Baseline	$ 95,503,000	0%
BEB Only	$ 133,271,000	100%
Mixed Fleet: BEB and FCEB	$ 137,105,000	100%
FCEB Only	$ 150,182,000	100%

6 Fuel Assessment

The Fuel Assessment estimates fuel consumption and cost for each of the fuel technologies—diesel, electric and hydrogen—studied in the relevant scenario. This assessment calculates fuel costs using 2020 prices.

Using ZEB performance data from the route simulation, CTE analyzed expected bus performance on each block in LAVTA's service catalog to calculate daily fuel required to complete that block. CTE completed this analysis for each of the four fleet scenarios, estimating the fuel costs unique to each fleet projection throughout the transition period.

The Fuel Assessment includes operation and maintenance costs for fueling infrastructure for both BEBs and FCEBs. Fuel cost estimates are based on the assumptions shown in **Table 13** below.

Table 13 – Fuel Cost Assumptions

Fuel	Cost	Source
Diesel	\$2.24/DGE	LAVTA-contracted rate
Hydrogen (trucked)	\$7.95/kg	Contracted rate at OCTA
Electricity	Varies	PG&E Commercial EV Tariff Schedule

The primary source of energy for a BEB comes from the local electrical grid. Utility companies typically charge separate rates for total electrical energy used (kilowatt-hours (kWh) or megawatt-hours (MWh)) and for peak power demand (kilowatts (kW) or megawatts (MW)) on a monthly basis. Peak demand is defined as the maximum amount of energy that a customer pulls from the grid for any 15-minute window within a month. Demand charges are then applied on a per kW basis to that maximum demand in addition to per kWh costs for energy consumption. As a transit agency adds more buses and chargers, the agency's energy consumption and the peak power demand both increase. Rates also vary throughout the year and throughout the day, making costs highly variable if charging is not managed. Charge management includes strategies like charging buses during times of day at which rates are lower, avoiding demand charges, and spreading out the number of buses charging at once to minimize increases in peak power demand.

Table 14 shows a summary of the PG&E Commercial EV rate schedule used in the Fuel Assessment to estimate electrical costs for BEBs. These rates are averaged from monthly rates and are a summarized version of PG&E's full rate schedule. Since this is a time-of-use (TOU) rate, the rate per kWh changes based on the time of day and year that the kWh was consumed. Since it is assumed that depot charged buses would fuel entirely in the Off-Peak hours between 9:00pm and 9:00am, the depot charge rate is the same as the Off-Peak rate. Since the On-Route charged buses operate partially in the On-Peak period, the On-Route per kWh rate is slightly higher. Most TOU rates also include a demand charge, which is dependent on the maximum demand that the meter measures in a given month. For PG&E's Commercial EV Rate, however, there is a subscription fee of $95.56/50kW of demand, which would apply to the demand at the depot, as well as at each of the On-Route charging stations. The depot charge rate and on-route charge rate included in the table represent the average cost per kilowatt-hour (kWh) rate expected for LAVTA.

Table 14 – PG&E Rate Schedule

<table>
<tr><td rowspan="7">Electric Utility Rates</td><td>Per meter charge</td><td colspan="3">NA</td></tr>
<tr><td rowspan="2">On Peak (per kWh)
Off-Peak (per kWh)
Super Off (per kWh)</td><td>summer</td><td>winter</td><td>annual</td></tr>
<tr><td>$0.35
$0.14
$0.11</td><td>$0.35
$0.14
$0.11</td><td>$0.35
$0.14
$0.11</td></tr>
<tr><td>Depot charge rate</td><td colspan="3">$0.14</td></tr>
<tr><td>On-Route charge rate</td><td colspan="3">$0.19</td></tr>
<tr><td>Depot Demand Charge (per 50kW/month)</td><td colspan="3">$95.56</td></tr>
<tr><td>On-Route Demand charge (per 50kW/month)</td><td colspan="3">$96.56</td></tr>
</table>

Charging Analysis

To accurately estimate energy consumption, peak power demand, and resulting costs, charging simulations at the depot for each year of the transition were conducted. Electrical energy consumption and peak power demand were estimated based on current block schedules and projections of BEB purchases. CTE then used PG&E tariff schedules to calculate the annual cost of charging. This annual cost is evaluated for each year of the study (2020–2040) to obtain a total charging cost of BEBs with depot charging for the transition period. This estimate of total charging cost is used as the total fuel cost for the BEB Only scenario and is used in the other fleet scenarios, where relevant, in addition to on-route charging costs, hydrogen fuel costs, or fossil-fuel costs.

The local utility, PG&E, calculates total energy costs, measured per kWh, using a time-of-use rate (TOU), as shown in **Table 14**. Ideally, buses would all charge exclusively in the least expensive Super Off-Peak and Off-Peak times for the lowest overall cost, which the buses at LAVTA should be able to achieve by charging at night.

Hydrogen Pricing Sensitivity Analysis

Although CTE assumes pricing remains at 2020 levels throughout the ZEB transition period, a sensitivity analysis was conducted for LAVTA regarding hydrogen pricing because it is widely believed that these prices will fall over time. The high end of the expected price is the current price paid by OCTA ($7.95/kg) and the bottom rate was estimated based on NREL and DOE projections at $5.50.[4,5] This pricing sensitivity is shown in the summary and total estimates for the fuel cell scenarios in **Figure 35**.

Low Carbon Fuel Standard Credits

For the zero-emission fleet scenarios, CTE included an estimation of the fuel cost reductions LAVTA would receive if it engages in CARB's Low Carbon Fuel Standard (LCFS) credit program. The LCFS program aims to reduce carbon emissions by setting carbon emissions intensity goals for the transportation sector and then reducing that limit over time. The current program extends through 2030 but is expected to be renewed within the next few years. In the LCFS program, one credit is equivalent to one metric ton of carbon dioxide reduction. Although this program is optional, these credits would allow LAVTA to greatly reduce their expected fuel costs. A graph illustrating an estimate of the potential for each scenario to generate LCFS credits will follow the Fuel Assessment graphs for each scenario; however, since the exact credit revenue would be difficult to predict at this stage, especially considering the uncertainty of potential hydrogen fuel pathways for LAVTA, only the initial Fuel Assessment values were included in the Total Cost Analysis. The discussion of LCFS credits is included illustrate the financial impact participating in the LCFS credit trading program could have on LAVTA's fuel costs and the state incentives related to zero-emission technology deployments.

Baseline

Figure 20 depicts energy consumption by fuel type over the transition period for the Baseline scenario. In this scenario, the fleet remains composed of only diesel-hybrid buses. Fleet energy use remains constant over the entire period at around 0.4 million DGE.

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[4] Melaina, M. and Penev, M. 2013. Hydrogen Station Cost Estimates Comparing Hydrogen Station Cost Calculator Results with Recent Estimates. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-56412 https://www.nrel.gov/docs/fy13osti/56412.pdf

[5] Hydrogen Production Tech Team Roadmap. 2017. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability). Washington, DC: Department of Energy. https://www.energy.gov/sites/prod/files/2017/11/f46/HPTT%20Roadmap%20FY17%20Final_Nov%202017.pdf

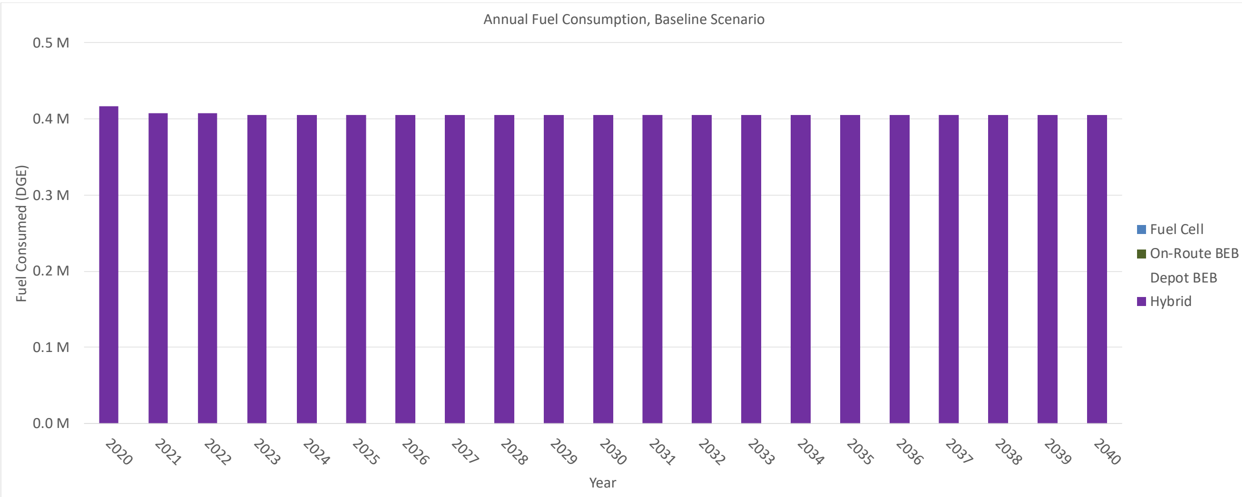


Figure 20 – Annual Fuel Consumption, Baseline Scenario

Figure 21 shows the annual fuel costs for each fuel type in the Baseline scenario, based on the consumption quantities shown in **Figure 20**. Total estimated fuel costs in 2040 are approximately $0.9 million. Since this scenario uses only diesel hybrids, the Baseline scenario fleet would not be eligible for LCFS credits.

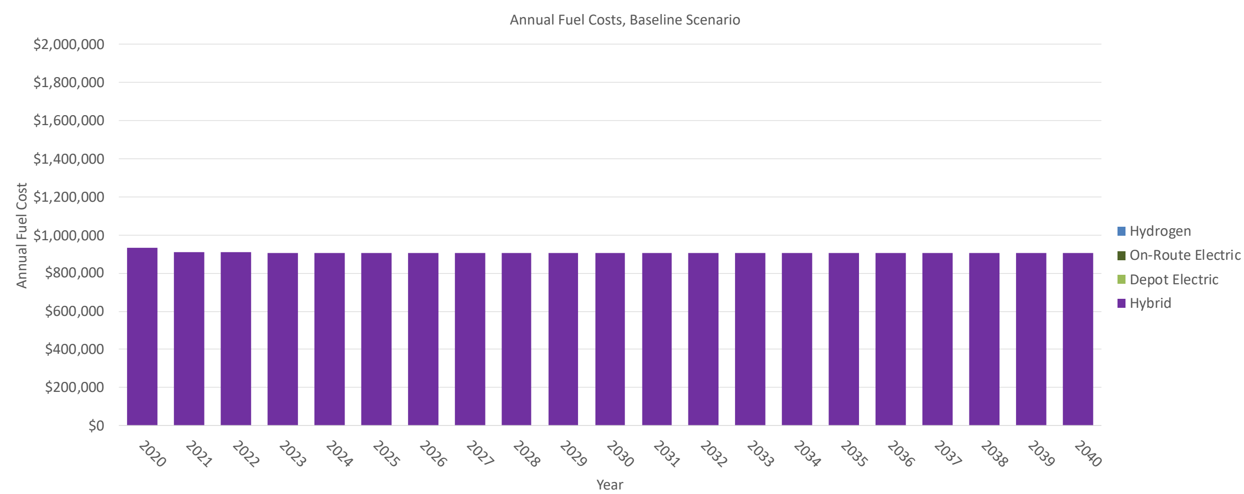


Figure 21 – Annual Fuel Costs, Baseline Scenario

BEB Only

The BEB Only scenario models a transition to an all-BEB fleet that employs depot-charging and on-route charging to extend bus range. The fuel costs for the BEB Only scenario are based on three key assumptions:

1. The total number of buses in the fleet does not increase.
2. The buses that are charged on-route incur additional demand charges and operate partially during peak time-of-use rates, resulting in on-route energy charges that are higher than depot energy charges.
3. The buses are assumed to charge fully at the depot and only require enough charging on-route to make up the difference between the battery capacity and the block demand. The rate for on-route energy consumption is only applied to the portion of the block's energy demand that exceeds the battery capacity of the bus.

Because bus replacements are based on block achievability, there may be instances where block coverage is insufficient and depot-charged BEBs cannot meet service requirements. In this scenario, on-route chargers are used to supplement depot charging to extend the range of buses, thus allowing the achievability of a 100% ZEB fleet. On-route charging allows an agency to add energy to buses while in service, providing the additional energy necessary to complete a block without having to travel the extra distance and take the extra time to return to a depot for charging.

Figure 22 depicts energy consumption for each fuel type over the transition period, assuming a combination of depot-charged and on-route charged BEBs. Legacy fuels are phased out as electricity consumption increases, reflecting an increasing number of BEBs in the fleet. Fleet energy use is reduced from about 0.4 million DGE in 2020 to just over 0.1 million DGE in 2040, an approximately 75% decrease.

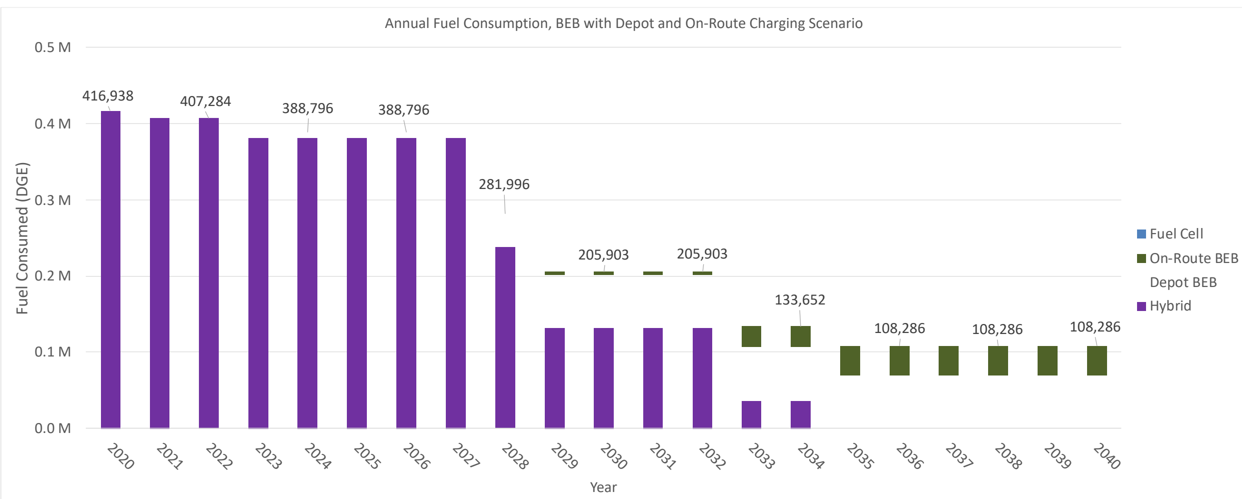


Figure 22 – Annual Fuel Consumption, BEB Only Scenario

Figure 23 shows the annual costs for each fuel type based on the quantities in **Figure 22**. Total estimated fuel costs in 2040 are approximately $1.15 million. The buses charged on-route incur additional demand charges and electricity use costs are slightly higher for on-route charging. These additional costs have been included in the figure below.

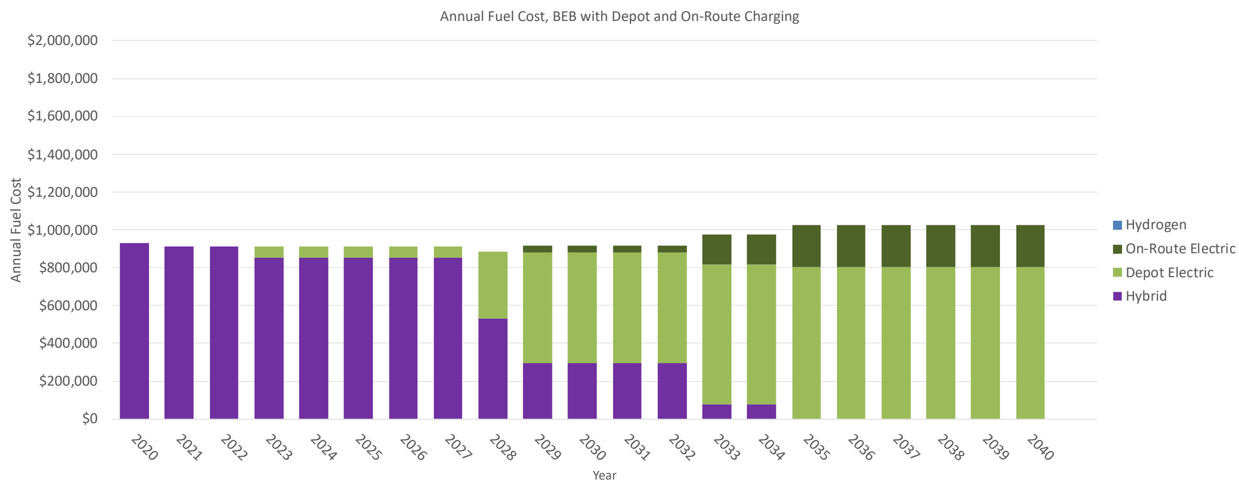


Figure 23 – Annual Fuel Costs, BEB Only Scenario

Operating BEBs would also make LAVTA eligible for LCFS credits. Procuring electricity from 100% renewable energy would generate the most credits for LAVTA. Purchasing Renewable Energy Credits (RECs) is one pathway to obtaining renewable energy and would enable LAVTA to qualify for LCFS credits while still receiving its energy from PG&E. **Table 15** below illustrates the credit revenue estimates through 2030.

Table 15 – LCFS Credit Revenue Estimates by Year, BEB Only Scenario

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of BEBs in Fleet	0	0	4	4	4	4	4	24	44	44
LCFS Credit Gross Value per BEB	$28,000	$27,000	$26,000	$25,000	$25,000	$24,000	$23,000	$22,000	$21,000	$21,000
Credit Processing Fee	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
LAVTA LCFS Credit Revenue	$ -	$ -	$97,000	$93,000	$90,000	$87,000	$84,000	$487,000	$862,000	$832,000

In this table, the LCFS credit gross value is calculated at an estimated 2% per year reduction rate from current credit pricing. Within this model, a broker service fee of 10% was subtracted from the gross credit value. Finally, although the current LCFS credit program only extends through

2030, speculating on how the pricing will trend after the program renewal is challenging. Therefore, in **Figure 24** below, 2030 the per bus LCFS credit revenue remains at 2030 values.

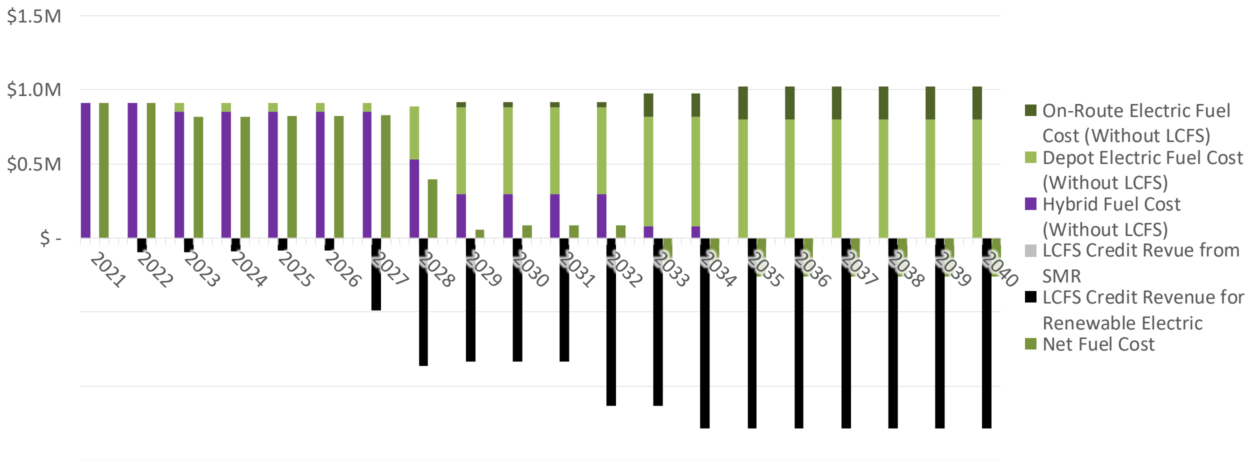


Figure 24 - Potential LCFS Credit Revenue for 100% Renewable Electric, BEB Only Scenario

Mixed Fleet BEB and FCEB

In the Mixed Fleet: BEB and FCEB scenario, BEBs replace diesel-hybrid buses on all achievable blocks. FCEBs supplement the BEB fleet to cover the blocks that are not achievable with battery electric technologies. Building the fleet in this way ensures that all routes are achievable while minimizing the higher costs of FCEBs.

Figure 25 depicts energy consumption for each fuel type over the transition period for the Mixed Fleet: BEB and FCEB scenario. Legacy fuels are phased out as electricity and hydrogen consumption increases, reflecting an increasing number of BEBs and FCEBs in the fleet. Fleet energy use is reduced from about 0.4 million DGE in 2020 to just under 0.15 million DGE in 2040, an approximately 63% decrease.

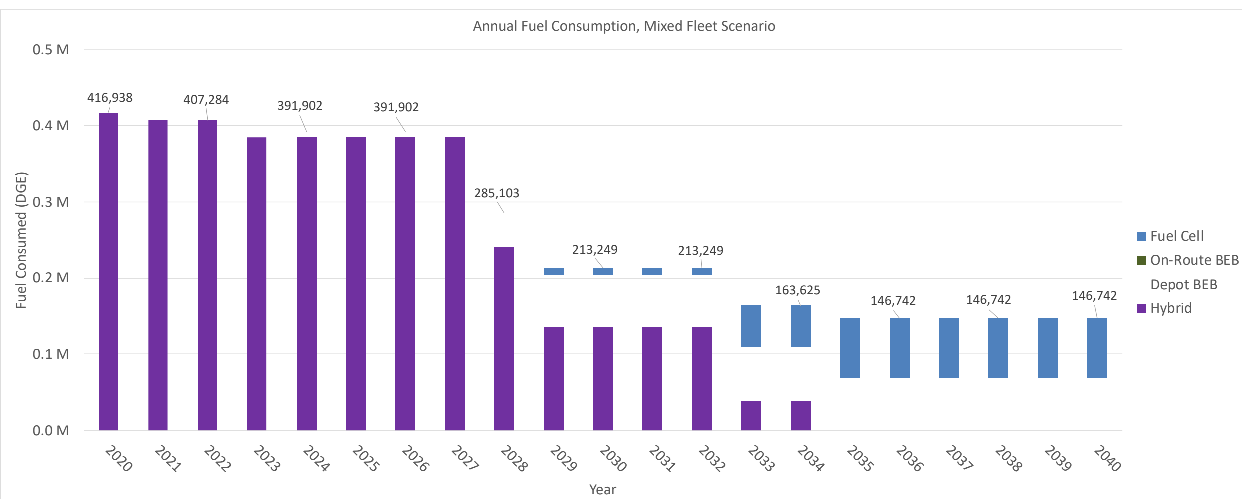


Figure 25 – Annual Fuel Consumption, Mixed Fleet Scenario

Figure 26 shows the estimated annual costs for each fuel type based on the quantities consumed, as shown in **Figure 25**. Total estimated fuel costs in 2040 are approximately $1.26 million, which are incurred from electricity use for BEBs and hydrogen fuel for FCEBs. Although the total amount of energy consumed decreases over the ZEB transition period (**Figure 25**), the total fuel costs increase over that timeframe. These trends reflect hydrogen's greater efficiency but also its higher costs compared to diesel fuel.

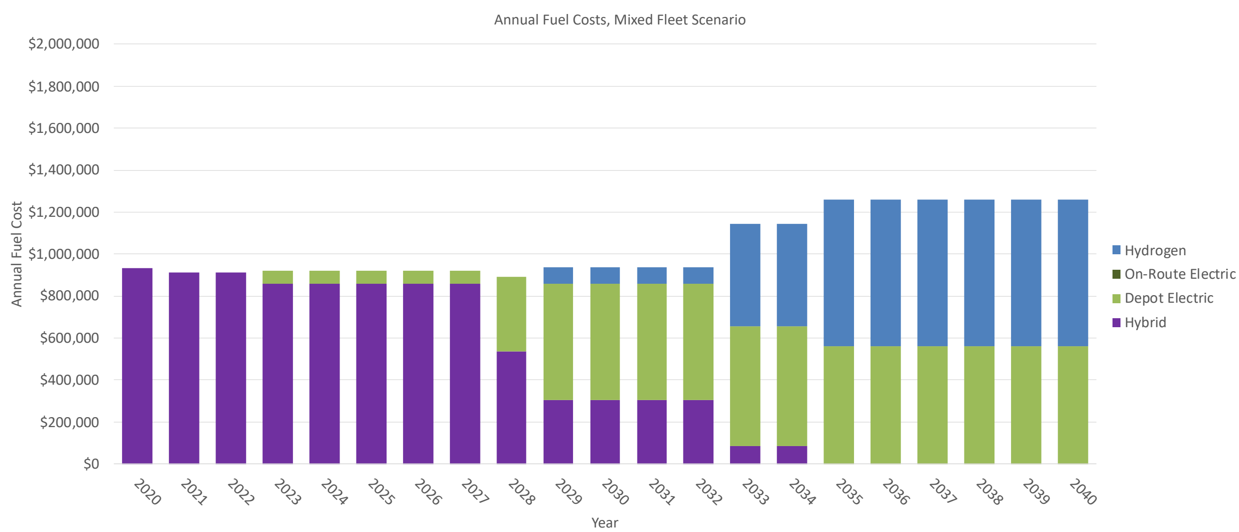


Figure 26 – Annual Fuel Costs, Mixed Fleet Scenario

The Mixed Scenario is also eligible for participation in the LCFS Credit Program; however, revenue potential for hydrogen is highly variable depending on how the fuel is produced. CTE therefore explored three potential hydrogen fuel production pathways for LCFS credits. The first pathway, fossil steam methane reformation (SMR), is currently the most common but, given that fossil fuels are used as to produce the hydrogen, this method is not very lucrative on the LCFS market. The second pathway, electrolysis using 100% renewable energy, generates a significant number of LCFS credits. The third pathway, dairy gas SMR, has a negative carbon intensity and would therefore generate the most LCFS credits of any of the pathways explored. For all the hydrogen fuel pathways explored in the Mixed Fleet Scenario, the LCFS credits that would be generated by the BEBs in the fleet remain constant because only the 100% renewable pathway was explored.

Table 16 – LCFS Credit Revenue Estimates by Year for Fossil Fuel SMR Hydrogen, Mixed Fleet Scenario

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of BEBs in Fleet	0	0	4	4	4	4	4	24	40	40
Number of FCEBs in Fleet	0	0	0	0	0	0	0	0	4	4
LCFS Credit Gross Value per BEB	$28,000	$27,000	$26,000	$25,000	$25,000	$24,000	$23,000	$22,000	$21,000	$21,000
LCFS Credit Gross Value per FCEB - SMR	$1,392	$1,136	$887	$647	$419	$198	$-	$-	$-	$-
Credit Processing Fee	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
LAVTA LCFS Credit Revenue	$ -	$ -	$97,000	$93,000	$90,000	$87,000	$84,000	$487,000	$784,000	$756,000

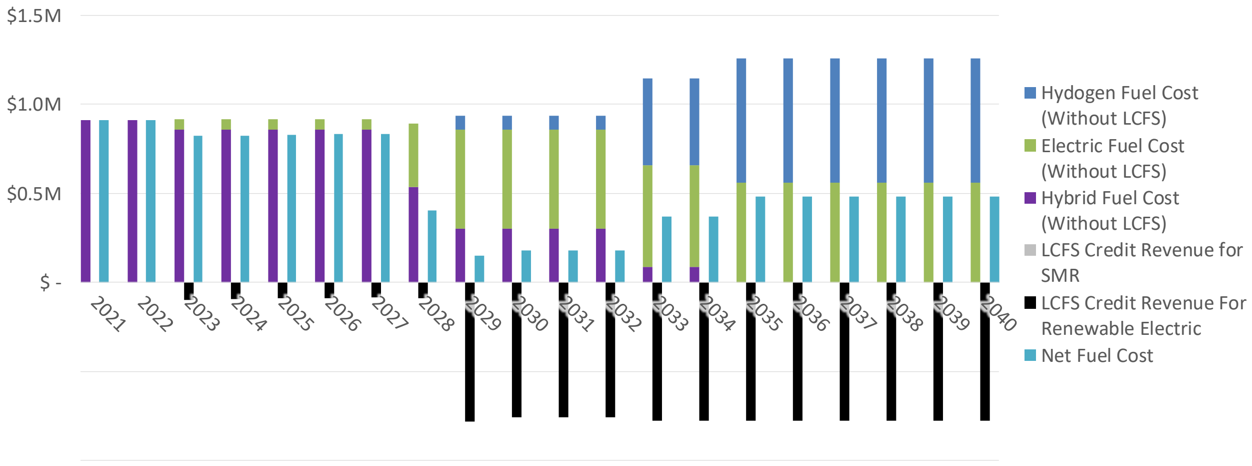


Figure 27 - Potential LCFS Credit Revenue for Fossil Fuel SMR Hydrogen, Mixed Fleet Scenario

Table 17 – LCFS Credit Revenue Estimates by Year for 100% Renewable Electrolysis Hydrogen, Mixed Fleet Scenario

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of BEBs in Fleet	0	0	4	4	4	4	4	24	40	40
Number of FCEBs in Fleet	0	0	0	0	0	0	0	0	4	4
LCFS Credit Gross Value per BEB	$28,000	$27,000	$26,000	$25,000	$25,000	$24,000	$23,000	$22,000	$21,000	$21,000
LCFS Credit Gross Value per FCEB - Electrolysis	$16,000	$15,000	$15,000	$14,000	$13,000	$13,000	$13,000	$12,000	$12,000	$11,000
Credit Processing Fee	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
LAVTA LCFS Credit Revenue	$ -	$ -	$97,000	$93,000	$90,000	$87,000	$84,000	$487,000	$827,000	$798,000

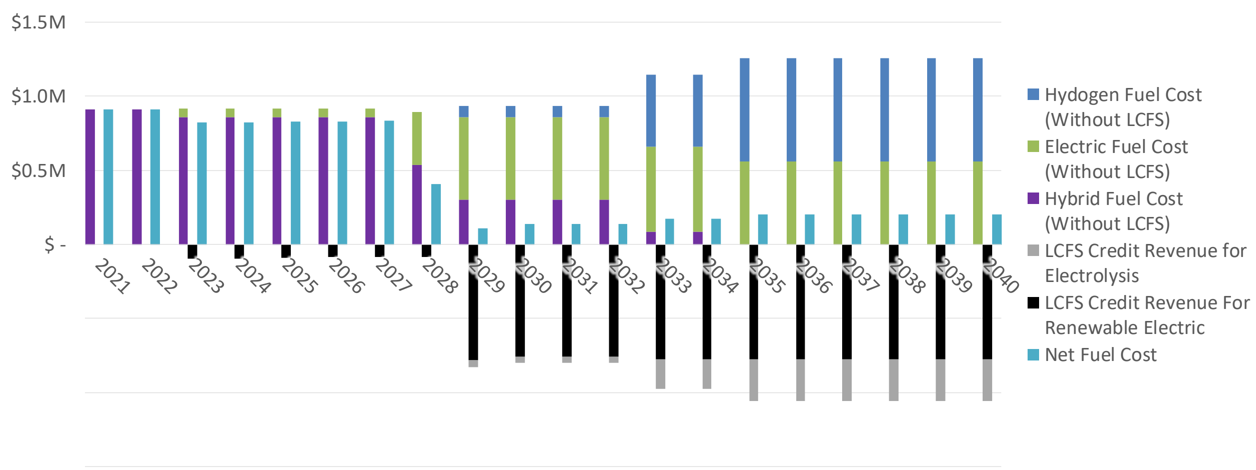


Figure 28 - Potential LCFS Credit Revenue for 100% Renewable Electrolysis Hydrogen, Mixed Fleet Scenario

Table 18 – LCFS Credit Revenue Estimates by Year for Dairy Gas SMR Hydrogen, Mixed Fleet

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of BEBs in Fleet	0	0	4	4	4	4	4	24	40	40
Number of FCEBs in Fleet	0	0	0	0	0	0	0	0	4	4
LCFS Credit Gross Value per BEB	$28,000	$27,000	$26,000	$25,000	$25,000	$24,000	$23,000	$22,000	$21,000	$21,000
LCFS Credit Gross Value per FCEB – Dairy Gas	$42,000	$41,000	$40,000	$39,000	$38,000	$37,000	$36,000	$35,000	$34,000	$33,000
Credit Processing Fee	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
LAVTA LCFS Credit Revenue	$ -	$ -	$97,000	$93,000	$90,000	$87,000	$84,000	$487,000	$906,000	$875,225

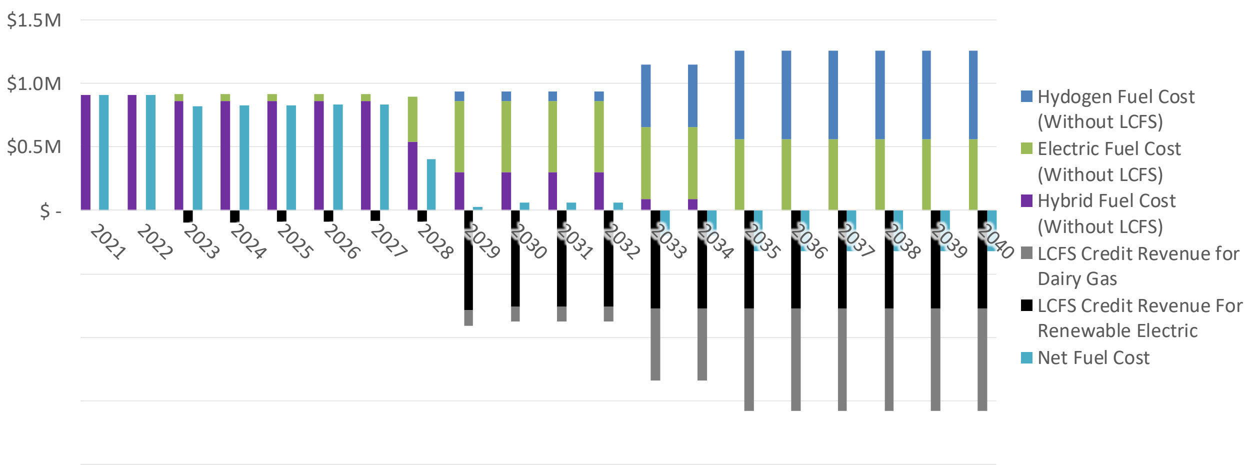


Figure 29 - Potential LCFS Credit Revenue for Dairy Gas SMR Hydrogen, Mixed Fleet Scenario

FCEB Only

Fuel cell electric buses are able to complete all of LAVTA's blocks by the end of the transition period in 2040. **Figure 30** depicts fuel consumption for each fuel type over the transition period for the FCEB Only scenario. Legacy fuels are phased out as hydrogen consumption increases, reflecting an increasing number of FCEBs in the fleet. Fleet energy use is reduced from about 0.4 million DGE in 2020 to just over 0.2 million DGE in 2040, an approximately 50% decrease.

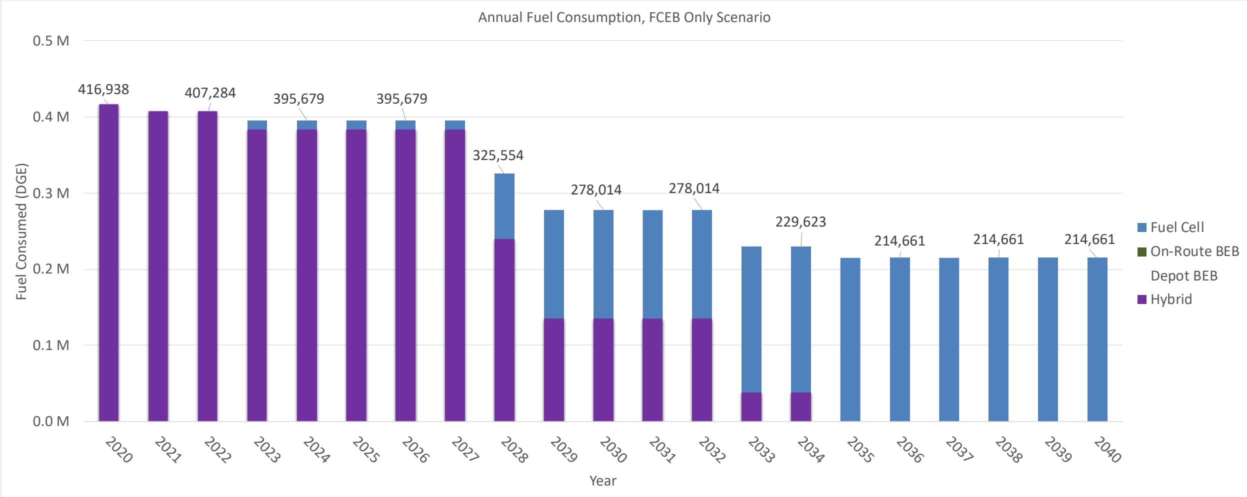


Figure 30 – Annual Fuel Consumption, FCEB Only Scenario

Figure 31 shows estimated annual costs for each fuel type based on the quantities consumed, as shown in **Figure 30**. Total estimated fuel costs, entirely from hydrogen fuel, in 2040 are approximately $2 million. As in the Mixed Fleet Scenario, the fuel costs increase over the transition period while the DGE consumption decreases. These trends reflect hydrogen's greater efficiency but also its higher costs compared to diesel fuel.

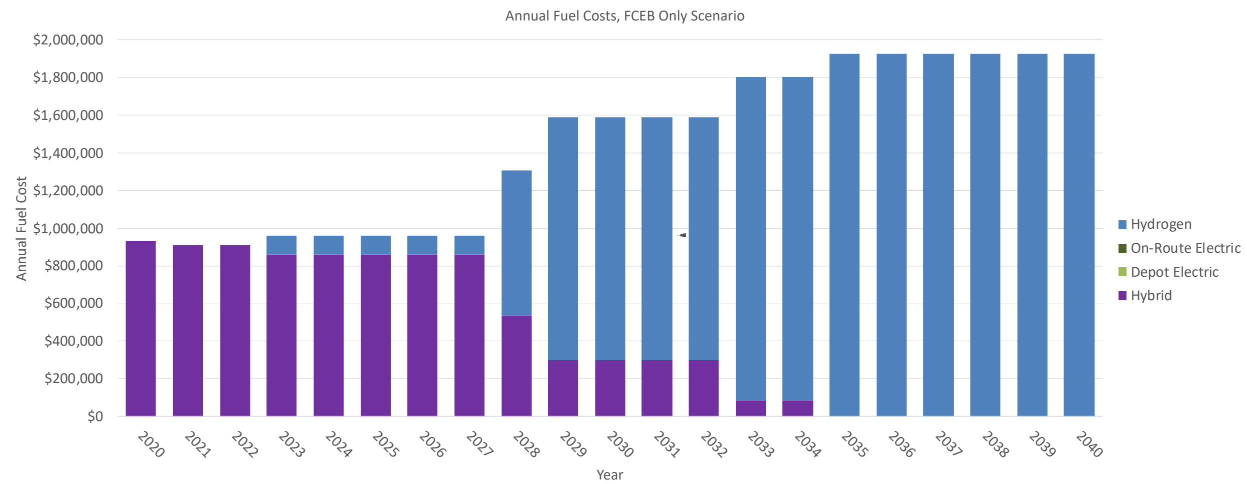


Figure 31 – Annual Fuel Costs, FCEB Only Scenario

The LCFS credit revenue in this scenario also depends largely on the method of hydrogen production for the fuel that LAVTA purchases. Fossil fuel SMR generates the least LCFS credits, and dairy gas SMAR generates the most.

Table 19 – LCFS Credit Revenue Estimates by Year for Fossil Fuel SMR Hydrogen, FCEB Only Scenario

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of FCEBs in Fleet	0	0	4	4	4	4	4	24	44	44
LCFS Credit Gross Value per FCEB - SMR	$1,392	$1,136	$887	$647	$419	$198	$-	$-	$-	$-
Credit Processing Fee	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
LAVTA LCFS Credit Revenue	$ -	$ -	$3,000	$2,000	$1,000	$700	$ -	$ -	$ -	$ -

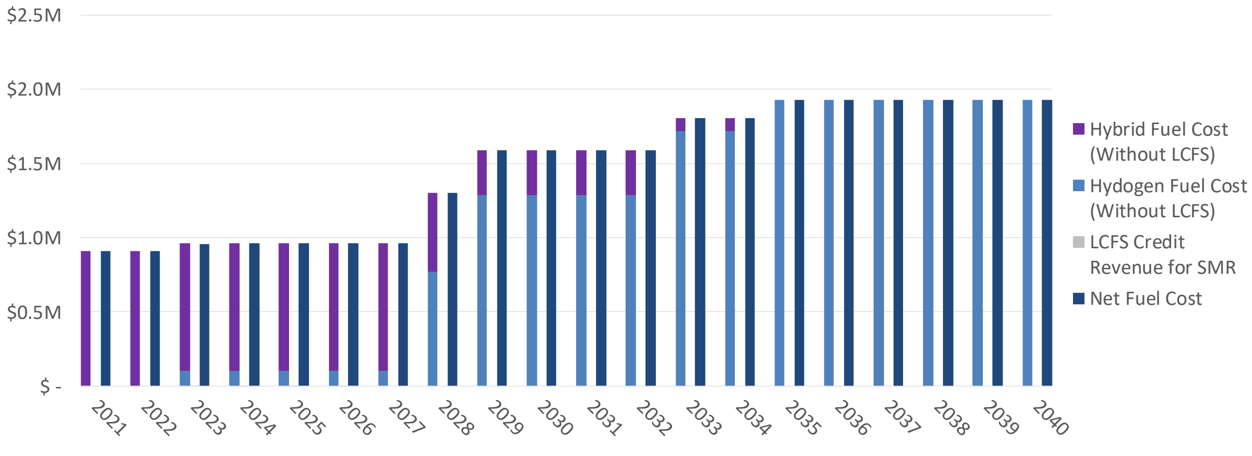


Figure 32 - Potential LCFS Credit Revenue for Fossil Fuel SMR Hydrogen, FCEB Only Scenario

Table 20 – LCFS Credit Revenue Estimates by Year for 100% Renewable Electrolysis Hydrogen, FCEB Only Scenario

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of FCEBs in Fleet	0	0	4	4	4	4	4	24	44	44
LCFS Credit Gross Value per FCEB - Electrolysis	$16,000	$15,000	$15,000	$14,000	$13,000	$13,000	$13,000	$12,000	$12,000	$11,000
Credit Processing Fee	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
LAVTA LCFS Credit Revenue	$ -	$ -	$54,000	$52,000	$50,000	$48,000	$47,000	$271,000	$479,000	$462,000

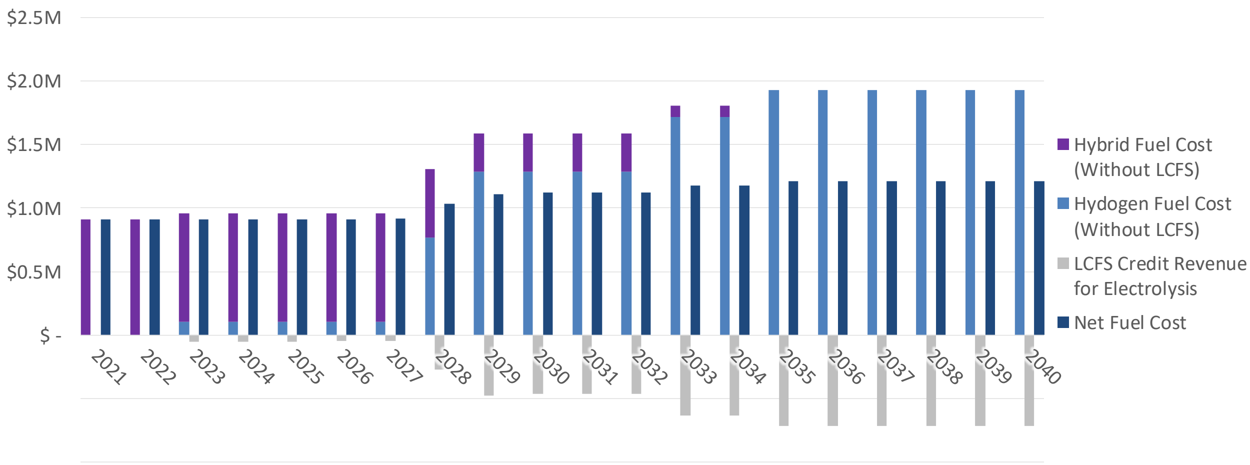


Figure 33 - Potential LCFS Credit Revenue for 100% Renewable Electrolysis Hydrogen, FCEB Only Scenario

Table 21 – LCFS Credit Revenue Estimates by Year for Dairy Gas SMR Hydrogen, FCEB Only Scenario

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of FCEBs in Fleet	0	0	4	4	4	4	4	24	44	44
LCFS Credit Gross Value per FCEB – Dairy Gas	$42,000	$41,000	$40,000	$39,000	$38,000	$37,000	$36,000	$35,000	$34,000	$33,000
Credit Processing Fee	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
LAVTA LCFS Credit Revenue	$ -	$ -	$143,000	$139,000	$135,000	$132,000	$129,000	$752,000	$1,343,000	$1,308,000

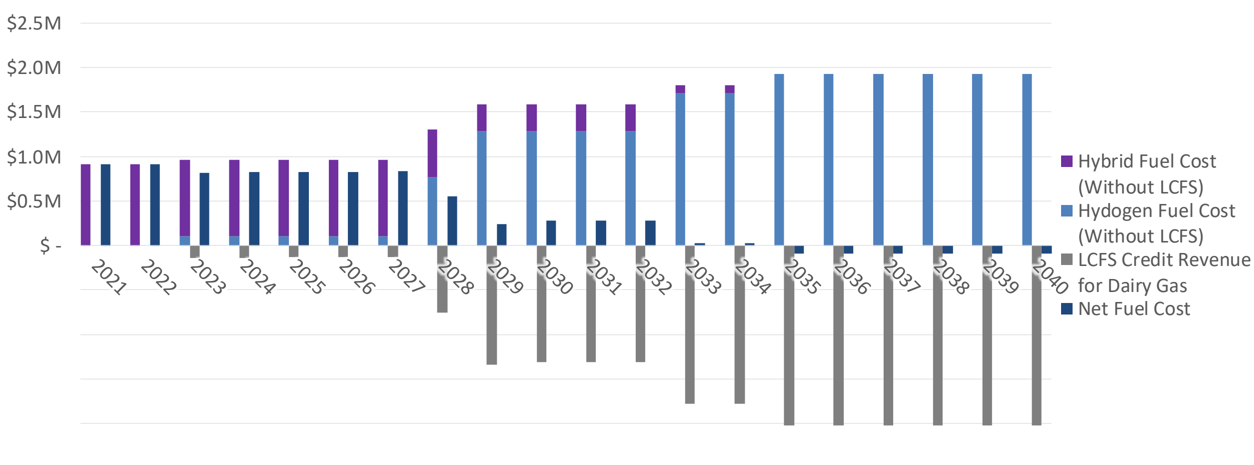


Figure 34 – Potential LCFS Credit Revenue for Dairy Gas SMR Hydrogen, FCEB Only Scenario

Fuel Assessment Cost Comparison

The Fuel Assessment includes all fuel costs over the transition for each scenario. **Figure 35** shows the cumulative fuel costs for each scenario over a twenty-year period. **Table 22** - Total Fuel Costs Over Entire Transition Period, Fuel Assessment shows the combined total costs and the percentage of the fleet that is zero-emission in 2040.

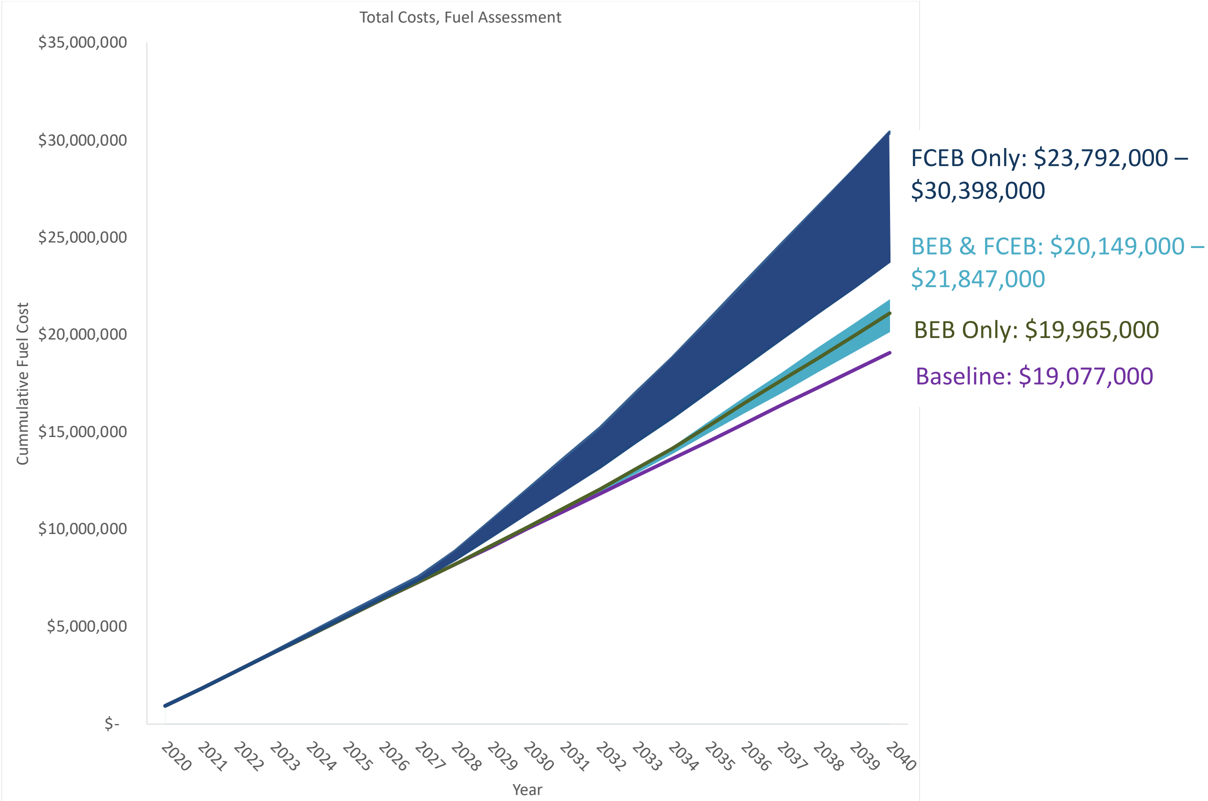


Figure 35 – Total Costs, Fuel Assessments

Table 22 - Total Fuel Costs Over Entire Transition Period, Fuel Assessment

Scenario	Cumulative Fuel Cost	Average Annual Fuel Cost	% ZEB in 2040
Baseline	$ 19,077,000	$ 954,000	0%
BEB Only	$ 19,965,000	$ 1,025,000	100%
Mixed Fleet: BEB and FCEB	$ 20,149,000 – $ 21,833,000	$ 1,007,000 – $ 1,092,000	100%
FCEB Only	$ 23,792,000 – $ 30,398,000	$ 1,190,000 – $ 1,520,000	100%

7 Maintenance Assessment

One of the anticipated benefits of operating a BEB or FCEB fleet is reduced maintenance costs. Early adopters of ZEB technologies have reported that a transit agency may attain 30% to 50% in maintenance cost savings for a BEB compared to an ICE vehicle. These savings result from there being fewer fluids to replace (no engine oil or transmission fluid), fewer brake changes due to regenerative braking, and far fewer moving parts than in an internal combustion engine. The savings in traditional maintenance costs may be offset by the cost of battery or fuel cell replacements over the life of the buses. These costs, however, may be covered by extended warranties.

Diesel-hydrid bus labor and maintenance costs were provided by LAVTA for their current fleet. BEB labor and maintenance costs were estimated as a 35% reduction on the diesel-hybrid cost, which was based on industry expectations and labor and maintenance costs from King County as reported by the U.S. DOE National Renewable Energy Laboratory (NREL).[6] Hydrogen maintenance costs were based on OCTA's reported labor and maintenance costs. It should be noted that this FCEB maintenance per mile value is based on the costs for the first year of service at OCTA. Therefore, this cost is likely higher than expected over time since this is a first generation vehicle.

In addition to labor and materials, this study also estimates the cost impact of midlife overhauls for major components for each type of bus. **Table 23** shows the assumed costs of scheduled and unscheduled labor and maintenance used in this analysis.

Table 23 – Labor and Materials Cost Assumptions

Type	Estimate (Per Mile)	Source
40' Hybrid	$ 0.38	LAVTA
40' BEB	$ 0.25	U.S. DOE & NREL
40' FCEB	$ 0.59	OCTA price used

Assumptions used in this analysis are given in **Table 24.** Cost assumptions for fossil-fuel buses are based on LAVTA data. Midlife battery overhaul cost estimates for BEBs are based on extended warranty costs provided by bus OEMs, and the FCEB battery warranty cost is a prorated estimate of that rate based on battery storage capacity.

[6] Eudy, Leslie and Matthew Jeffers. 2019. Foothill Transit Agency Battery Electric Bus Progress Report: Data Period Focus: Jul.2018 through Dec. 2018. Golden, CO: National Renewable Energy Laboratory. NREL/PR-5400-72209. https://afdc.energy.gov/files/u/publication/foothill_transit_beb_progress_rpt_5-2019.pdf.

Table 24 - Midlife Overhaul Cost Assumptions

Type	Overhaul Scope	Estimate	Source
Diesel	Engine/Transmission Overhaul	$50k per bus	LAVTA
BEB	Warranty Cost	$75k per bus	Bus OEM
FCEB	Battery Replacement Warranty Fuel Cell Overhaul	$16.7k per bus $40k per bus	Estimate Based on Bus OEM Fuel Cell OEM

Note that there are spikes in the expected maintenance costs six years after a large number of buses are purchased, such as 2021 and 12 years later when those buses are replaced in 2033. The 12-year replacement cycle creates a cyclical pattern in maintenance costs in midlife years because the diesel-hybrids would be expected to incur a midlife overhaul at that time. Since this scenario represents a fleet that stays entirely composed of diesel-hybrid buses, the peaks consistently repeat every 12 years at the midlife of large purchases. In non-midlife years, the annual price is around $780,000 and, in the years, where up to 20 buses are expected to reach the midlife in the same year, the price increases to $1.78 million. **Figure 36** shows the combined labor, materials, and midlife overhaul costs for the Baseline scenario for each year of the transition, in 2020 dollars.

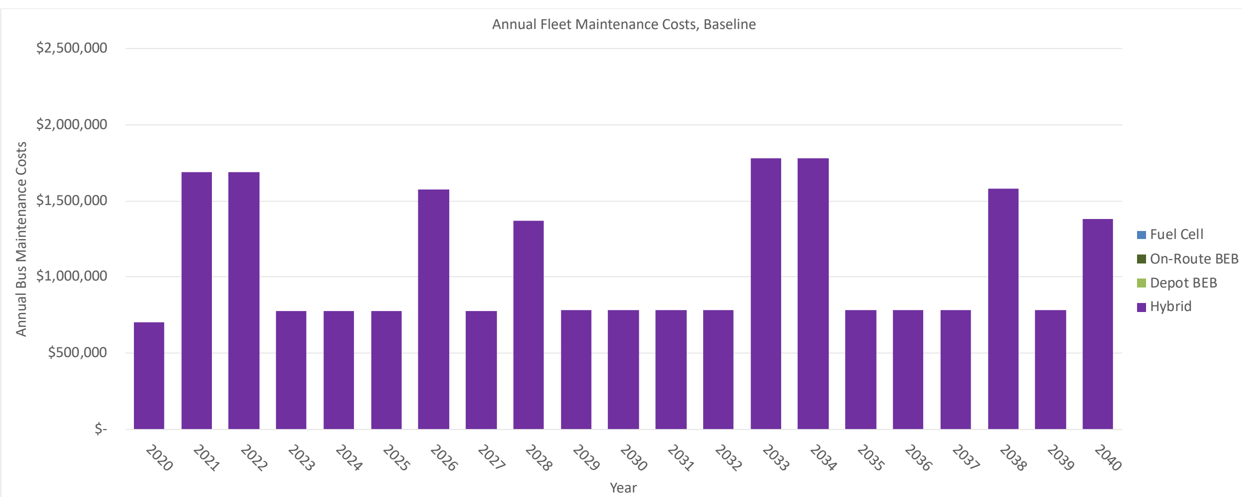


Figure 36 - Annual Fleet Maintenance Costs, Baseline

BEB Only

Figure 37 shows the combined labor, materials, and midlife overhaul costs for the BEB Only scenario for each year of the transition, in 2020 dollars. For the Depot with On-Route Charging scenario, warranty costs are used in place of the midlife battery replacement, so there are spikes in the expected maintenance costs the same years that a large number of buses are purchased, such as 2028. In this scenario, the 12-year replacement cycle shifts the cyclical pattern in maintenance costs from non-purchasing years to purchasing years. Comparing 2020 to 2032—a non-purchasing and non-midlife year when the fleet is composed of only hybrids compared to when the fleet is mostly BEBs—the annual maintenance drops from around $780,000 to around $500,000. Despite the $75,000 for the warranty exceeding the $50,000 expected for the midlife overhaul of the hybrids, the reduced per mile maintenance expected for the BEBs results in a 4% reduction of maintenance costs for this scenario compared to the Baseline.

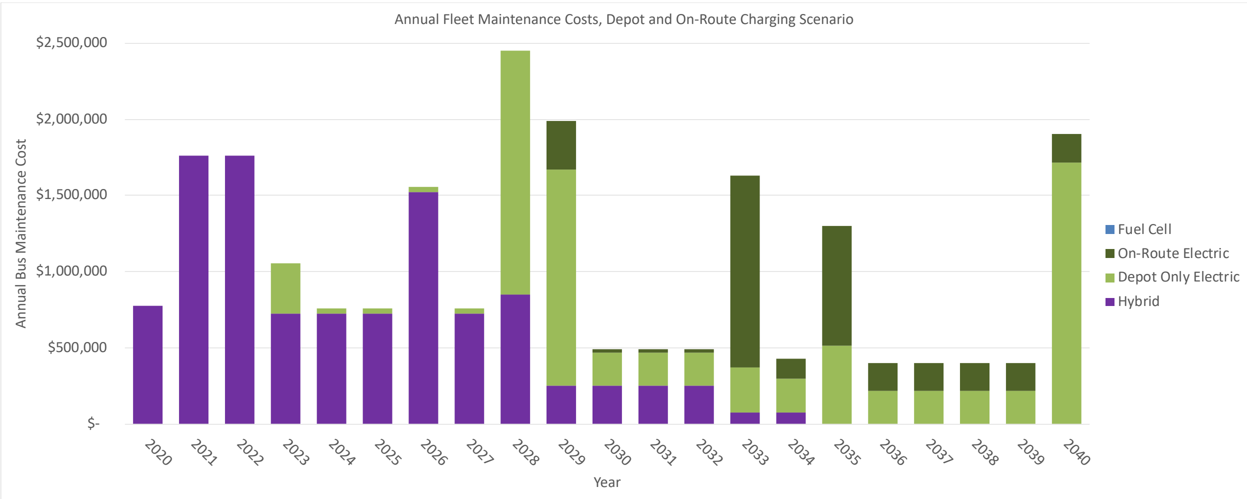


Figure 37 - Annual Fleet Maintenance Costs, BEB Only Scenario

Mixed Fleet: BEB and FCEB

Figure 38 shows the combined labor, materials, and midlife overhaul costs for the Mixed Fleet: BEB and FCEB scenario for each year of the transition, in 2020 dollars. Unlike in the BEB Only scenario, the FCEB scenarios have their largest maintenance costs at the midlife overhaul. These events coincide because the FCEBs have a smaller warranty cost—$16,700 as opposed to $75,000 for BEBs because FCEBs have a significantly smaller battery on board— that applies to their purchase year. Their fuel cells, however, are expected to be replaced midlife—six years after purchasing. This timing results in the years with the highest expected maintenance amounts being years that are at the buses' midlife. Comparing 2020 to 2032 shows a slight decrease in expected maintenance costs per mile due to the fact that the per-mile maintenance cost for the BEBs is lower than that of the diesel-hybrids.

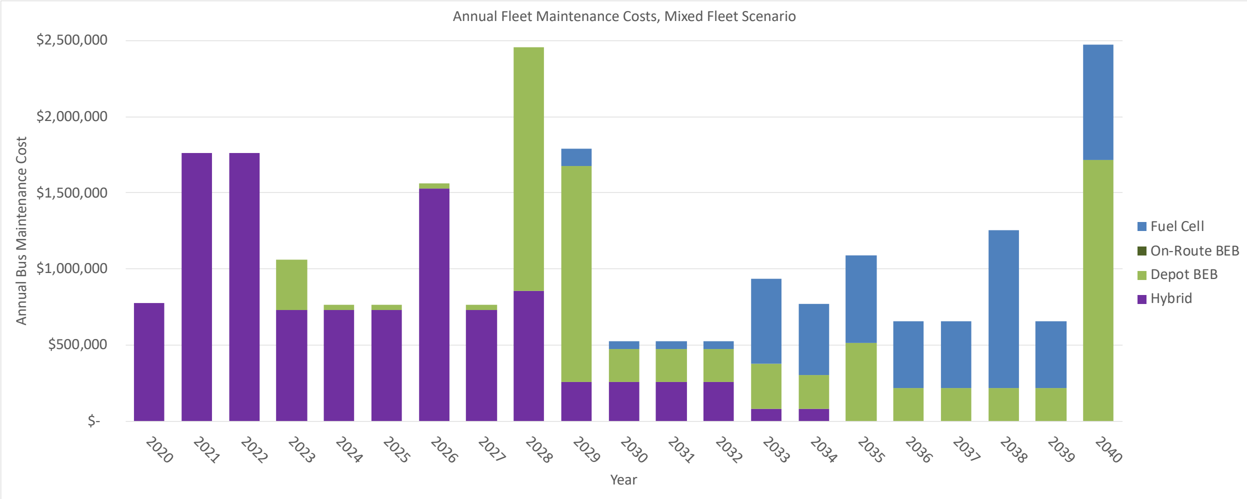


Figure 38 - Annual Fleet Maintenance Costs, Mixed Fleet Scenario

FCEB Only

Figure 39 shows the combined labor, materials and midlife overhaul costs for the FCEB Only scenario for each year of the transition, in 2020 dollars. As discussed with the Mixed Fleet scenario, FCEB's have significant maintenance costs at their midlife when the fuel cells are expected to be replaced. Comparing 2020 to 2032 reveals a slight increase in expected maintenance costs per mile compared to the Baseline or the BEB Only scenarios. This increase is a result of using OCTA's reported maintenance cost, which was used to estimate the maintenance costs for FCEBs in this study; OCTA's reported costs were higher than the estimates used for the diesel-hybrids or BEBs.

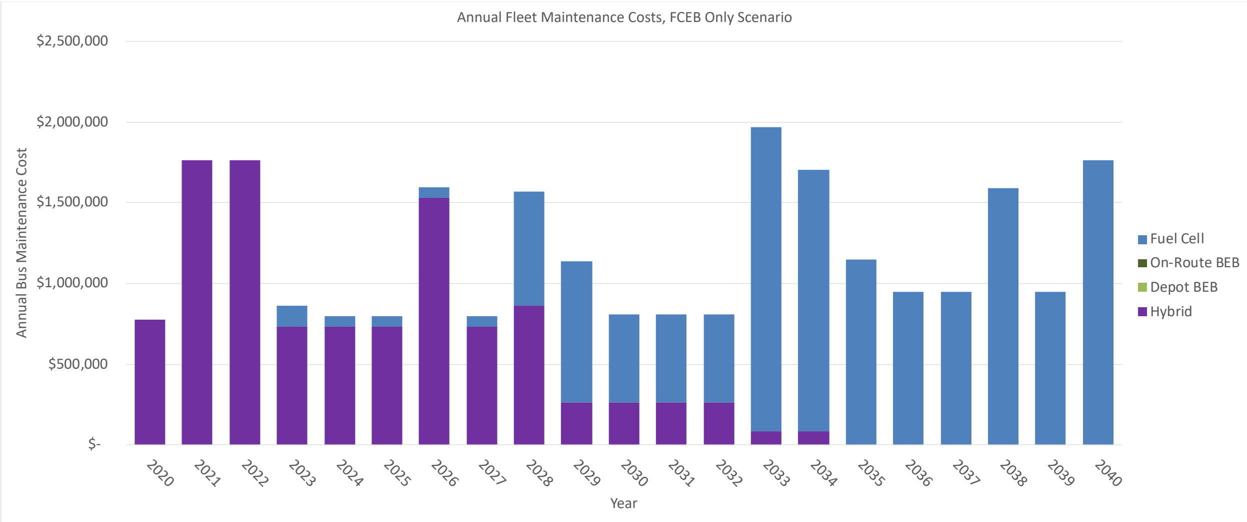


Figure 39 - Annual Maintenance Costs, FCEB Only Scenario

Maintenance Assessment Cost Comparison

The Maintenance Assessment includes all labor, materials and, overhaul costs over the transition for each scenario. **Figure 40** shows the cumulative maintenance costs for each scenario.

Table 25 shows the total maintenance costs for each scenario. All of these scenarios are within $3 million of each other at the end of the 20-year period. The FCEB Only scenario incurs the most maintenance costs while the BEB Only incurs the least. The fact that the FCEB Only scenario was more expensive than the BEB Only Scenario —despite the difference in the $75,000 for the BEB battery warranty and the $56,700 for the FCEB fuel cell replacement and battery warranty cost—shows that the differential in the per-mile maintenance cost of $0.25 per mile for BEBs and $0.59 per mile for FCEBs had a larger impact on the overall annual maintenance costs for the technologies than the warranties costs. It should also be noted that the BEB Depot and On-Route Charging scenario cost about $1 million less than the Baseline scenario over the 20-year transition period.

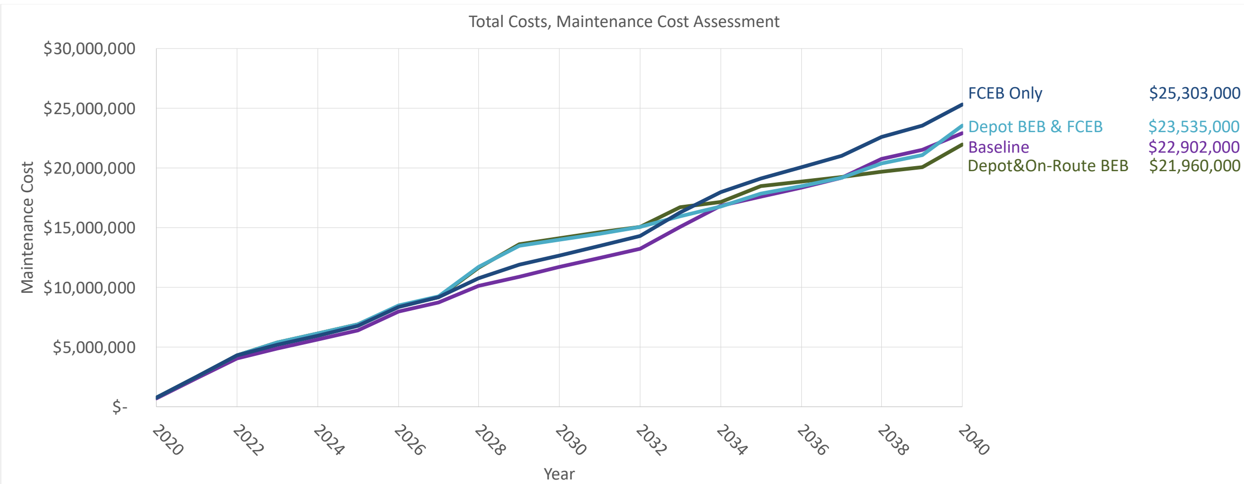


Figure 40 - Total Costs, Maintenance Assessments

Table 25 - Total Costs, Maintenance Assessments

Scenario	Cost	% ZEB
Baseline	$ 22,902,000	0%
BEB Only	$ 21,960,000	100%
Mixed Fleet: BEB and FCEB	$ 23,535,000	100%
FCEB Only	$ 25,303,000	100%

8 Facilities Assessment

The Facilities Assessment determines the scale of supporting infrastructure—charging infrastructure for BEBs and hydrogen infrastructure for FCEBs—necessary to meet the projected energy use estimated in the Fleet and Fuel Assessments. Facilities costs are then estimated based on the assessed infrastructure requirements for the given fleet. This section is divided between battery-electric infrastructure and hydrogen fueling infrastructure, which are further subdivided by their relevant assessment scenarios. Also, since the Baseline assumes that LAVTA already has the facilities necessary to support their diesel hybrid fleet, the Baseline was not included in the facilities assessment. Since LAVTA will be moving their depot from Rutan Court to their new facility at Atlantis Court, the BEB scenarios will include charging infrastructure at Rutan Court for the initial four bus deployment before the full facility build out occurs at the Atlantis Court facility. The charging infrastructure at Rutan Court would be put in place to support BEBs deployed prior to the shift in depots. Some of the costs of the electrical upgrades may be offset by PG&E's EV Fleet Program. If one of the BEB scenarios is pursued by LAVTA, the agency should apply to participate in this program. Similarly, since the permanent FCEB infrastructure cannot be scaled down to the level of four buses, the FCEB Only Scenario would involve a mobile fueler at Rutan Court before there is permanent infrastructure installed at the Atlantis Court facility.

Battery-Electric Charging Scenarios Depot Infrastructure

Scaling to a fleetwide BEB deployment requires a significantly different approach to charging and substantial infrastructure upgrades compared to smaller pilot deployments. With small BEB pilot deployments, charging requirements are met relatively easily with a handful of plug-in pedestal chargers and minimal infrastructure investment. For fleetwide BEB transitions, plug-in charging is impractical as charger dispenser cables can create hazards in the bus yard. Instead, the preferred approach is to use overhead pantograph or reel dispensers attached to gantries installed above bus parking lanes.

In addition to the installation of charging stations, improvements to existing electrical infrastructure, such as upgrades to switchgear or service connections, are required to support deployment of BEBs. Planning and design work, including development of detailed electrical and construction drawings required for permitting, is necessary once specific charging equipment has been selected. To define the installation timeline and costs for charging equipment, the scope of work is broken into four key project types: planning, structural, power upgrades, and charger installation. These projects are typically sized and scheduled to meet near-term charging requirements rather than immediately building out all necessary infrastructure for a full fleet transition.

CTE and AECOM developed estimates for components of each project type to build up a total cost estimate by project type. Assumptions used for BEB infrastructure are shown in **Table 26**. Conceptual layouts for the BEB Only Scenario, prepared by AECOM, are provided in **Appendix A1** – LAVTA Depot Site Plans, **.** As previously mentioned, when LAVTA begins its ZEB transition in 2023, the depot and administrative facilities will still be located at the Rutan Court facility, but will be moving to a new facility on Atlantis Court before its next ZEB purchase in 2028. In the BEB scenarios, LAVTA elected to pursue installation of two pedestal chargers at the Rutan facility to support the initial four buses, but the full BEB facility buildout will take place at the Atlantis Court location. AECOM did note that deploying the initial four BEBs from Rutan Court will likely require a transformer upgrade unless the existing load on the transformer is below 60kVA but did not identify any other factors that might impede the four-bus deployment.

AECOM also supplied a report including the power requirements, equipment and raceway routing, gantries, and phasing for Atlantis Court as an electric charging depot for both the BEB Only Scenario and the Mixed Fleet: BEB and FCEB Scenario.

For both the BEB Only Scenario and the Mixed Fleet Scenario, AECOM expects that, in 2027, gantries and chargers are installed for the next 40 buses at Atlantis Court. This installation will require a contractor lay-down area to cover the existing driveway and use of temporary access driveways to the north of the existing driveway. At this stage, there will be hybrid parking on the north half of the parking lot, with BEB parking on the southern half. This stage of the project also encompasses phase 1 of the power upgrade phasing outlined by AECOM. To accommodate the demand resulting from the addition of this series of 120kW chargers, a new 480 volt, 3-phase service and a new 2500kVA transformer will be required. See Appendix A1 – LAVTA Depot Site Plans, Depot and On-Route Charging Scenario Phase 1 - 2027 and **A5** for 2027 phasing plan.

In the BEB Only Scenario, the remaining hybrid parking will be converted to additional BEB parking in 2032. This project will require the contractor lay-down area to shift to the north and cover one of the temporary access driveways. At this stage, lot access is also possible through the primary driveway, as well as one of the temporary driveways. At this stage, the second phase of the power upgrade phasing is scheduled to occur in order to accommodate the 13 chargers being added to charge the 24 additional buses. This will require a 2000kVA transformer, as well as a switchboard rated for 2500A at 480V, three-phase. See **Appendix A2** for 2032 phasing plan.

In that same year for the Mixed Fleet Scenario, the same BEB infrastructure projects and service upgrades would be needed. This is also the time when the hydrogen fueling infrastructure will be installed. See **Appendix A6** for 2032 phasing plan.

The final site plans for the completed transition can be seen in the 2035 site layouts in **Appendix A3** for Depot and On-Route Charging Scenario and **A7** for the Mixed Fleet.

Although some of the costs that AECOM supplied such as the power upgrade costs, were estimated as part of CTE's analysis included in this Master Plan, it is recommended that more detailed cost analysis be done before build and or funding obligation based on AECOM's recommendations.

Table 26 – BEB Infrastructure Project Cost Assumptions

Project	Cost Estimate Metrics	Source
Infrastructure Planning	$200k per project	Engineer’s estimate
Structural Projects (Gantries, Conduit, duct banks, etc.)	Design/Construction: avg. $117k per bus	Engineer’s estimate, includes 20% contingency
Power Upgrade Projects	Design, Construction, & Equip: $96k per MW	Engineer’s estimate, includes 20% contingency
Charging Projects	Charging Equipment & Installation: $89k per bus	Quotes and estimates, includes 20% contingency

Key assumptions applied in LAVTA’s Facilities Assessment are as follows:

- Gantry structures are used at each depot;
- One plug-in reel or overhead pantograph per bus;
- Two buses per 120 kW charger;
- Two charge windows, i.e. no more than half the buses charge at any given moment;
- Off-peak, overnight charging with automated charge management software; and
- Dispenser capacity to serve up to 80% of the fleet at a time; no movement of buses overnight.

On-Route Charging Infrastructure

The BEB Only scenario has on-route charging infrastructure in addition to the depot charging infrastructure already developed and presented in the previous section. The addition of on-route charging supports deployment and on-route charging of 27 electric buses in addition to 41 depot-only charged buses before 2040. In this section, the on-route infrastructure costs are summarized along with the depot infrastructure costs.

Although it is not always the case, on-route chargers may not require additional support structures, such as gantries, to be built and may not require any structural project planning, as depot chargers do. Required infrastructure projects for on-route chargers include planning, power upgrade, and charger purchase and installation, which can be summarized as design costs and equipment costs. **On-route** chargers were assumed to be located at transit hubs, the Livermore Transit Center and The East Dublin Pleasanton BART station already planned for and utilized in LAVTA’s service.

 shows the cost assumptions used in the following sections to estimate costs for on-route charging infrastructure. This study did not include the costs of land acquisition for on-route charging sites. On-route chargers were assumed to be located at transit hubs, the Livermore

Transit Center and The East Dublin Pleasanton BART station already planned for and utilized in LAVTA's service.

Table 27 – On-Route Infrastructure Project Cost Assumptions

Project	Cost Estimate Metrics	Source
Structural Projects (Gantries, Conduit, duct banks, etc.)	Design/Construction: avg. 30k per bus	Engineer's estimate, includes 20% contingency
Power Upgrade Projects	Design, Construction, & Equip: $264k per MW	Engineer's estimate, includes 20% contingency
Charging Projects	Charging Equipment & Installation: $39k per bus	Quotes and estimates, includes 20% contingency

BEB Only On-Route Charging Projects

It is assumed that each on-route charging project will cost around $2.7 million per site. The number of on-route projects occurring in a given year are shown in **Figure 41**, below. A total of two on-route charging sites will be required to serve the additional 27 on-route-charged buses, which is expected to cost around $5.4 million. The East Dublin Pleasanton BART Station and the Livermore Transit Center have been identified as potential sites for on-route stations. Site designs for the two identified potential on-route station sites can be found in **Appendix A9**.

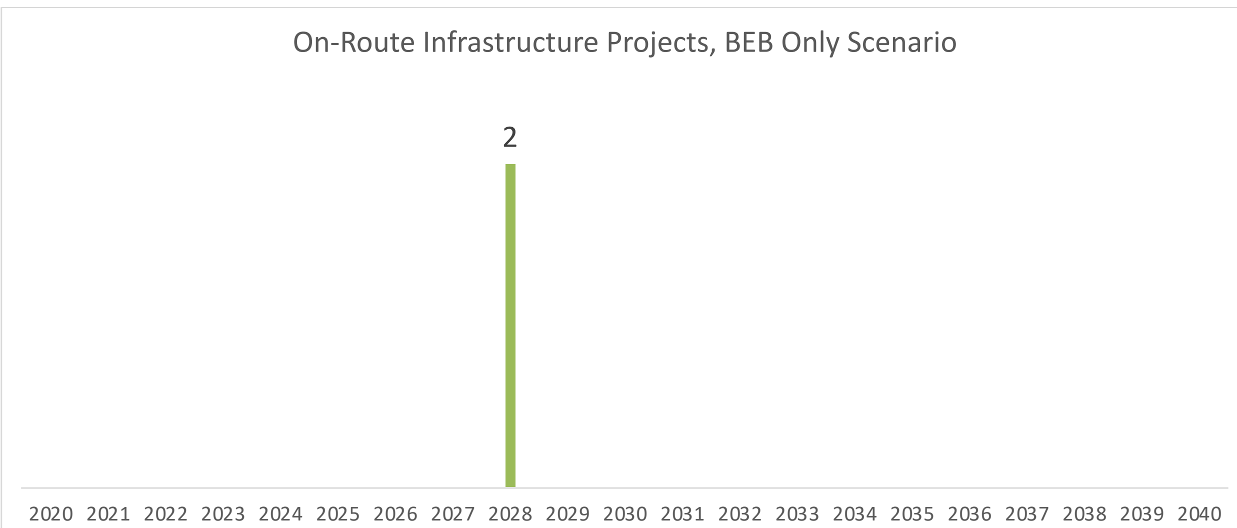


Figure 41 - On-Route Infrastructure Projects, BEB Only Scenario

BEB Only Depot Planning Projects

In addition to on-route charger projects, the Depot and On-Route Scenario also requires infrastructure planning at the depot. Planning is estimated to cost $200,000 at each depot. One $200,000 project is therefore planned for LAVTA over the transition period.

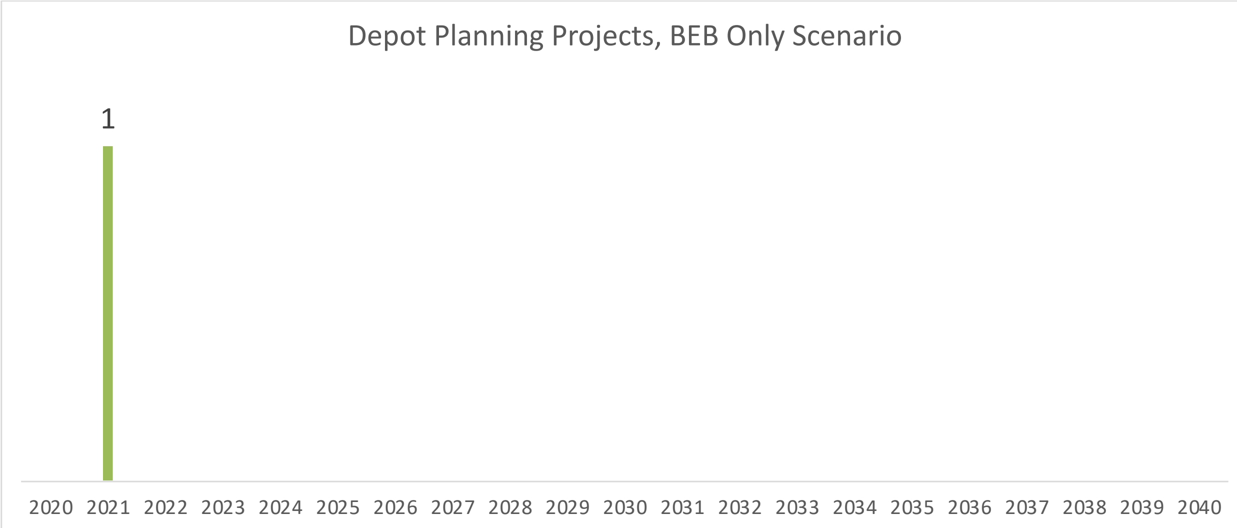


Figure 42 - Depot Planning Projects, BEB Only Scenario

BEB Only Depot Structural Projects

Structural projects include (1) trenching and build out duct banks from the switchgear to the charger pads, (2) construction of charger pads (i.e. foundation for charging equipment), (3) construction of gantry foundations and overhead gantry structures that hold the dispensers, and (4) installation of conduit from switchgear to charger pads and gantries. **Table 28** shows the detailed cost assumptions for structural projects. These cost assumptions also apply to other projection scenarios. Duct bank cost is incurred only once per depot, other costs are on a per gantry basis.

Table 28 – Structural Project Cost Assumptions

Item	Cost	Unit
Initial Duct/Bank	$ 300,000	per depot
Gantry & Foundation	$ 450,000	per gantry
Incremental Duct Bank/Conduit	$ 22,000	per gantry
Charger Pad (3 chargers per gantry)	$ 25,000	per gantry
Contingency	20%	on project costs
Design Engineering	6%	on project costs and contingency

Each bar in the figure below indicates a structural project to add overhead gantry capacity to the depot. **Figure 43** shows the number of gantries added in a given year. Each gantry can serve up to six buses. A total of 12 gantries will be needed at LAVTA's Atlantis depot.

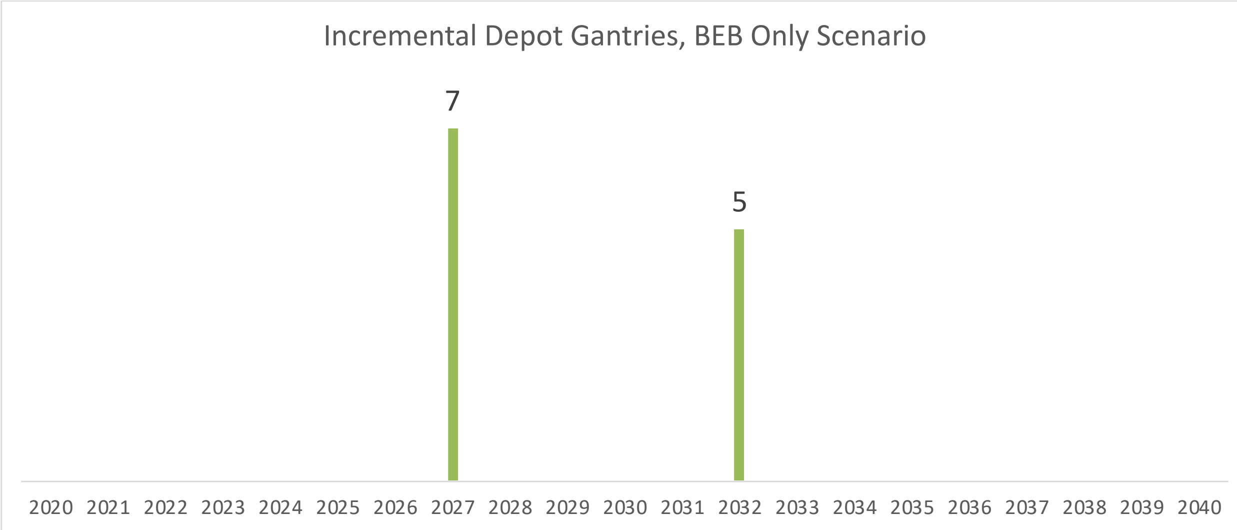


Figure 43 –Incremental Depot Gantries, BEB Only Scenario

Figure 44 shows the total annual costs of structural projects by depot for the BEB Only scenario. These costs include the initial duct bank costs, gantry and foundation costs, incremental duct bank/conduit costs, and charger pad costs per gantry, sequenced in accordance with the costs in the table above. On top of these costs, 20% contingency and 6% engineering costs are added.

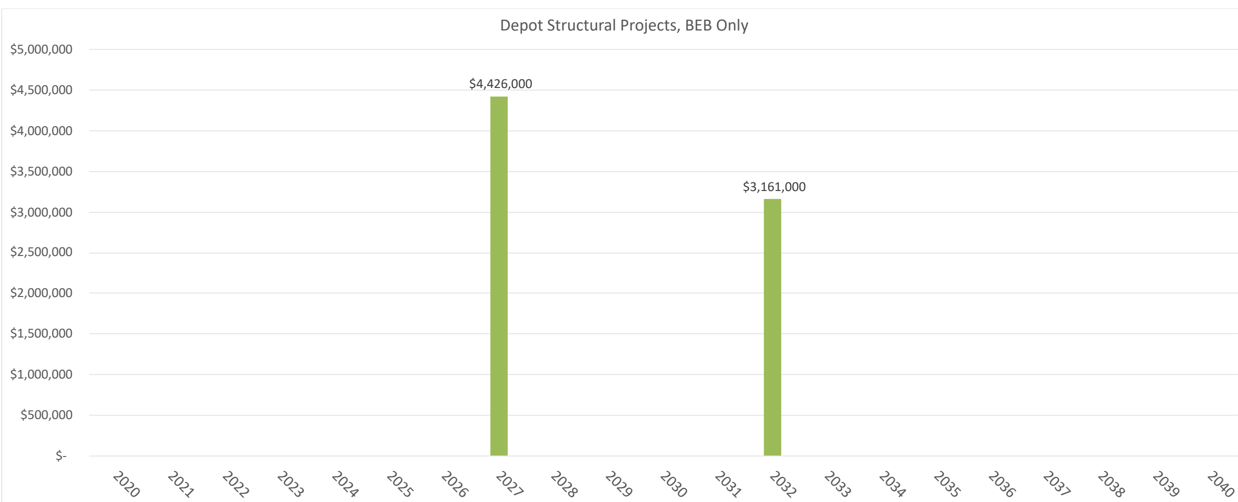


Figure 44 – Annual Depot Structural Projects Cost, BEB Only Scenario

BEB Only Power Upgrade Projects

Power upgrade projects include construction of transformer foundations and installation of transformers. It is assumed that transformers will be modular, and incremental power requirements are met over time. The table below shows the estimated costs for depot power upgrade projects.

Table 29 – Depot Power Upgrade Cost Assumptions, BEB Only Scenario

Transformer/Switchback Pad	Cost	Unit
Transformer	Covered by PG&E	
Trench and Ductbank	$ 30,000	per project
Construction, Equipment (1 MW)	$ 125,000	per project
Construction, Equipment (2 MW)	$ 125,000	per project
Construction, Equipment (4 MW)	$ 250,000	per project
Contingency	20%	on project costs
Design Engineering	6%	on project costs and contingency

Figure 45 shows incremental required electrical demand, in megawatts, for each depot. Each entry indicates the minimum amount of power that must be added in a given year to meet the growing demand at a given facility as more BEBs are purchased.

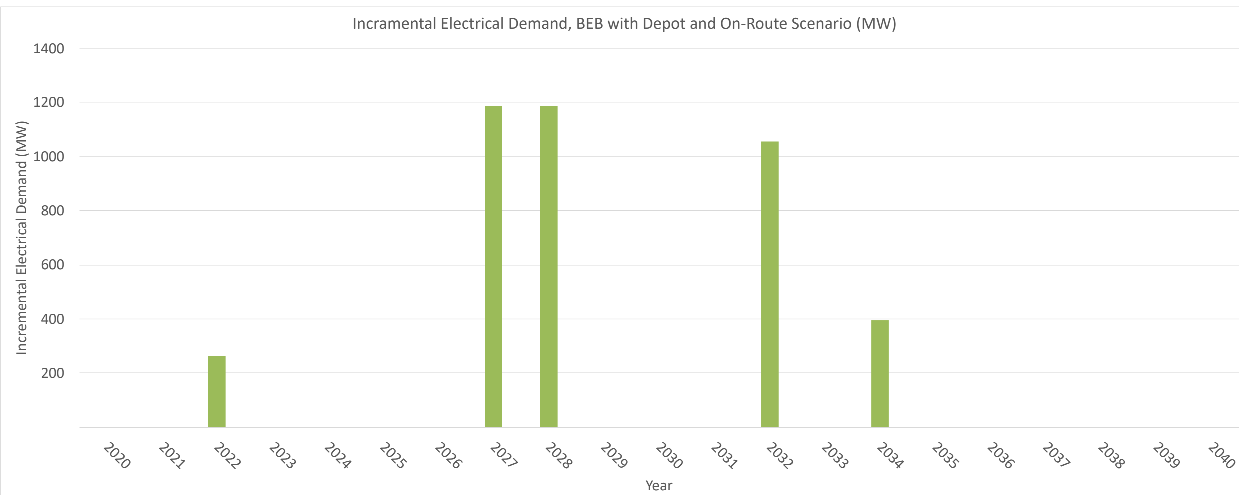


Figure 45 – Incremental Depot Electrical Demand, BEB Only Scenario (MW)

Power upgrades are consolidated to occur in selected years, in accordance with the required demand in **Figure 45.** These recommended upgrades are shown in **Figure 46**. LAVTA will need to add an additional estimated 6 MW of capacity to its system by 2040 to accommodate charging for 68 BEBs.

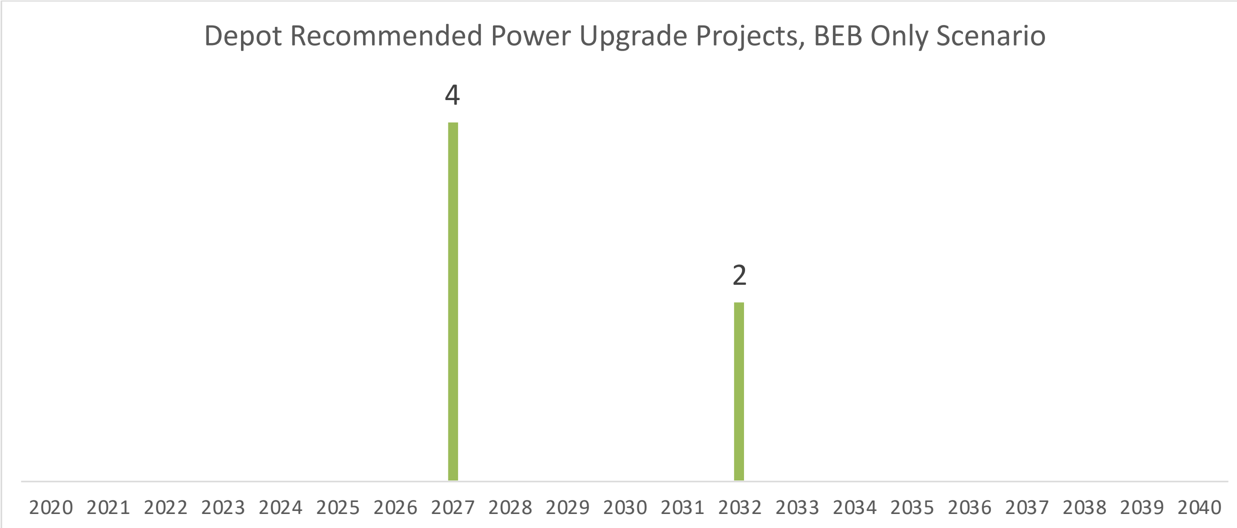


Figure 46 – Depot Recommended Power Upgrade Projects, BEB Only Scenario (MW)

The total cumulative cost of power upgrade projects at the depot, in 2020 dollars, is provided in Error! Reference source not found.. Total estimated power upgrade costs over the project life are approximately $0.57 million.

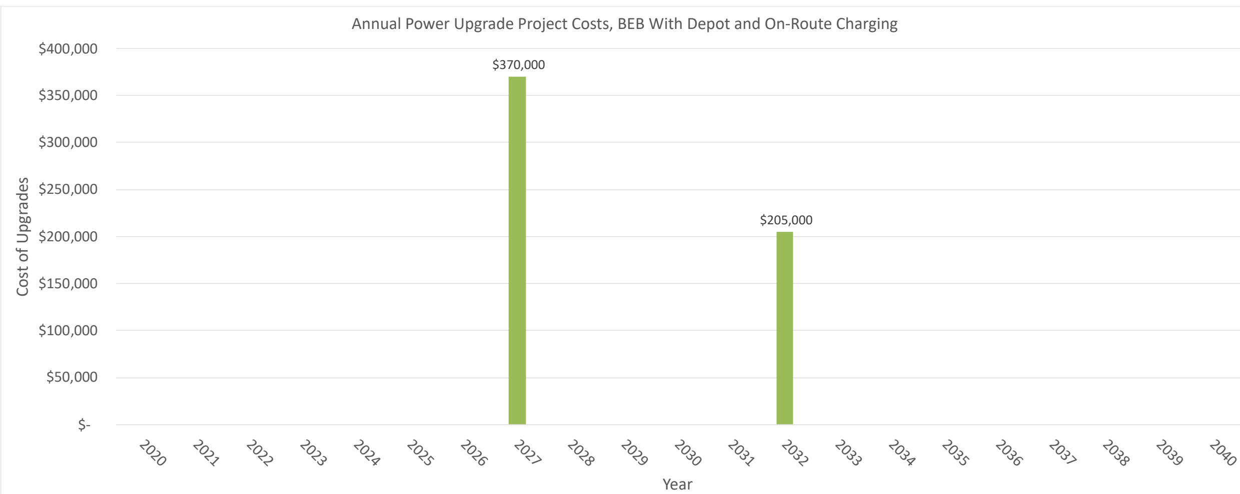


Figure 47 – Depot Annual Power Upgrade Project Costs, BEB Only Scenario

BEB Only Depot Charger Installation Projects

Charging projects include purchase and installation of 120 kW chargers and dispensers. Each bus will require one dispenser. Every two buses (40-foot and larger) will require one charger. Dispensers are expected to be either overhead reel or pantograph style. **Table 30** provides the costs assumed for charger and dispenser installs. As seen in **Figure 48** and **Figure 49**, in total, this scenario would require 33 chargers (66 dispensers) at LAVTA's Atlantis site.

Table 30 - Dispenser and Charger Project Cost Assumptions

Item	Cost	Unit
Charger	$ 120,000	per 120 kW charger
Charger Installation	$ 12,000	per 120 kW charger
Dispenser/Pantograph	$ 10,000	per dispenser
Dispenser Installation	$ 5,000	per dispenser
Contingency	20%	on project costs

Figure 48 and **Figure 49** show the annual dispensers and charger installations by depot for each year of the project.

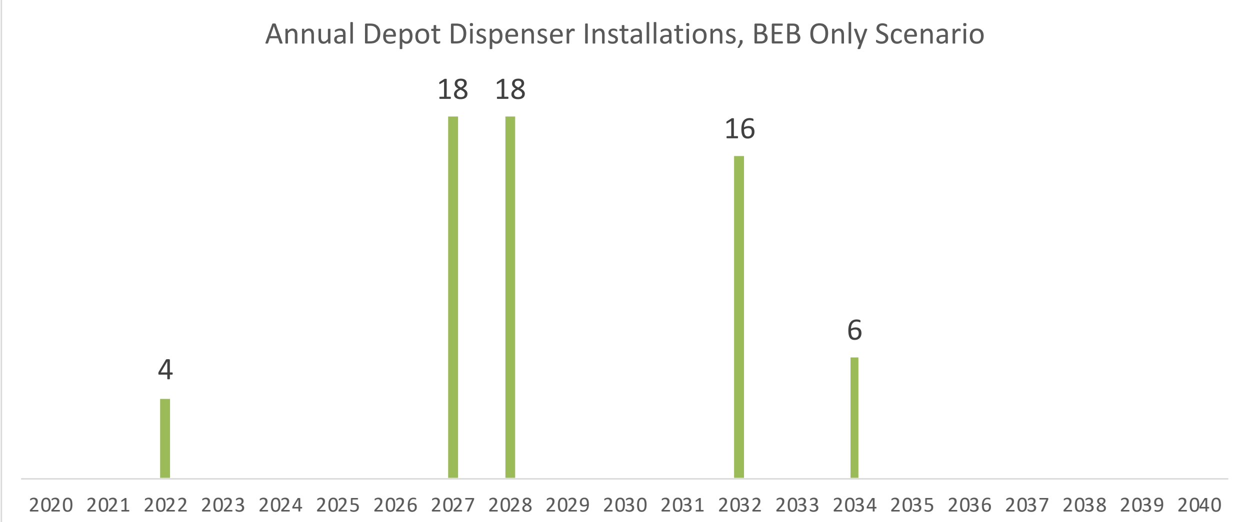


Figure 48 – Annual Depot Dispenser Installations, BEB Only Scenario

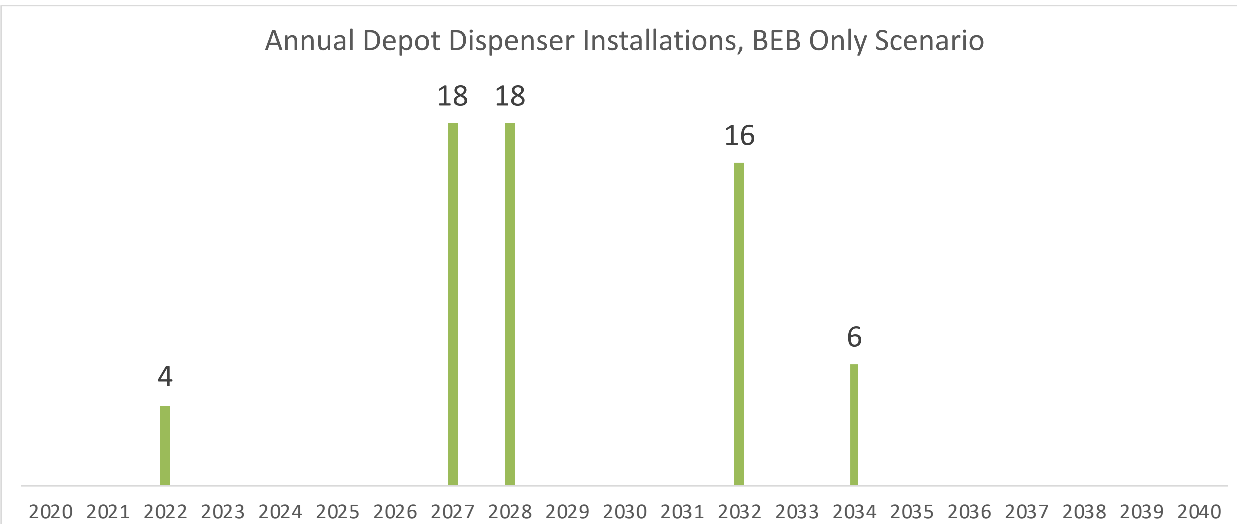


Figure 49 – Annual Depot Charger Installations, BEB Only Scenario

Figure 50 shows the annual cost of charger and dispenser installations based on these cost assumptions and the above estimated charger and dispenser quantities.

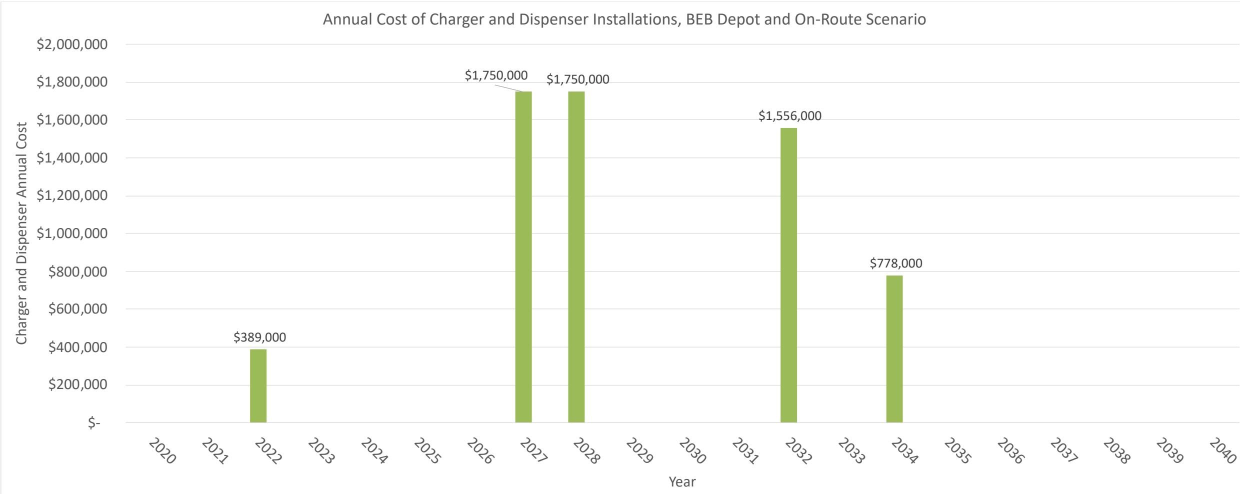


Figure 50 - Annual Cost of Depot Charger and Dispenser Installations, BEB Only Scenario

BEB Only (with Depot and On-Route Charging) Infrastructure Cost Summary

Table 31 summarizes all costs for charging infrastructure for the BEB Only scenario. **Figure 51** - Cumulative Total Infrastructure Costs, BEB Only Scenario shows the cumulative total cost breakdown. The estimated total infrastructure costs for the BEB Only scenario is approximately $20 million. This total cost includes all gantry structural projects, all power upgrade projects, all charger and dispenser installations, all planning projects, design engineering costs and the added 20% contingency on all costs, as well as the design and equipment costs for on-route charging infrastructure.

Table 31 - Total Infrastructure Costs, BEB Only Scenario

Depot	Cost
Atlantis	$ 14,387,000
On-Route	$ 5,370,000
Total	**$ 19,757,000**

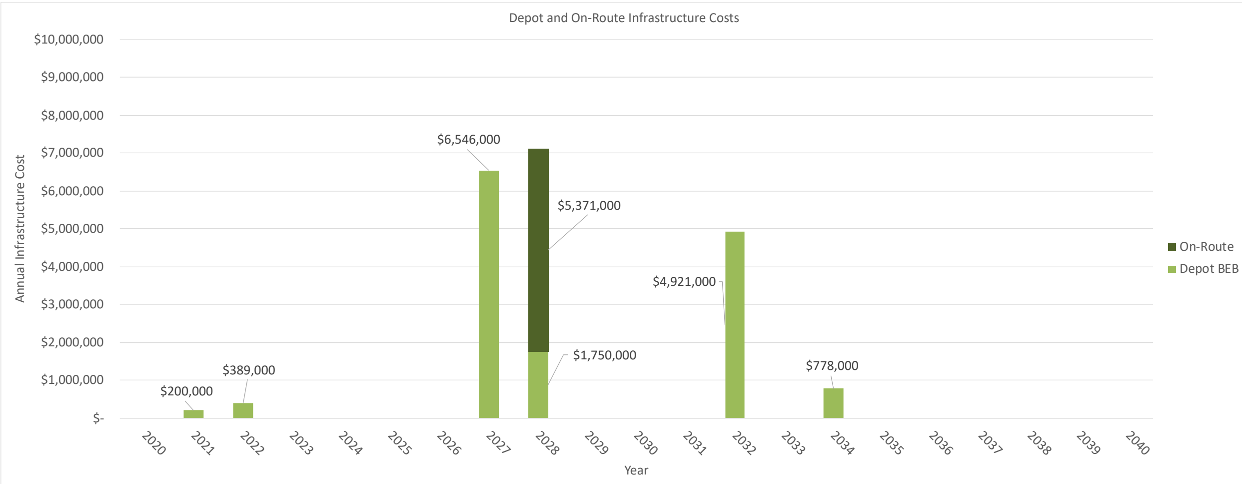


Figure 51 - Cumulative Total Infrastructure Costs, BEB Only Scenario

Mixed Fleet: BEB and FCEB Scenario – BEB Facility

Mixed Fleet Charging Scenario Depot Planning Projects

In the Mixed Fleet Scenario, BEB infrastructure planning will be required at the depot. Planning is estimated to cost $200,000 for planning the infrastructure transition at the Atlantis depot. One $200,000 project is therefore planned for LAVTA over the transition period.

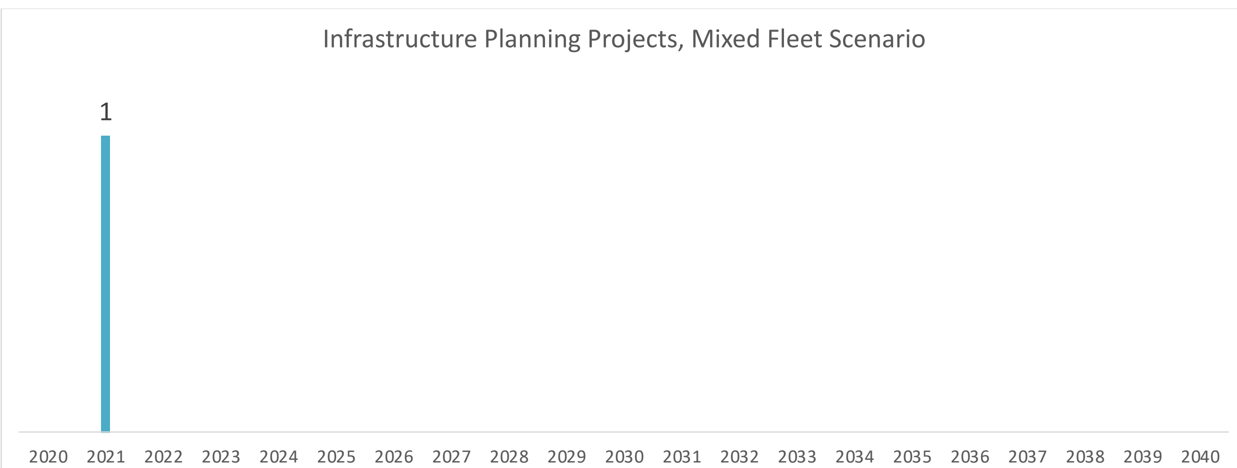


Figure 52 - Planning Projects, Mixed Fleet Charging Scenario

Mixed Fleet Charging Structural Projects

Structural projects include (1) trenching and build out duct banks from the switchgear to the charger pads, (2) construction of charger pads (i.e., foundation for charging equipment), (3) construction of gantry foundations and overhead gantry structures that hold the dispensers, and (4) installation of conduit from switchgear to charger pads and gantries. See **Table 32** for the detailed cost assumptions for structural projects. Duct bank cost is incurred only once per depot, other costs are on a per gantry basis.

Table 32 - Structural Project Cost Assumptions

Item	Cost	Unit
Initial Duct/Bank	$ 300,000	per depot
Gantry & Foundation	$ 450,000	per gantry
Incremental Duct Bank/Conduit	$ 22,000	per gantry
Charger Pad (3 chargers per gantry)	$ 25,000	per gantry
Contingency	20%	on project costs
Design Engineering	6%	on project costs and contingency

Each entry in the table below indicates a structural project to add overhead gantry capacity to the depot. **Figure 53** shows the number of gantries added in a given year at the depot. Each gantry can serve up to eight buses. A total of 7 gantries will be needed at LAVTA to support BEB charging in this scenario.

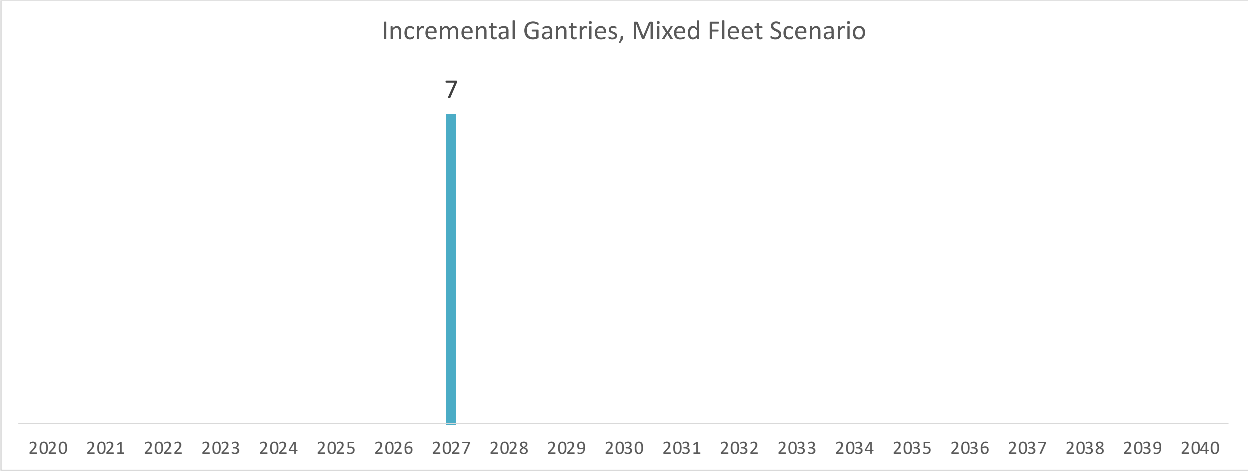


Figure 53 – Incremental Gantries, Mixed Fleet Charging Scenario

Figure 54 – Annual Structural Projects Cost, Mixed Fleet Scenario shows the total annual costs of structural projects by depot for the Mixed Fleet Charging scenario. These costs include the initial duct bank costs at each depot, plus gantry and foundation costs, incremental duct bank/conduit costs and charger pad costs per gantry, sequenced in accordance with the above tables. On top of these costs, 20% contingency and 6% engineering costs are added.

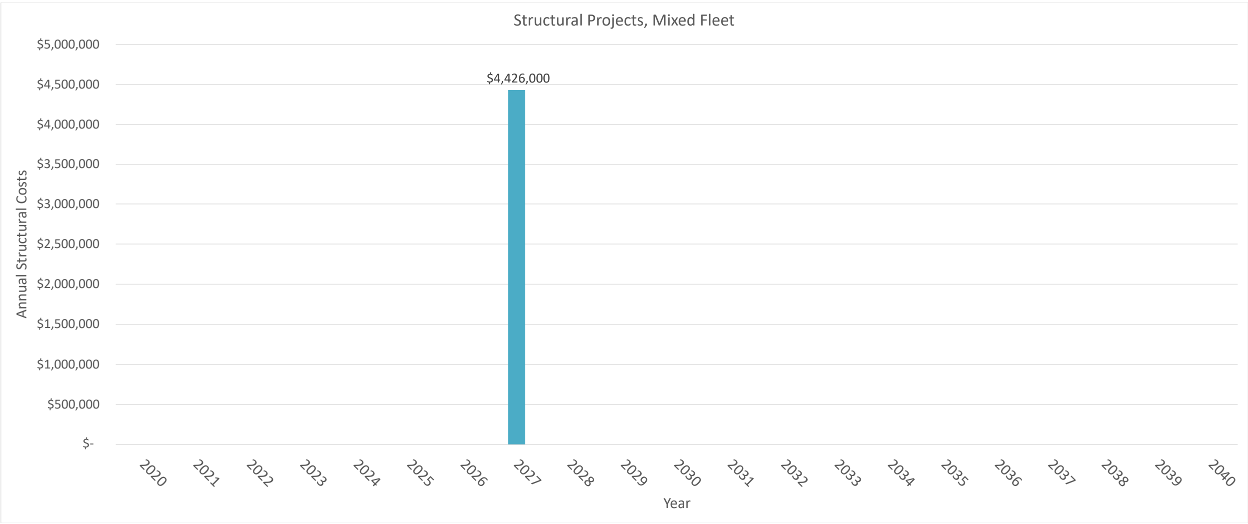


Figure 54 – Annual Structural Projects Cost, Mixed Fleet Scenario

Mixed Fleet Power Upgrade Projects

Power upgrade projects include construction of transformer foundations and installation of transformers. It is assumed that transformers will be modular, and incremental power requirements are met over time. **Table 29** shows the estimated costs for depot power upgrade projects.

Figure 55 shows incremental required electrical demand, in megawatts, for each depot. Each entry indicates the minimum amount of power that must be added in a given year to meet the growing demand at a given facility as more BEBs are purchased.

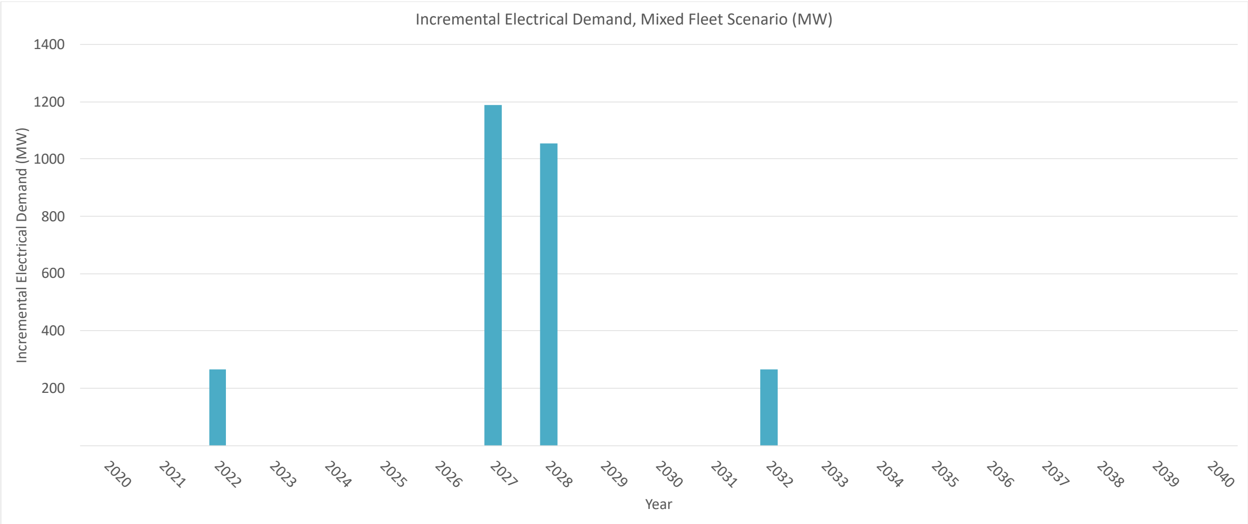


Figure 55 – Incremental Electrical Demand, Mixed Fleet Scenario (MW)

Power upgrades are consolidated to occur in selected years, in accordance with the required demand in **Figure 55.** These recommended upgrades are shown in **Figure 56**. LAVTA will need to add an additional estimated 4 MW of capacity to its system by 2040 to accommodate charging for 41 BEBs.

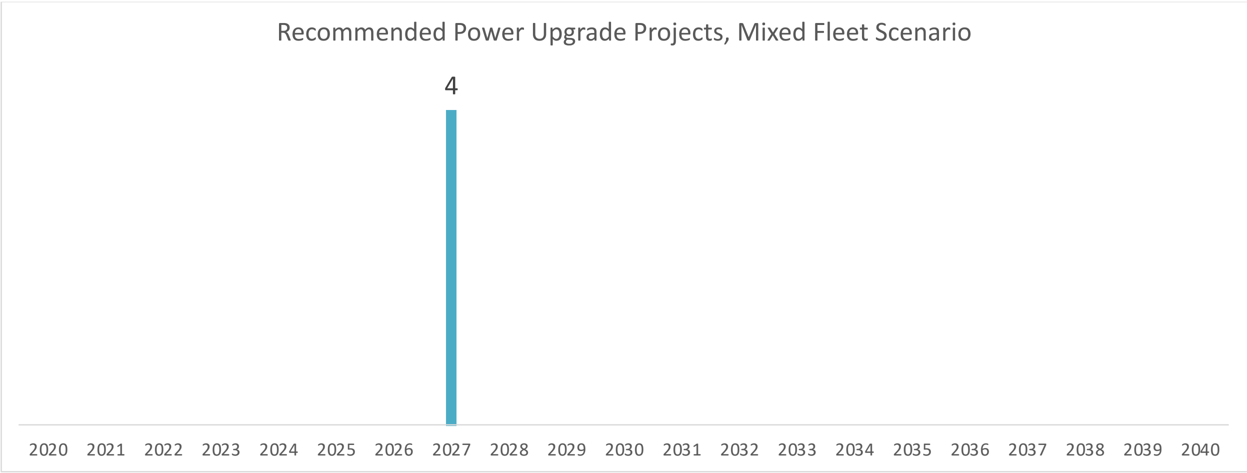


Figure 56 – Recommended Power Upgrade Projects, Mixed Fleet Charging Scenario (MW)

The total cumulative cost of power upgrade projects at the depot, in 2020 dollars, is provided in **Figure 57** – Annual Power Upgrade Project Costs, Mixed Fleet Charging Scenario. Total estimated power upgrade costs over the project life are approximately $0.3 million.

Figure 57 – Annual Power Upgrade Project Costs, Mixed Fleet Charging Scenario

Mixed Fleet Charger Installation Projects

Charging projects include purchase and installation of 120 kW chargers and dispensers. Each bus will require one dispenser. Every two buses (40-foot and larger) will require one charger with two dispensers. Dispensers are expected to be either overhead reel or pantograph style.

Table 30 above provides the costs assumed for charger and dispenser installs. As seen in **Figure 58** – Annual Dispenser Installations, Mixed Fleet Charging Scenario **and Figure 59** – Annual Charger Installations, Mixed Fleet Charging Scenarioin total, this scenario would require 21 chargers (42 dispensers) at LAVTA.

Figure 58 – Annual Dispenser Installations, Mixed Fleet Charging Scenario **and Figure 59** – Annual Charger Installations, Mixed Fleet Charging Scenarioshow the annual dispensers and charger installations by depot for each year of the project.

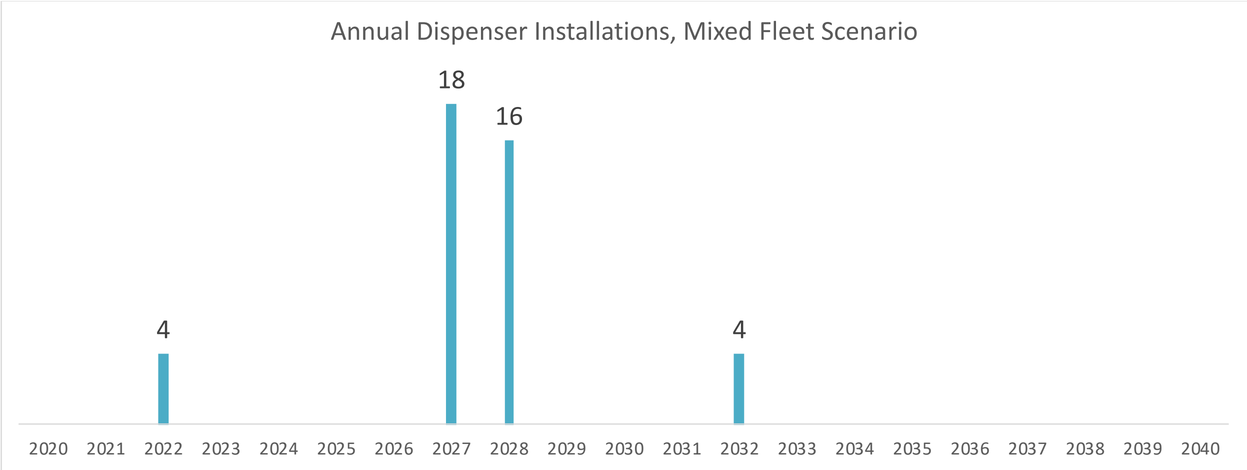


Figure 58 – Annual Dispenser Installations, Mixed Fleet Charging Scenario

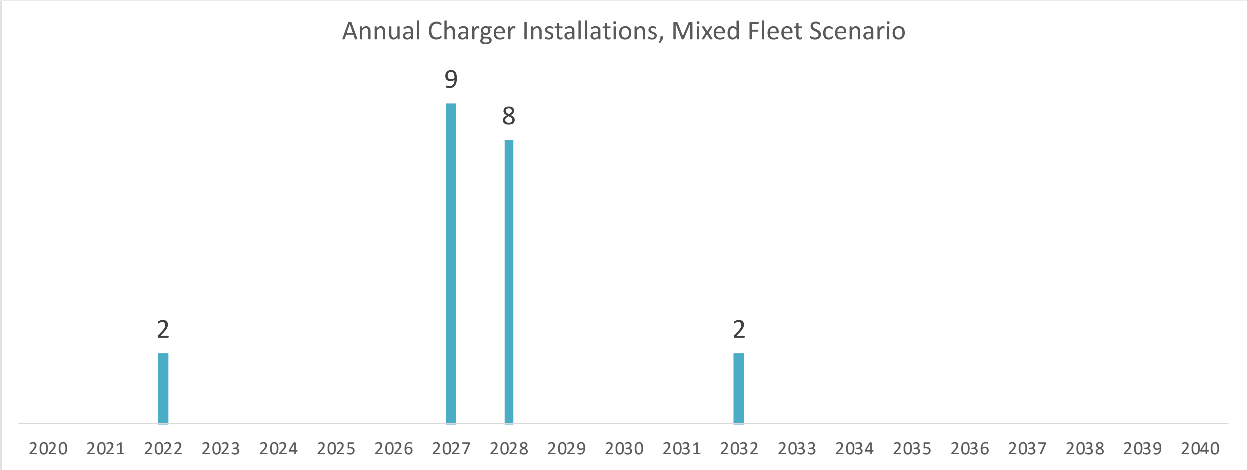


Figure 59 – Annual Charger Installations, Mixed Fleet Charging Scenario

Figure 60 shows the annual cost of charger and dispenser installations based on these cost assumptions and the above estimated charger and dispenser quantities.

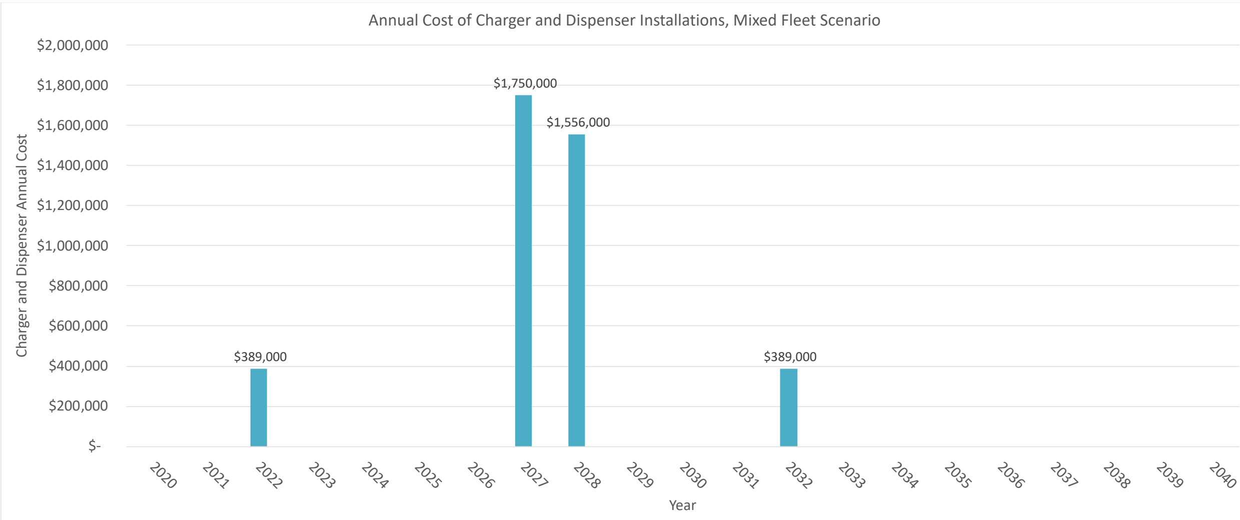


Figure 60 - Annual Cost of Charger and Dispenser Installations, Mixed Fleet Charging Scenario

Mixed Fleet Charging Infrastructure Cost Summary

Table 33 summarizes all costs for charging infrastructure for the Mixed Fleet scenario. **Figure 61** shows the cumulative total cost breakdown for the BEBs in the fleet. The estimated total BEB infrastructure costs for the Mixed Fleet scenario are approximately $9.0 million. This total cost includes all gantry structural projects, all power upgrade projects, all charger and dispenser installations, all planning projects, design engineering costs and the added 20% contingency on all costs, as well as the design and equipment costs for on-route charging infrastructure.

Table 33 - Total BEB Infrastructure Costs, Mixed Fleet Scenario

Depot	Cost
Atlantis	$ 9,011,000
Total	**$9,011,000**

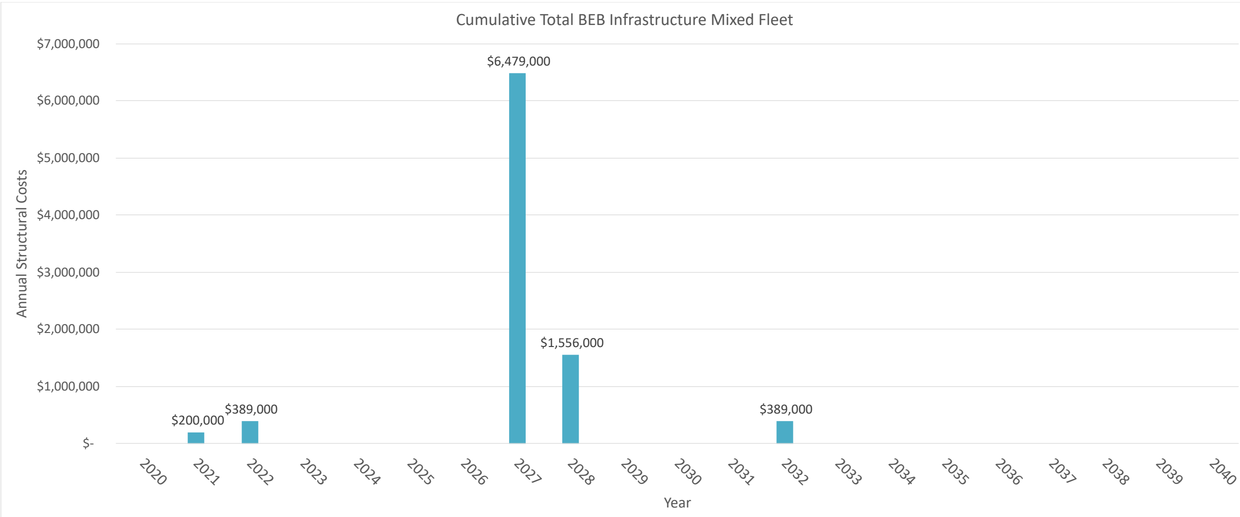


Figure 61 - Cumulative Total BEB Infrastructure Costs, Mixed Fleet Scenario

Hydrogen Fuel Cell Infrastructure Scenarios

To define the timeline and costs to build hydrogen fueling infrastructure, CTE breaks the scope of work into four key project types: (1) planning, (2) structural, (3) maintenance bay upgrades, and (4) fueling. Rather than building out the infrastructure all at once, projects are sized and scheduled to meet near-term fueling requirements.

50-Bus Mechanical Projects

For hydrogen fueling equipment, it is economical to package projects in 50-bus increments with all necessary mechanical and fueling components included except for liquid hydrogen storage tanks. Storage tanks can be added in a modular fashion as demand increases, separately from other fueling components. The 50-bus mechanical projects include:

1. Two dispensers (additional dispensers may be added);
2. All mechanical process equipment and hydrogen wetted components;
3. Design, engineering, and permitting;
4. Construction;
5. Demolition of existing pavement, and excavation;
6. Installation of new equipment foundations;
7. All electrical conduit, conductors, and termination;
8. Emergency shut down and notification system;
9. Mechanical installation; and
10. Electrical utilities and switchgear.

For LAVTA, Fiedler Group conducted an assessment of the FCEB infrastructure requirements at this facility for the Mixed Fleet: BEB and FCEB scenario and the FCEB Only Scenario. Fiedler

Group has over 60 years of experience working on innovative engineering and design projects and is widely viewed as the industry expert on hydrogen fueling station design.

Since both of the scenarios involving FCEBs had several years where there would only be four or five FCEBs in the yard, in the Mixed Scenario and the FCEB Only Scenario respectively, Fiedler Group recommends using a mobile fueler until the number of FCEBs meets or exceeds 19 buses. The infrastructure for a mobile fueler is expected to cost around $72,000 per year. In the Mixed Scenario, that cost is incurred for four years and in the FCEB Only Scenario, it is incurred for five years. When the permanent station is installed, the 50-bus incremental design cost is estimated at around $4.2 million with the incremental capacity expected at $300,000. The other major cost of hydrogen infrastructure is the maintenance bay upgrades required to make the bays hydrogen safety compliant. Upgrading all 14 of the bays at Atlantis Court is estimated at $1.9 million. This cost also assumes that some gas detection equipment will already be installed in the Atlantis Court maintenance bays during construction.

Hydrogen storage must comply with safety distance requirements outlined by the National Fire Protection Association (NFPA). These requirements are primarily outlined in NFPA 2 8.3.2.3.1.6(A) and NFPA 2 8.3.2.3.1.6(B) and are designed to prevent ignition of the hydrogen. Fiedler Group reviewed these hydrogen storage requirements, including siting location with consideration of physical protection minimum distances and alternate minimum distances, as well as hydrogen dispensing requirements and selected a location for the hydrogen storage and fueling infrastructure that complies with these regulations. This site layout can be seen in **Appendix A5-A7** for the Mixed Fleet Scenario and **A8** for the final FCEB Only Layout.

For the assessment of the permanent fueling facility, Fiedler Group assumed liquid hydrogen would be trucked in and stored on site in an above-ground tank. According to Fiedler Group's estimates, for each 50-bus increment, a 15,000-gallon tank will be needed. In the Mixed Scenario, that tank is expected to be installed in 2033 when there are 19 FCEBs in the fleet. In the FCEB Only Scenario, it will be installed when the capacity for the full 68 bus transition is reached in 2028. The size of these tanks allows for storage of four service days' worth of fuel. Two dispensers will be required, both to allow for all the buses to be fueled within an eight-hour window and for the purpose of redundancy.

Fiedler Group worked with AECOM to integrate hydrogen fueling infrastructure into the BEB project design phasing. These designs can be seen in **Appendix A5-A7**. The FCEB Only Scenario site design can be seen in **Appendix A8**.

The cost estimates that Fiedler Group provided for FCEB infrastructure were integrated into CTE's Facilities Assessment and are summarized in **Table 34.** These estimates are based on the 50-bus increments employed by Fiedler Group.

Table 34 – FCEB Infrastructure Planning Assumptions

Project	Cost Estimate	Source
Infrastructure Planning	$200,000 per depot	Engineer's estimate
50-Bus Incremental Mechanical Equipment and Installation Package	Varies by facility; Includes design, permitting, and installation for two (2) dispensers; all mechanical process equipment; electrical utilities and switchgear. Excludes storage tanks.	Engineer's estimate, vendor quotes
Incremental Addition of 15,000 Liquid Hydrogen Tank	$300,000 per tank for installation	Engineer's estimate, vendor quotes
Maintenance Upgrades	Electrical, Lighting, Ventilation, and Gas Detection - $191,500 to upgrade all of LAVTA's maintenance bays	Engineer's estimate

Storage Capacity Projects

Storage capacity projects include the incremental addition of one or more 15,000-gallon liquid hydrogen storage tanks. Tanks are sized at 15,000 gallons to accommodate one truckload of liquid hydrogen, or approximately 3,000 kilograms. Storage capacity projects are planned in conjunction with bus mechanical projects to reduce disruptions for construction projects. This practice is standard and has been successfully implemented at OCTA and AC Transit and was recommended by Fiedler Group to San Diego Metropolitan Transit System and Long Beach Transit. The required capacity of hydrogen storage at a given depot is sized to accommodate an approximately four-day supply of average daily fuel use.

Mixed Fleet: BEB and FCEB Scenario – FCEB Facilities

In the Mixed Fleet: BEB and FCEB scenario, charging infrastructure is required to service a total of 41 BEBs while additional hydrogen fueling infrastructure services 27 FCEBs. All buses transition to zero-emission in this scenario.

In addition to BEB charging, hydrogen fueling is required to support the Mixed Fleet: BEB and FCEB scenario. For the FCEB fueling costs, the scope of work is broken into four key project types: (1) planning, (2) structural, (3) maintenance bay upgrades, and (4) fueling. Infrastructure is built out over time as necessary to support FCEB deployment.

Planning Projects

The building of hydrogen infrastructure will require planning at the depot. It is assumed that a planning project costs $200,000, occurring as shown in the table below, and occurs only once per depot. The total cost of planning projects for the one depot is therefore approximately $200,000.

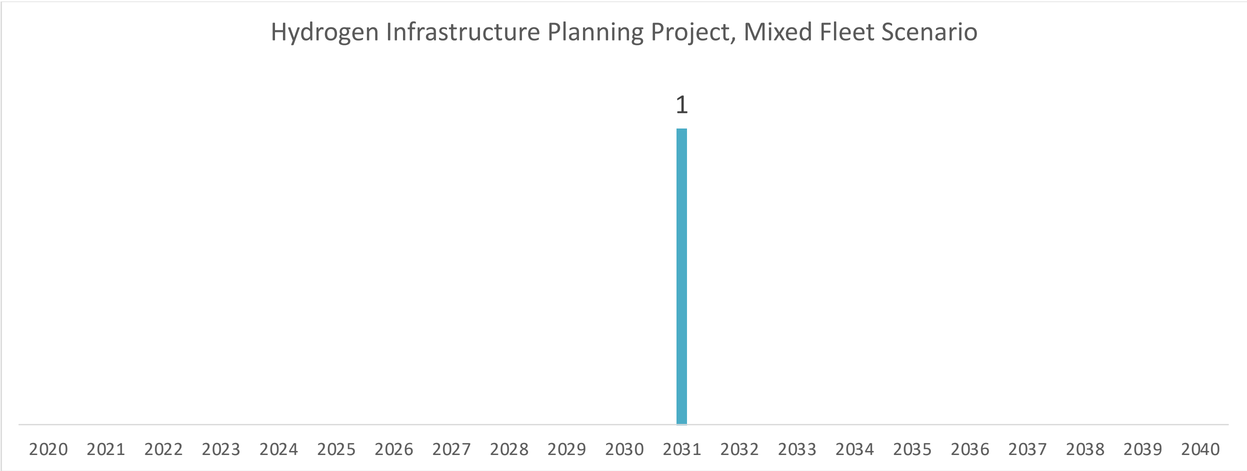


Figure 62 - Planning Projects, Mixed Fleet Scenario

Figure 63 shows the estimated mechanical projects by year. Costs vary per project in a given year due to the scale of the implementation at each depot. Building mechanical infrastructure is grouped into one phase to minimize disruption of service and capital expenses. The total cost of mechanical projects to support the Mixed Fleet scenario is approximately $4.1 million for the one project expected in this scenario.

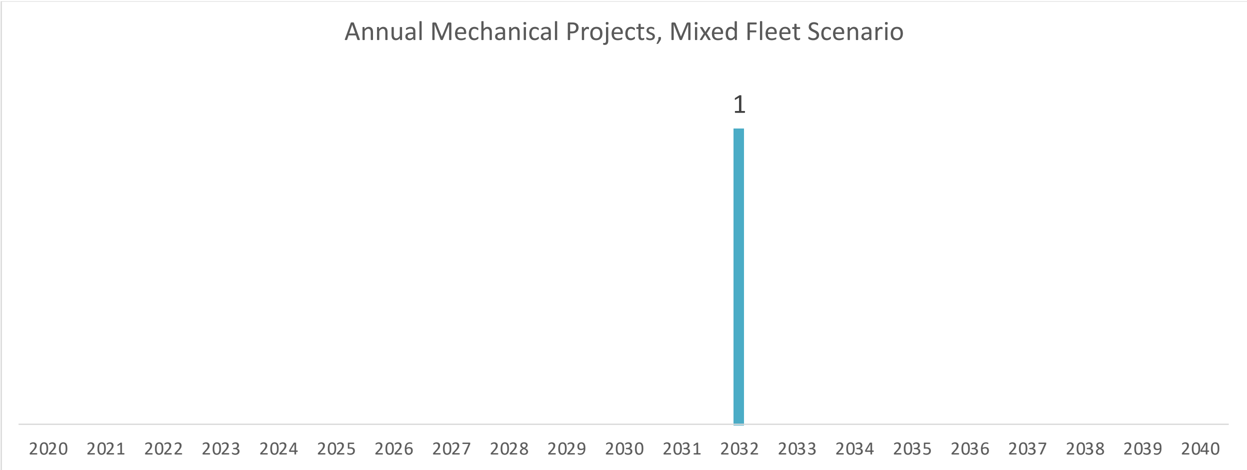


Figure 63 - Mechanical Projects, Mixed Fleet Scenario

Storage Capacity Projects

Figure 64 shows the planned storage capacity project and costs by year. The total storage capacity projects costs approximately $300,000 over the life of the study with one project in 2028 at LAVTA.

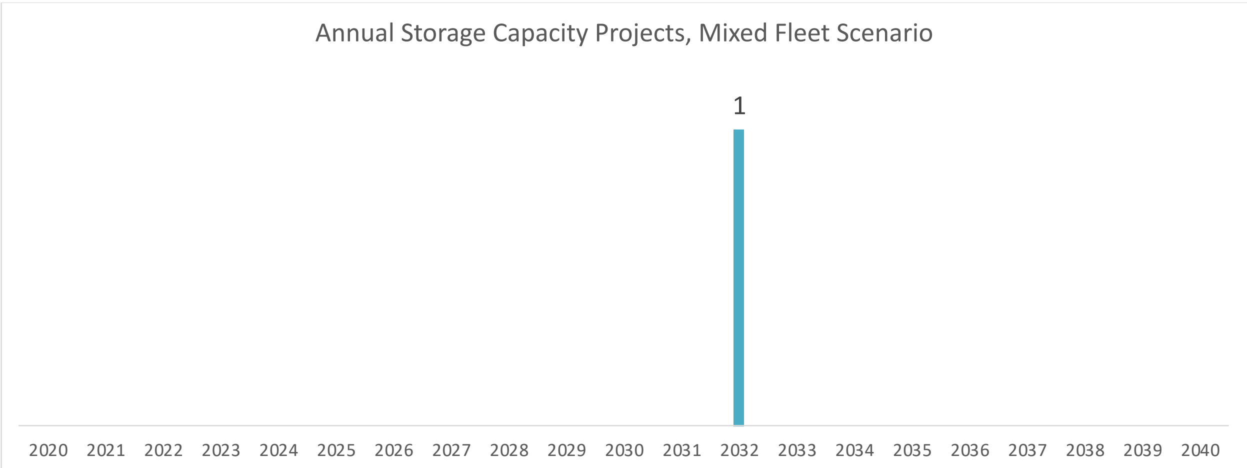


Figure 64 - Storage Capacity Projects, Mixed Fleet Scenario

Maintenance Bay Upgrade Projects

Maintenance bays at each depot require hydrogen detection and exhaust equipment to ensure safety. **Figure 65** indicates the timing and location of upgrade projects, as well as the number of bays that require upgrades at each depot. All 14 maintenance bays will require upgrades so that all bays will be able to service FCEBs.

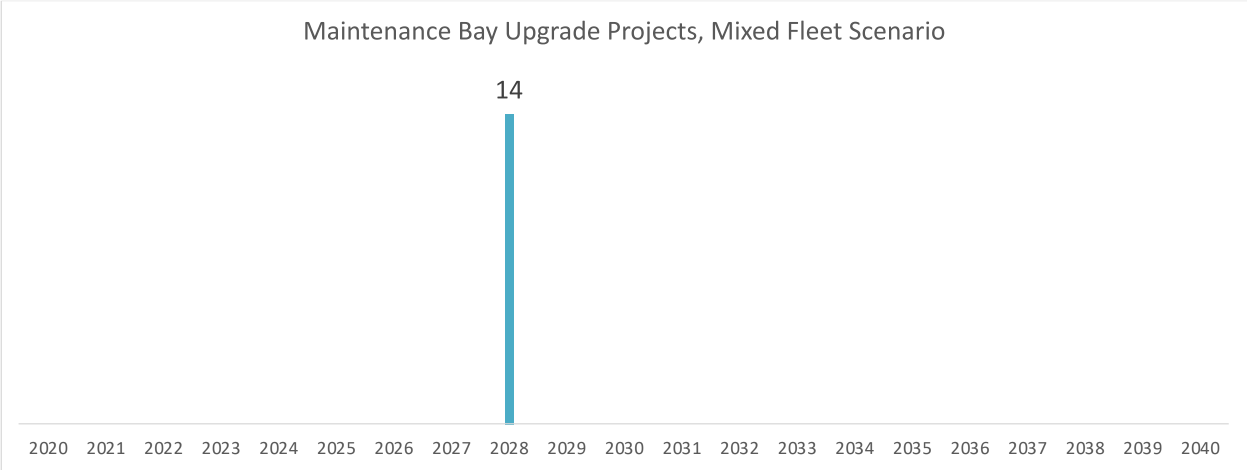


Figure 65 - Hydrogen Maintenance Bay Upgrade Projects, Mixed Fleet Scenario

At LAVTA, CTE assumed nearly $14,000 per bay for the required upgrades. This cost comes from the requirement of additional ventilation systems necessary for hydrogen detection. Since LAVTA is in the process of building a new facility, these costs are reduced from what they would usually be for upgrading a diesel maintenance bay, because designing the bays for servicing FCEBs will be less expensive than retrofitting an existing bay. For maintenance bay upgrade projects, CTE estimates a total cost of $1,900,000 at LAVTA in 2028.

Mixed Fleet FCEB Infrastructure Summary

Figure 61 provides the total infrastructure costs for the Mixed Fleet scenario for the entire transition period. The total build of required FCEB infrastructure will cost approximately $5.1 million for the FCEB Only scenario. It is important to note that this scenario also includes procurement of 41 BEBs between 2023 and 2033, which will require additional charging infrastructure, as outlined in the BEB infrastructure section. The cost of these projects combined would be around $19.8 million. **Figure 67** shows a cumulative summary of infrastructure costs by year.

Annual costs for the FCEB infrastructure portion of the mixed fleet are provided in **Figure 66**. The total combined infrastructure costs for the Mixed Fleet Scenario can be seen in **Figure 67** - Cumulative Infrastructure Costs, Mixed Fleet: BEB and FCEB Scenario**.**

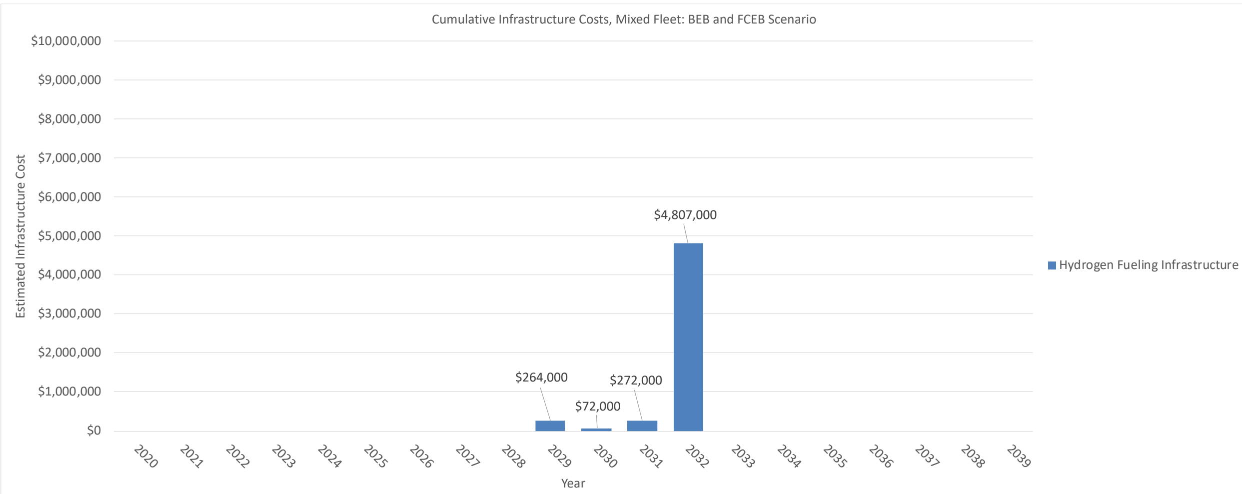


Figure 66 - Annual FCEB Infrastructure Costs, Mixed Fleet: BEB and FCEB Scenario

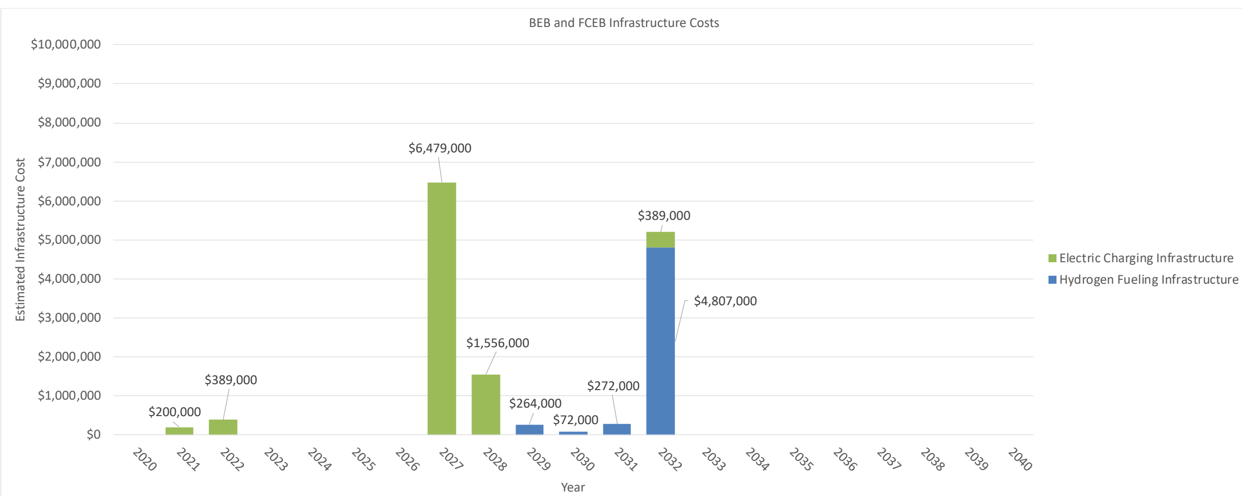


Figure 67 - Cumulative Infrastructure Costs, Mixed Fleet: BEB and FCEB Scenario

FCEB Only

The FCEB Only scenario assumes that FCEBs are utilized to run all of LAVTA's routes by 2035. The following estimates calculate necessary hydrogen infrastructure costs to support a fleet of 68 FCEBs by 2035.

Planning Projects

The building of permanent hydrogen infrastructure will require planning at each depot. It is assumed that each planning project will cost $200,000, occurring as shown in the graph below, and only once per depot. The total cost of planning projects for the one depot is therefore approximately $200,000.

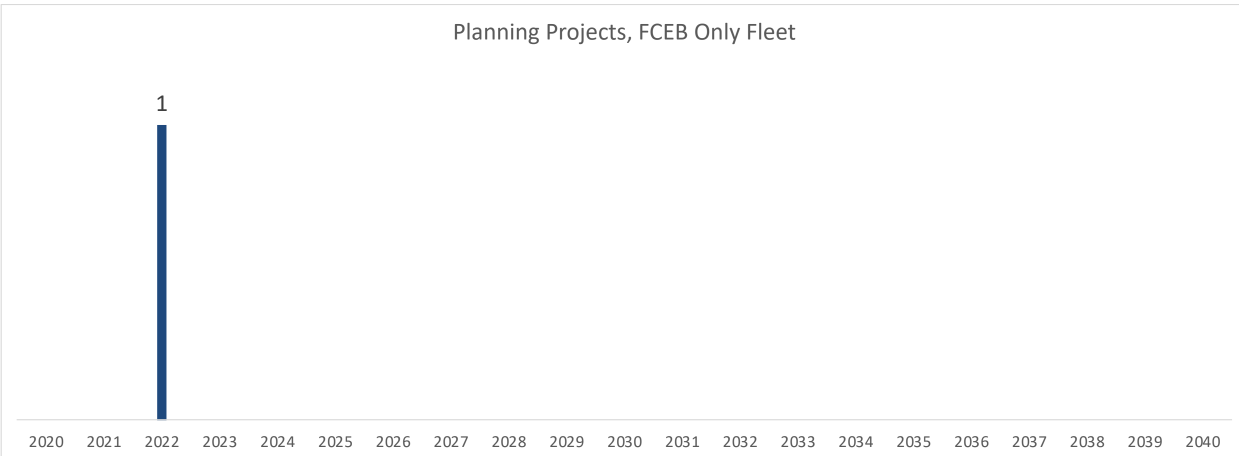


Figure 68 – Planning Projects, FCEB Only Scenario

Figure 69 shows the estimated mechanical projects by year. Costs vary per project in a given year due to the scale of the implementation at each depot. Building mechanical infrastructure at each depot are grouped into no more than two phases to minimize disruption of service and capital expenses. The total cost of mechanical projects to support the FCEB Only scenario is approximately $4.2 million, and the project is scheduled in 2027.

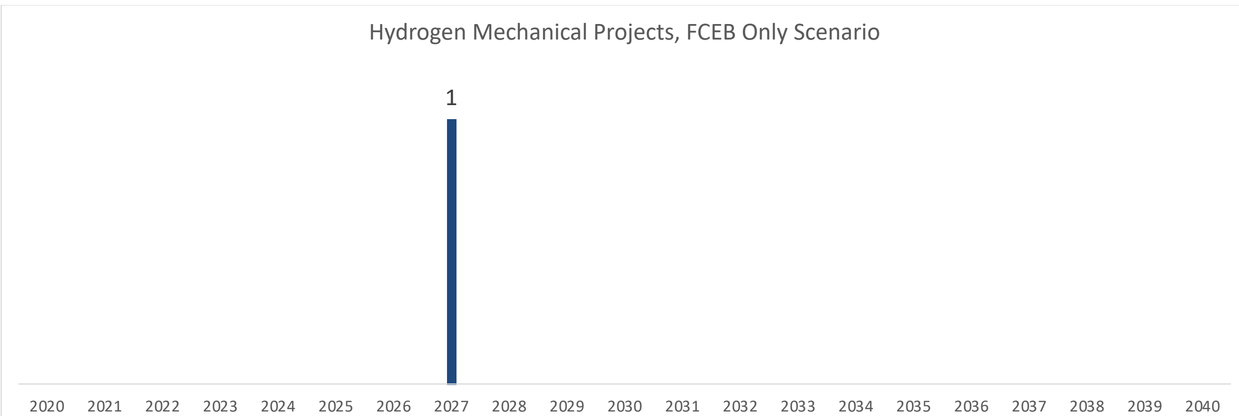


Figure 69 – Hydrogen Mechanical Projects, FCEB Only Scenario

Storage Capacity Projects

Figure 70 - Hydrogen Storage Capacity Projects, FCEB Only Scenarioshows the planned storage capacity projects and costs by year and depot. The total storage capacity projects will cost approximately $0.6 million over the life of the study. There will be a single project in 2027 that will add the capacity for the initial 50-bus capacity tank, as well as the additional capacity for the 18 additional buses required in the full fleet transition.

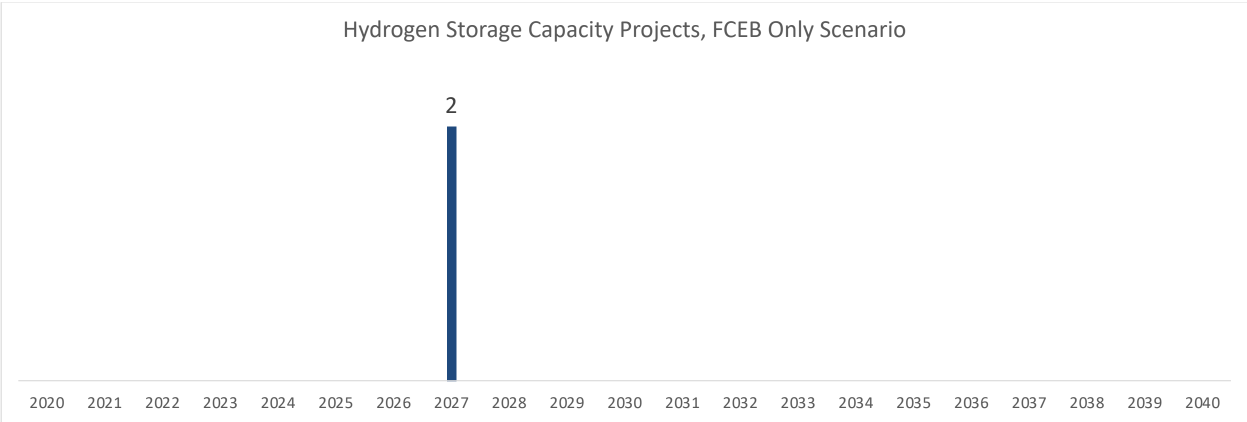


Figure 70 - Hydrogen Storage Capacity Projects, FCEB Only Scenario

Maintenance Bay Upgrade Projects

Maintenance bays at each depot will require hydrogen detection and exhaust equipment to ensure safety. **Figure 71** indicates the timing and location of upgrade projects, as well as the number of bays that require upgrades. A total of 14 maintenance bays will require upgrades.

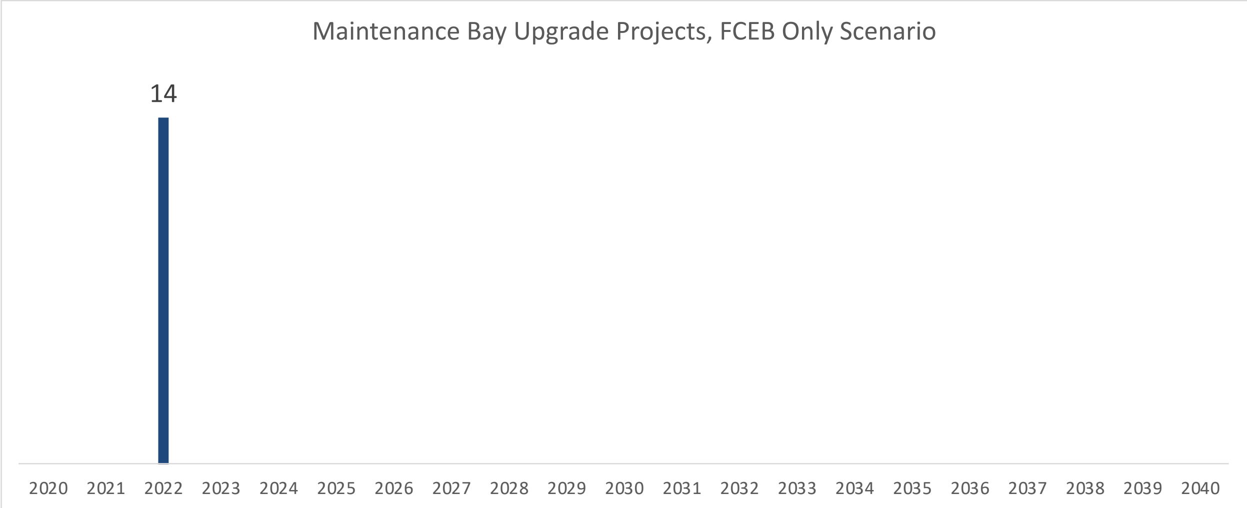


Figure 71 - Hydrogen Maintenance Bay Upgrade Projects, FCEB Only Scenario

CTE assumed $13,600 per bay for the required upgrades. This cost comes from the requirement of additional ventilation systems. For maintenance bay upgrade projects, CTE estimates a total cost of $1,900,000 for LAVTA in 2022.

FCEB Only Infrastructure Summary

Table 35 provides the total infrastructure costs for the FCEB Only scenario for the entire transition period. The total build of required FCEB infrastructure will require approximately $9.8 million for the FCEB Only scenario. **Figure 72** shows a cumulative summary of infrastructure costs by year at the depot including the cost of the mobile fuelers prior to the install of the permanent infrastructure in 2027.

Table 35 – Total Infrastructure Costs, FCEB Only Scenario

Depot	Cost
Atlantis	$ 9,752,000
Total	**$ 9,752,000**

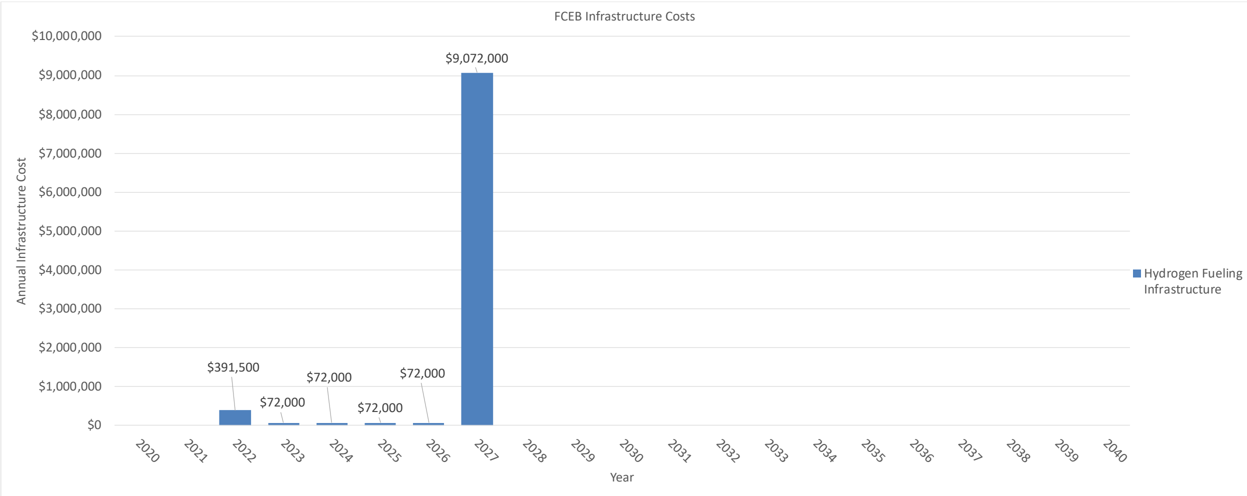


Figure 72 - Cumulative Infrastructure Costs, FCEB Only Scenario

Facilities Assessment Cost Comparison

The Facilities Assessment includes all infrastructure-related costs over the transition for each scenario. **Figure 73** shows the cumulative infrastructure costs for each scenario. **Table 36** shows the combined total costs and percentage of ZEBs in the fleet in 2040.

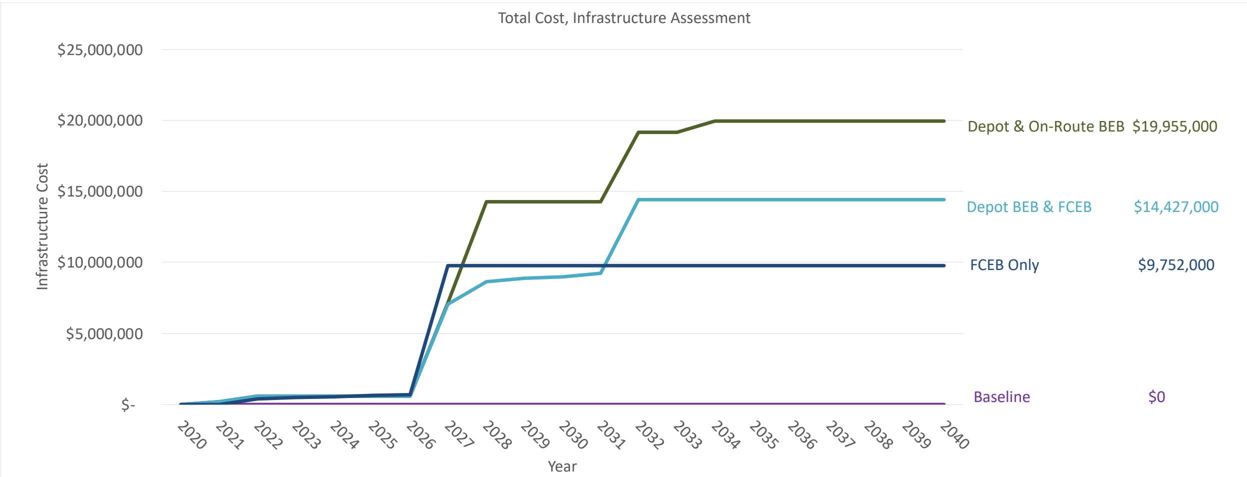


Figure 73 - Total Cumulative Costs, Facilities Assessment

Table 36 - Total Cumulative Costs, Facilities Assessment

Scenario	Cost	% ZEB in 2040
Baseline	$ 0	0%
BEB Only	$ 19,955,000	100%
Mixed Fleet: BEB and FCEB	$ 14,427,000	100%
FCEB Only	$ 9,752,000	100%

9 Total Cost of Ownership Assessment

The Total Cost of Ownership Assessment compiles the results from the Fleet, Fuel, Facilities, and Maintenance Assessments to show cumulative and annual costs throughout the transition period for each scenario. It includes selected capital and operating costs of each fleet scenario over the transition timeline. Other costs may be incurred (e.g. incremental operator and maintenance training) during a fleet transition; however, these four assessment categories are the key drivers in ZEB transition decision-making.

This study assumes no cost escalation or any cost reduction due to economies of scale for ZEB technology because there is no historical basis for these assumptions. Future changes to LAVTA's service level, depot locations, route alignments, block scheduling, or other operations are unknown. The analyses below provide best estimates using the information currently available and the assumptions detailed throughout this report.

Costs by Scenario

The following sections show total costs per scenario, broken down by assessment type.

Baseline

Figure 74 shows the combined fleet, fuel, facilities, and maintenance costs for the Baseline scenario in 2020 dollars. Since bus capital costs represent the most expensive cost examined, the peaks in these expenses occur during large purchasing years. Compared to bus costs, the fluctuations in fueling and maintenance cost are minimal and appear fairly stable from one year to the next. Since this scenario assumes that the necessary infrastructure is already present at the depot, there are no infrastructure costs associated with the Baseline scenario. The total combined cost is approximately $138 million over twenty years from 2020 to 2040. This scenario estimates a total of 68 diesel-hybrids in service in 2040.

Figure 74 – Total Costs by Type, Baseline Scenario

BEB Only

Figure 75 shows the combined fleet, fuel, facilities, and maintenance costs for the BEB Only scenario in 2020 dollars. The total combined cost is approximately $195 million over the length of the transition, from 2020 to 2040. This scenario estimates a total of 68 total BEBs in service by 2040. The trends in the total cost fluctuations between years are largely the same as the Baseline and are also the result of bus capital costs being the main component of yearly costs. Infrastructure costs factor in towards the beginning of the project and maintenance and fueling costs remain relatively stable from year to year.

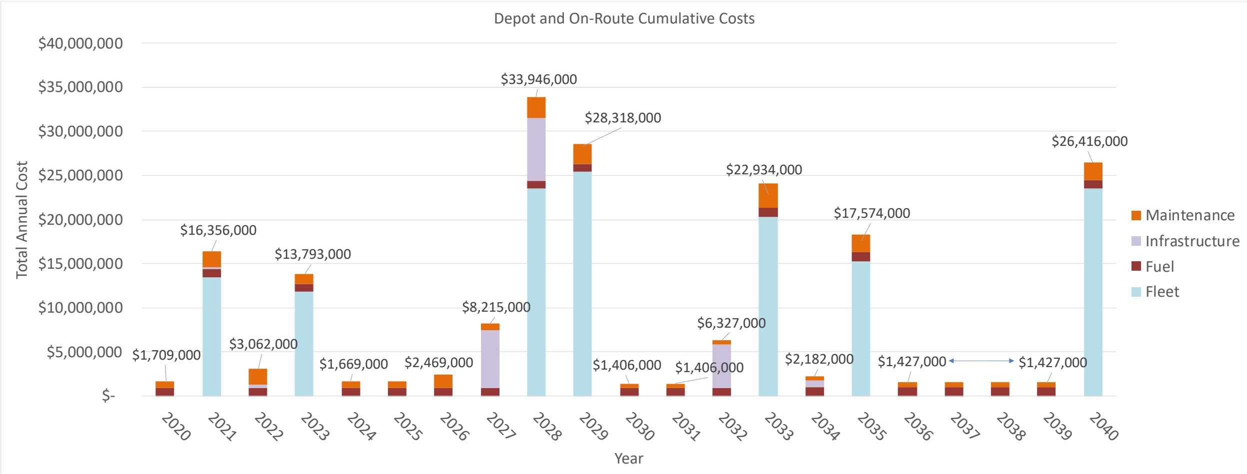


Figure 75 – Total Costs by Type, Depot and On-Route Charging Scenario

Mixed Fleet: BEB and FCEB

Figure 76 shows the combined fleet, fuel, facilities, and maintenance costs related to the Mixed Fleet: BEB and FCEB scenario in 2020 dollars. The total combined cost is approximately $197 million over the length of the transition, from 2020 to 2040. This scenario estimates a total of 41 BEBs and 27 FCEBs (68 total ZEBs) in service by 2040. The patterns of this scenario's bus purchasing, maintenance costs, and fueling costs are similar to those of the previously discussed scenarios with the infrastructure costs being even more isolated towards the beginning of the project.

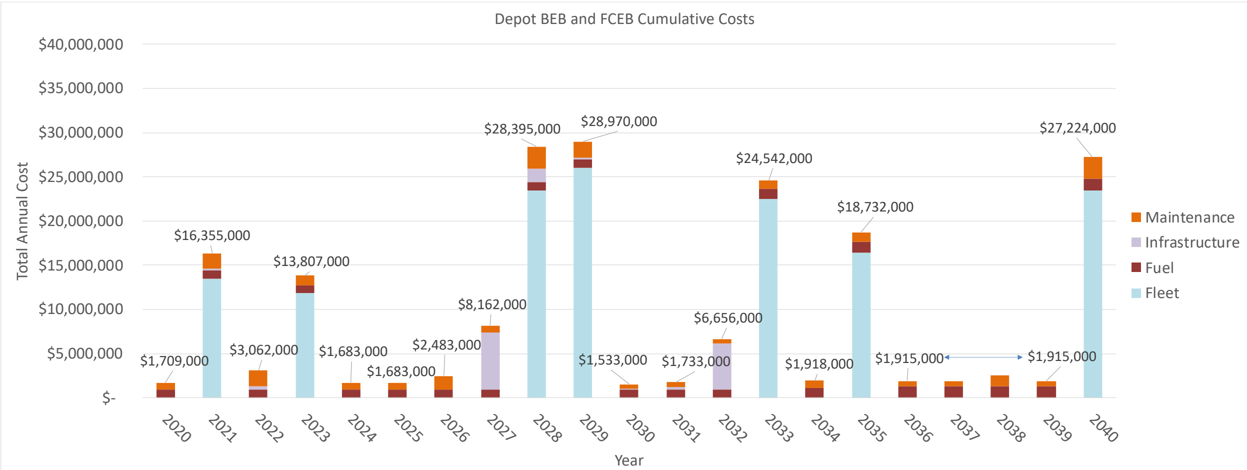


Figure 76 – Total Costs by Type, Mixed Fleet: BEB and FCEB Scenario

FCEB Only

Figure 77 shows the combined fleet, fuel, facilities, and maintenance costs related to the FCEB Only scenario in 2020 dollars. The total combined cost is approximately $216 million over the length of the transition, from 2020 to 2040. This scenario estimates a total of 68 FCEBs in service by 2040. The general trends of this scenario are similar to the previous two ZEB scenarios discussed although this scenario has the highest overall expense of any of the scenarios; however, because the infrastructure costs for FCEBs are significantly lower than the costs for FCEBs, this scenario's annual expenses never exceed $32 million, whereas the two scenarios with BEBs both have years that exceed $33 million.

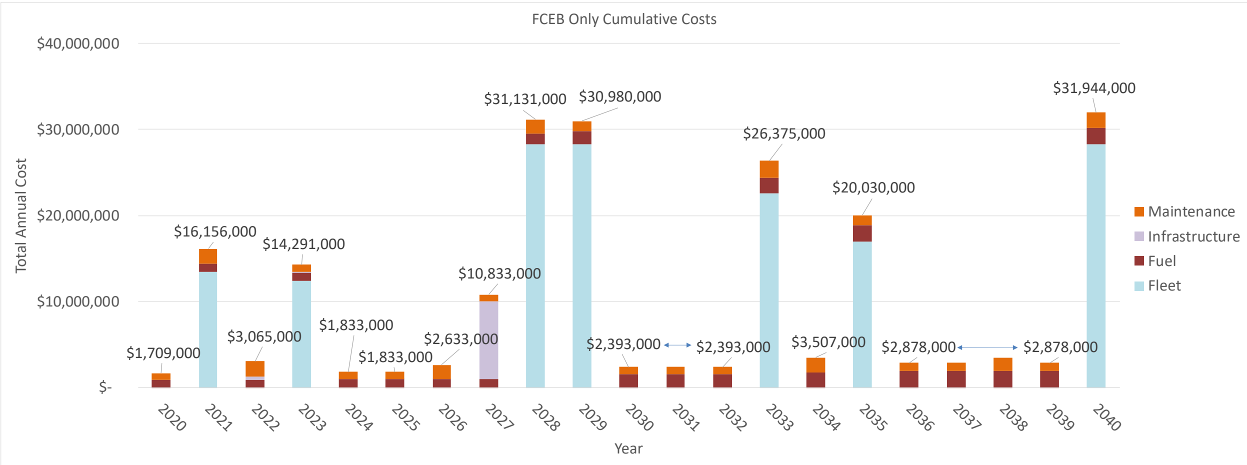


Figure 77 – Total Costs by Type, FCEB Only Scenario

Total Estimated Costs

Figure 78 shows the combined total costs from the assessments above, broken down by scenario. **Table 37** shows the detailed cost totals.

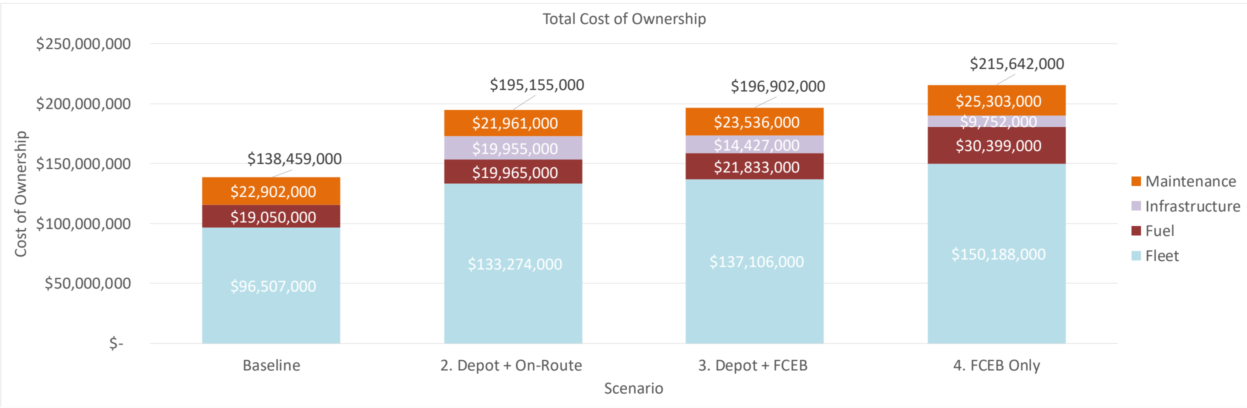


Figure 78 – Total Cost of Ownership, by Scenario

Table 37 – Total Cost of Ownership, by Scenario

Assessment Type	Baseline	BEB Only	Mixed Fleet: BEB and FCEB	FCEB Only
Fleet	$ 96,507,000	$ 133,274,000	$ 137,106,000	$ 150,188,000
Fuel*	$ 19,050,000	$ 19,965,000	$ 21,833,000	$ 30,399,000
Infrastructure	$ 0	$ 19,955,000	$ 14,427,000	$ 9,752,000
Maintenance	$ 22,902,000	$ 21,961,000	$ 23,536,000	$ 25,303,000
Total	**$ 138,459,000**	**$ 195,155,000**	**$ 196,902,000**	**$ 215,642,000**
% ZEB in 2040	**0%**	**100%**	**100%**	**100%**

*Excludes any potential LCFS credit revenue

10 Conclusions and Recommendations

ZEB technologies are in a period of rapid development and change. While the technologies have been proven in many pilot deployments, they are not yet matured to the point where they can easily replace current fossil-fuel technologies on a large scale. BEBs require significant investment in facilities and infrastructure and may require changes to service and operations to manage their constraints. On the other hand, FCEBs can provide an operational equivalent to diesel or CNG buses; however, the cost of buses, fueling infrastructure, and fuel are a significant hurdle.

CARB's ICT regulation is an achievement toward addressing the challenges of climate change and improving local air quality with a goal of 100% zero-emission transit fleets by 2040. However, as demonstrated in this analysis, there will be substantial costs and technical challenges to overcome. Transit agencies may be challenged to meet this goal while maintaining the same level of passenger service.

In an all-BEB strategy, total ZEB transitional costs are likely to be around $195 million not including LCFS credit revenue to offset fuel costs. By adding on-route charging, LAVTA could achieve a transition to a 100% battery-electric fleet without increasing fleet size or sacrificing block achievability. The difference in cost between this scenario and the Baseline scenario is largely the result of the price difference between diesel-hybrid buses and BEBs. Both 40-foot and 60-foot BEBs have completed Altoona testing and are acceptable under the CARB ICT regulation. The BEB Only scenario meets the CARB ICT regulation.

The Mixed Fleet: BEB and FCEB scenario achieves the transition of LAVTA's fleet to 100% zero-emission by 2040 with an estimated total cost of $197 million (not including LCFS credit revenue on fuel). This total cost falls between the BEB-only strategy on the low-cost end and the FCEB-only strategy on the high-cost end. Though the costs are considerably less for a mixed fleet deployment than the FCEB Only scenario, managing a mixed fleet through a transition presents its own complexities, such as installing new BEB infrastructure and installing new FCEB fueling infrastructure in a time frame that does not disrupt service. In this scenario, the depot would also need to have the capacity to fit both kinds of fueling infrastructure. LAVTA may also experience additional benefits as a result of the transition to ZEBs; one commonly cited benefit of ZEBs in the reduction in maintenance requirements. Less maintenance for ZEBs may result in the need for fewer maintenance bays.

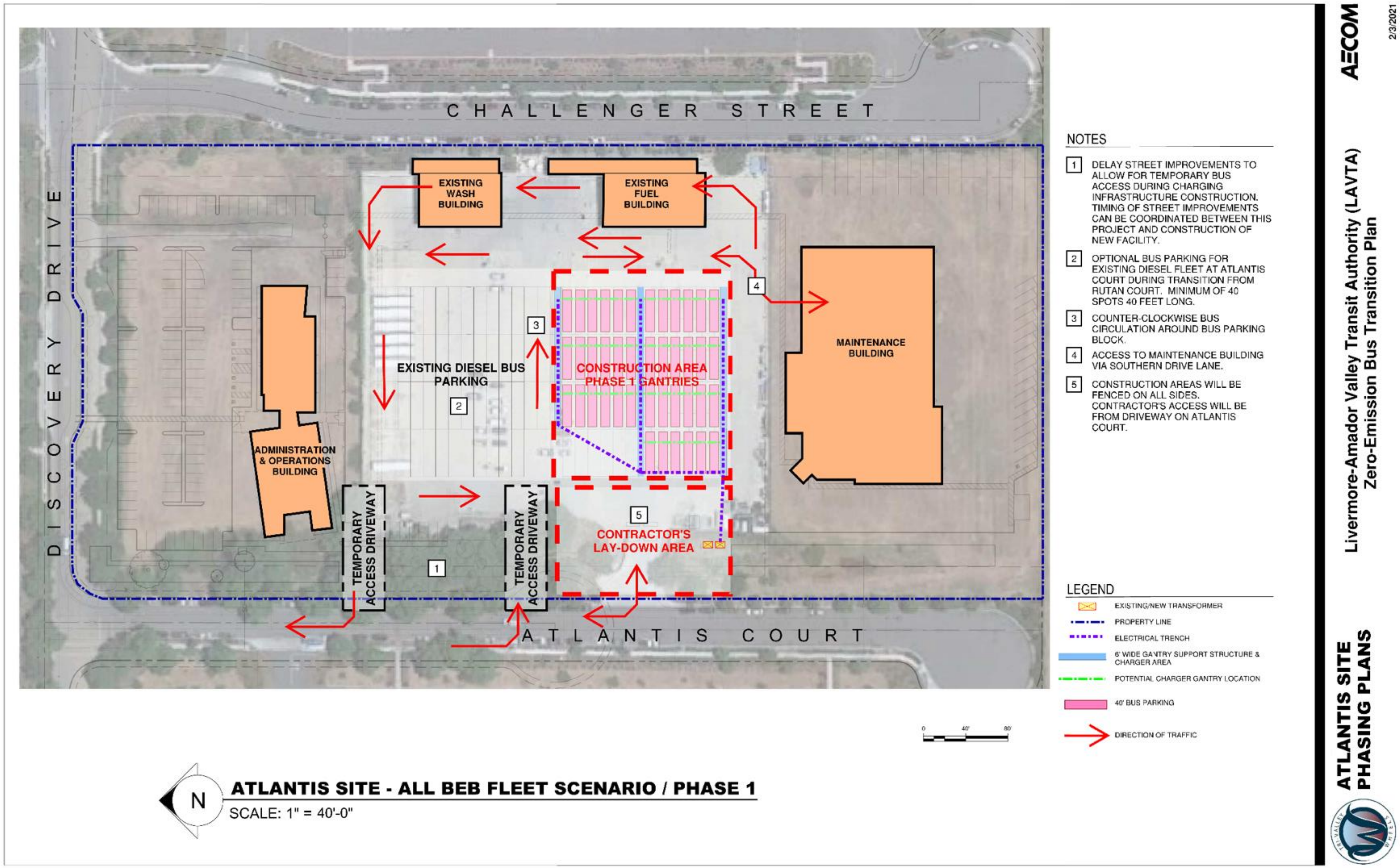
If LAVTA selects an FCEB Only strategy, total ZEB transitional costs are estimated at approximately $216 million (not including LCFS credit revenue on fuel) for replacement of 100% of the fleet with FCEBs by 2040. FCEB technology would allow service to continue unaltered without increasing fleet size. A primary assumption for the FCEB analysis is that FCEB buses will be available for all bus types and lengths during the transition period. Due to the lack of market diversity of FCEBs and hydrogen available in the United States, fuel costs and bus capital costs remain high. These costs are expected to come down in the future as more buses are deployed; however, more data is needed to understand how much they may fall. Additionally, data for FCEB maintenance costs reflect higher costs than what might be expected as agencies become more familiar with the technology. As such, there are more unknowns associated with costs for the FCEB Only scenario, and costs are more subject to change.

Given these considerations, the recommendations for LAVTA are as follows:

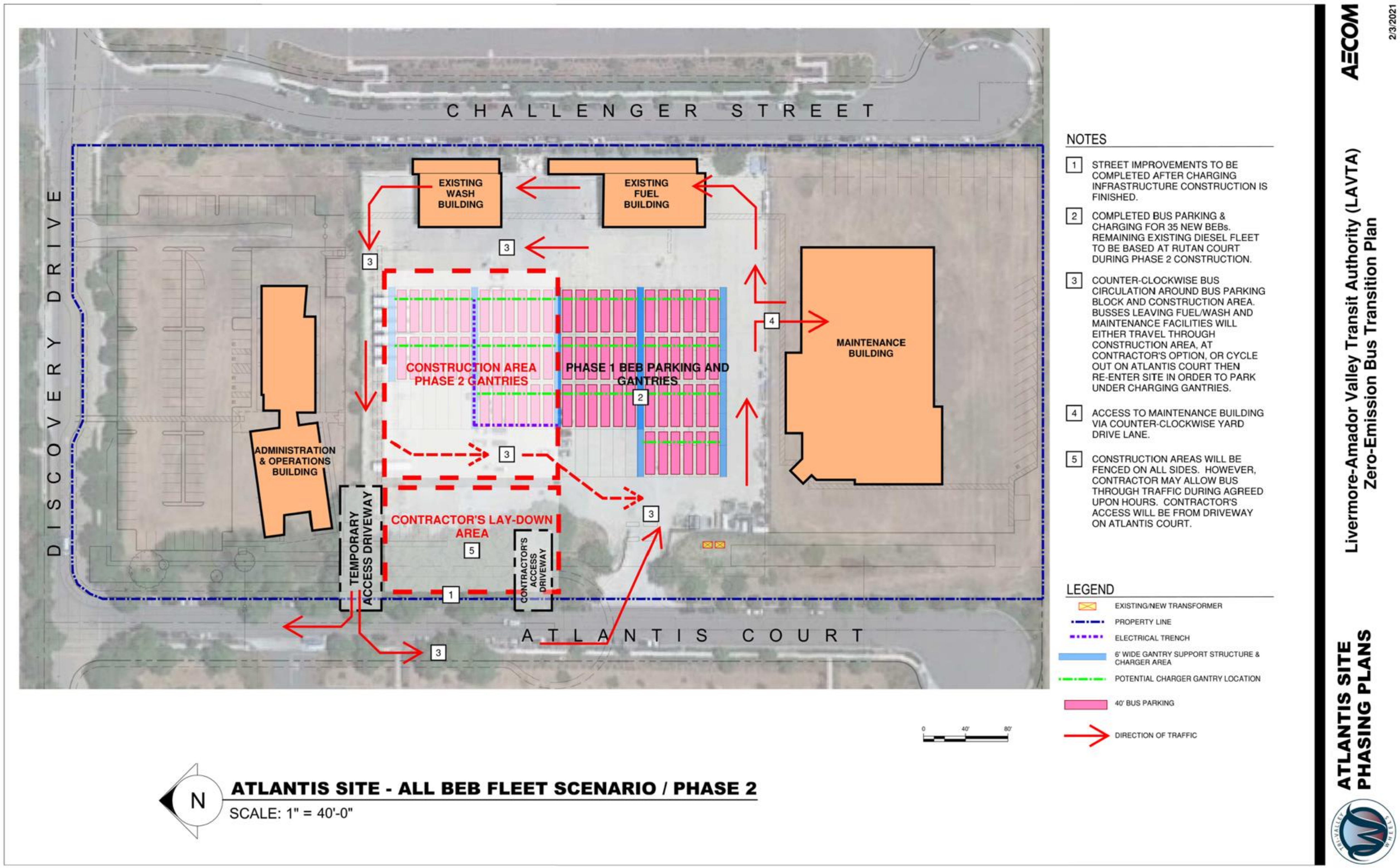
1. **Remain proactive with ZEB deployments:** For successful fleetwide deployment, BEBs will require charge management software, hardware, and standards to manage the fleetwide transition. For FCEB deployment to be competitive, lower fuel costs that will evolve over time with the production of hydrogen at scale will be required. LAVTA should move forward thoughtfully, taking advantage of various grant and incentive programs to offset the incremental cost for ZEB deployment. Incentive programs may be eliminated in future years as ZEB procurements are required instead of being optional.
2. **Target specific routes and blocks for early ZEB deployments:** LAVTA should consider the strengths of given ZEB technologies and focus those technologies on routes and blocks that take advantage of their efficiencies and minimize the impact of the constraints related to the respective technologies. For example, depot-charged BEBs for shorter routes and blocks, on-route charged BEBs for mid-range routes with layovers at a transit center, and FCEBs for long routes or routes with higher speeds and/or heavier loads, is recommended. These technologies cannot follow a one-size-fits-all approach from either a performance or cost perspective. Matching the technology to the service will be a critical best practice. Results from the ZEB Pilot Program will help to inform these decisions.

The transition to ZEB technologies represents a paradigm shift in bus procurement, operation, maintenance, and infrastructure. It is only through a continual process of deployment with specific goals for advancement that the industry can achieve the goal of economically sustainable, zero-emission public transit.

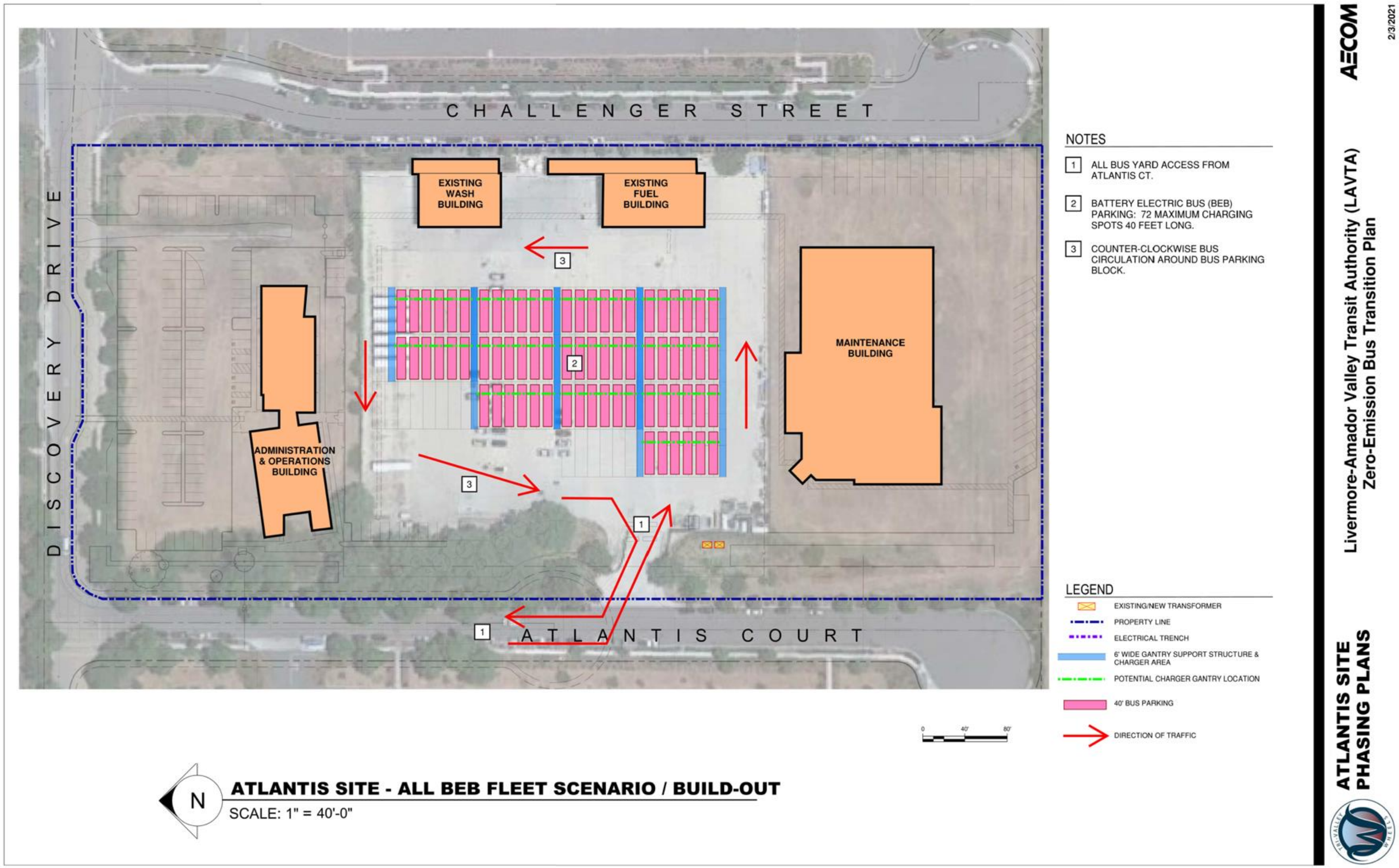
Appendix A1 – LAVTA Depot Site Plans, Depot and On-Route Charging Scenario Phase 1 - 2027



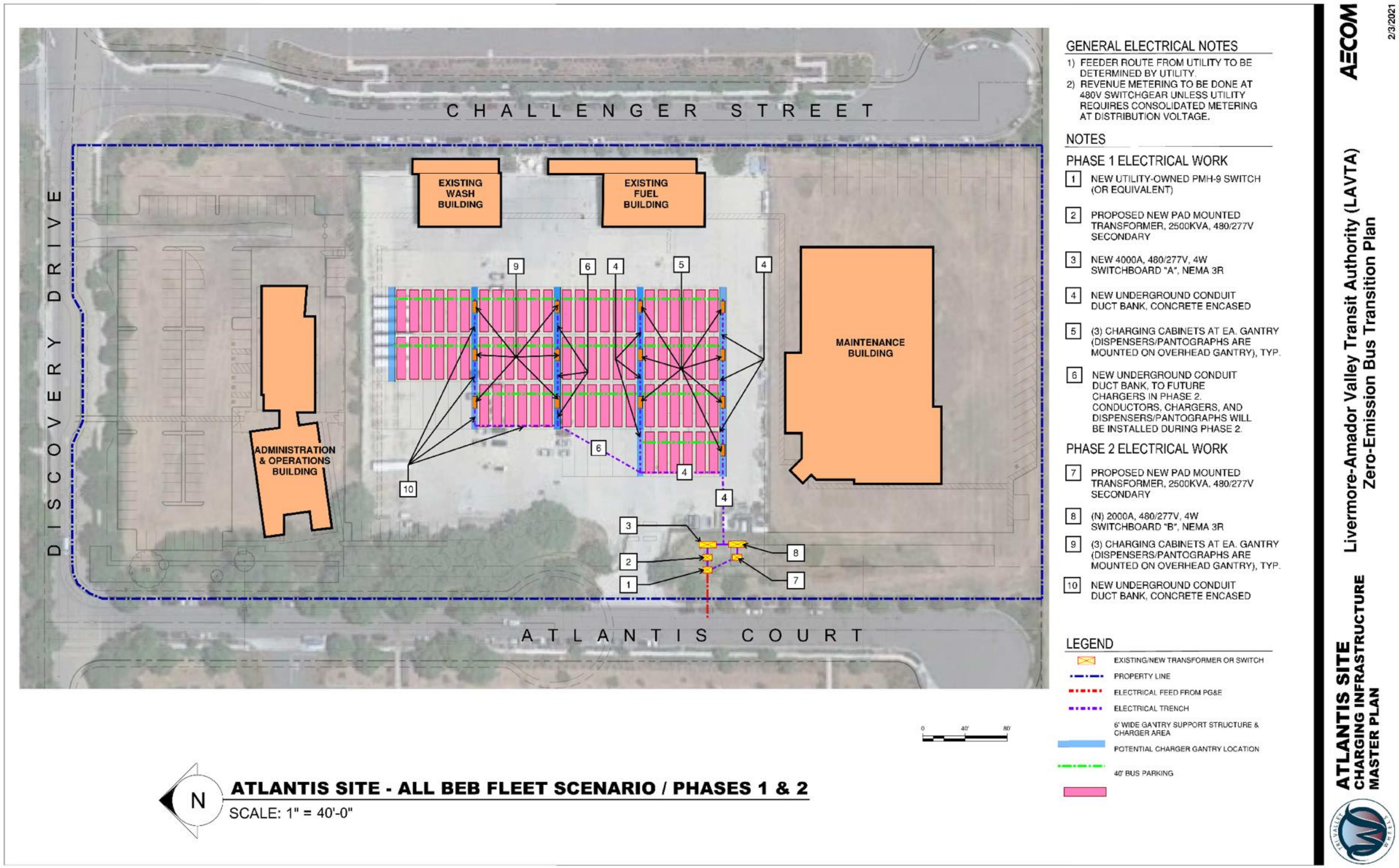
Appendix A2 – LAVTA Depot Site Plans, Depot and On-Route Charging Scenario Phase 2 - 2032



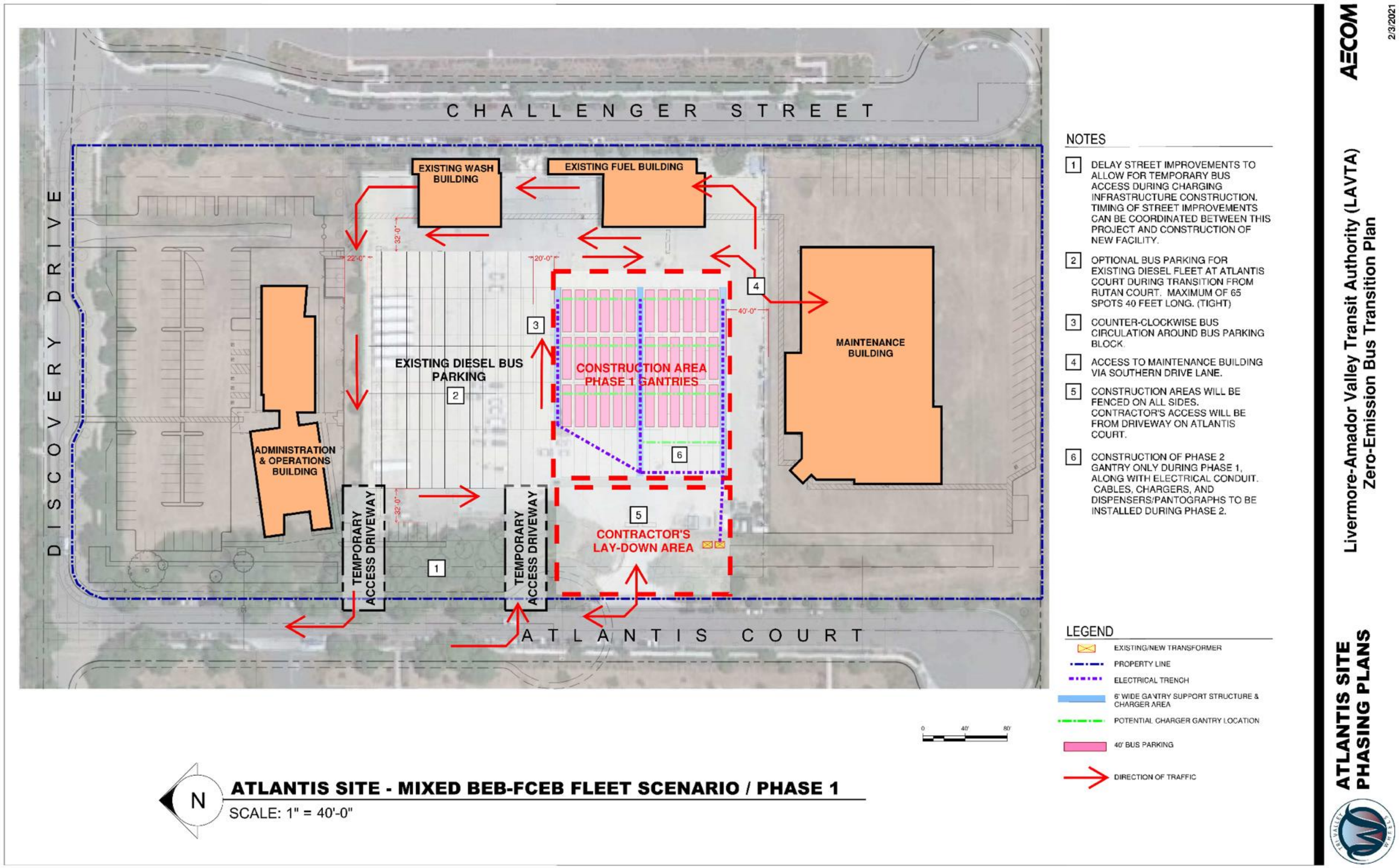
Appendix A3 – LAVTA Depot Site Plans, Depot and On-Route Charging Scenario Phase 3 - 2035



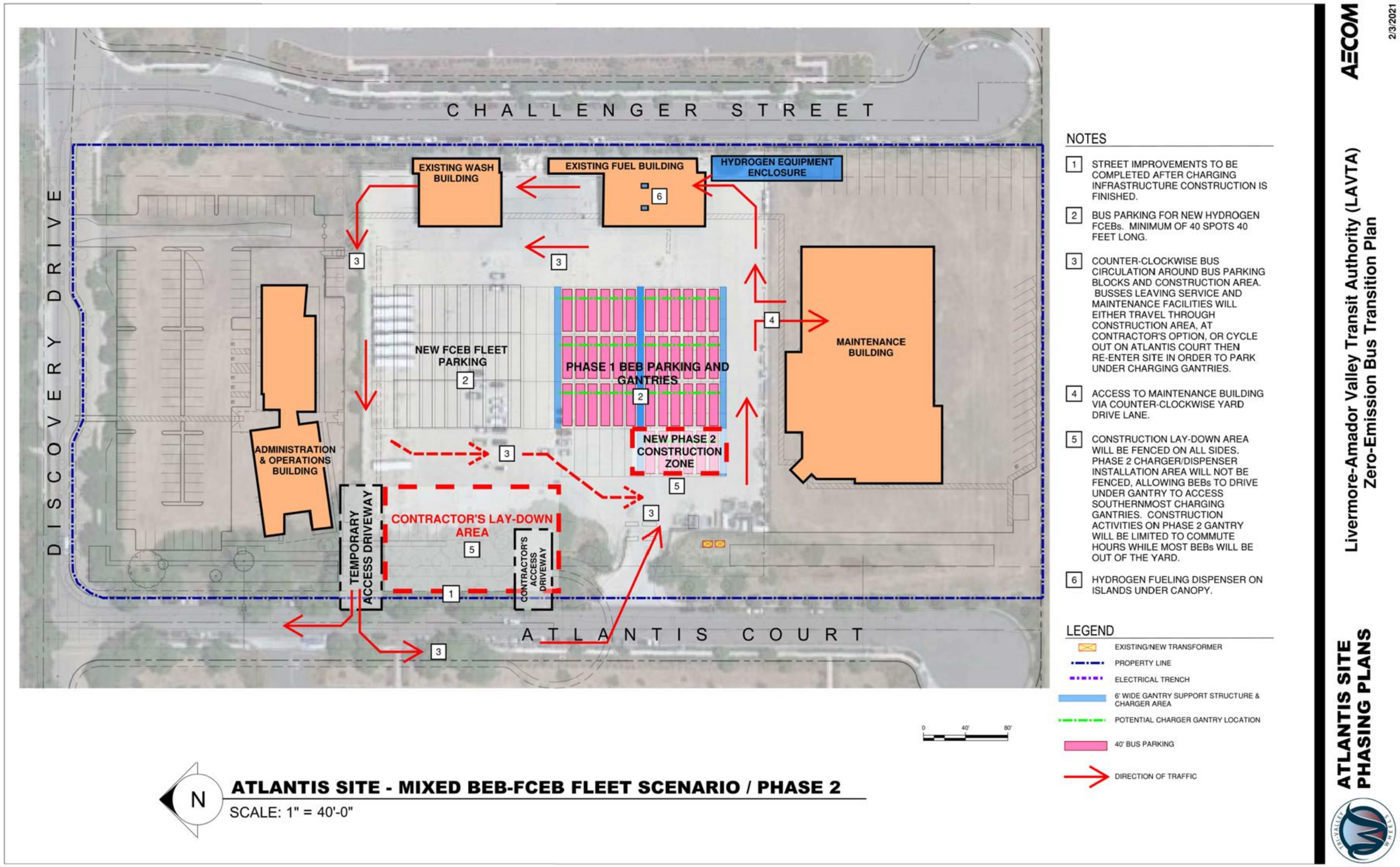
Appendix A4 – LAVTA Depot Site Plans, Depot and On-Route Charging Scenario Electrical Phasing



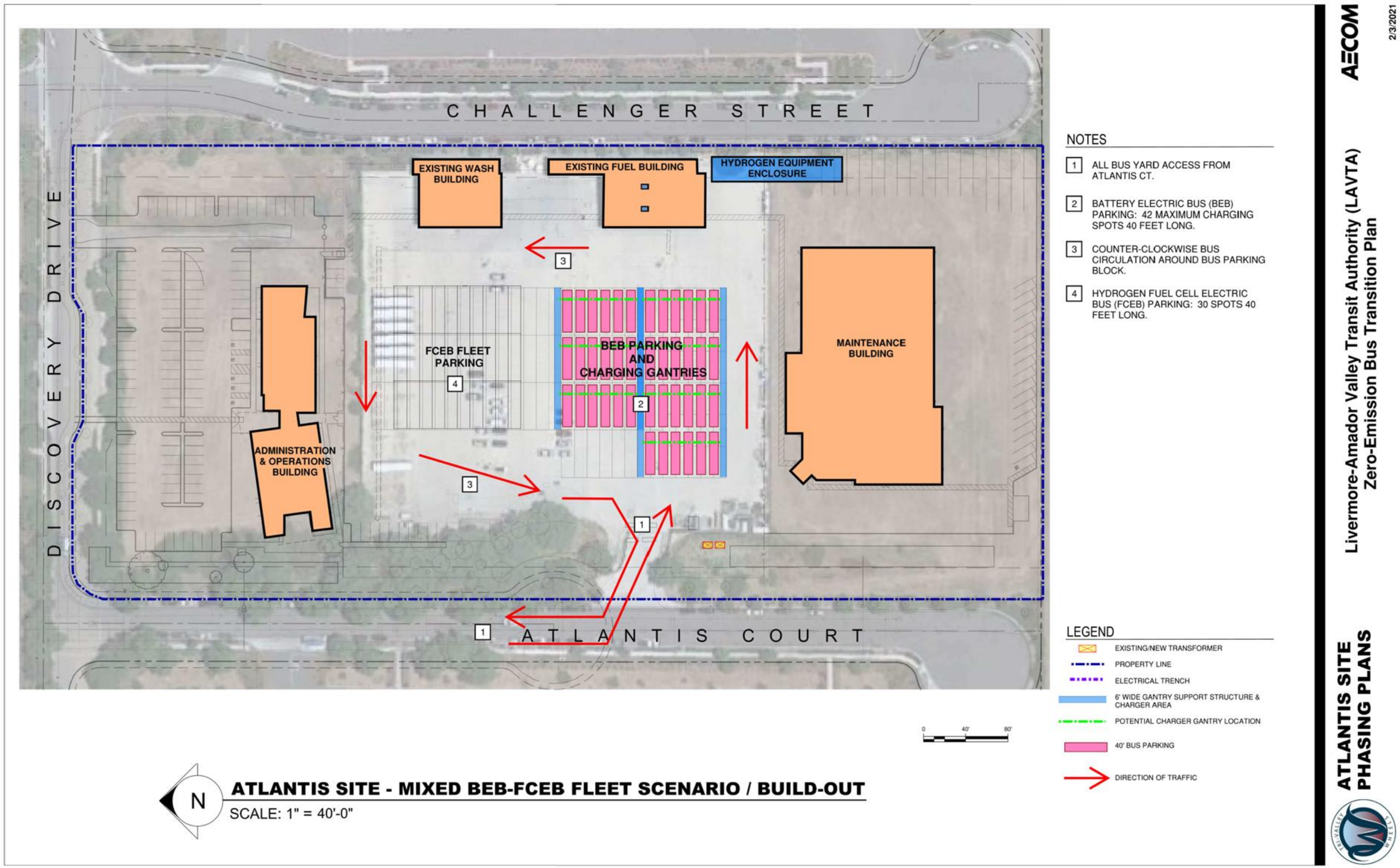
Appendix A5 – LAVTA Depot Site Plans, Mixed Fleet Scenario Phase 1 - 2027



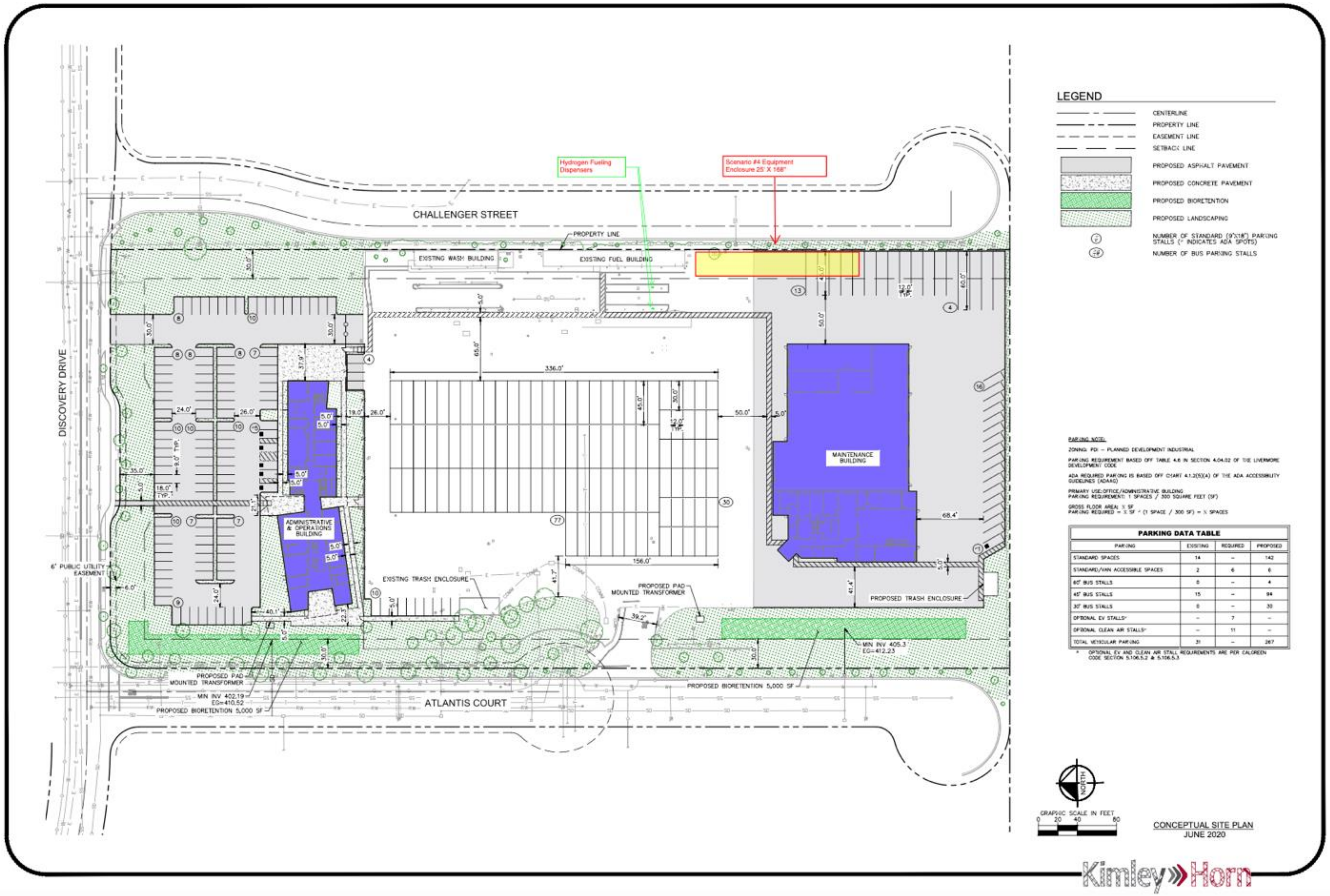
Appendix A6 – LAVTA Depot Site Plans, Mixed Fleet Scenario Phase 2 - 2032

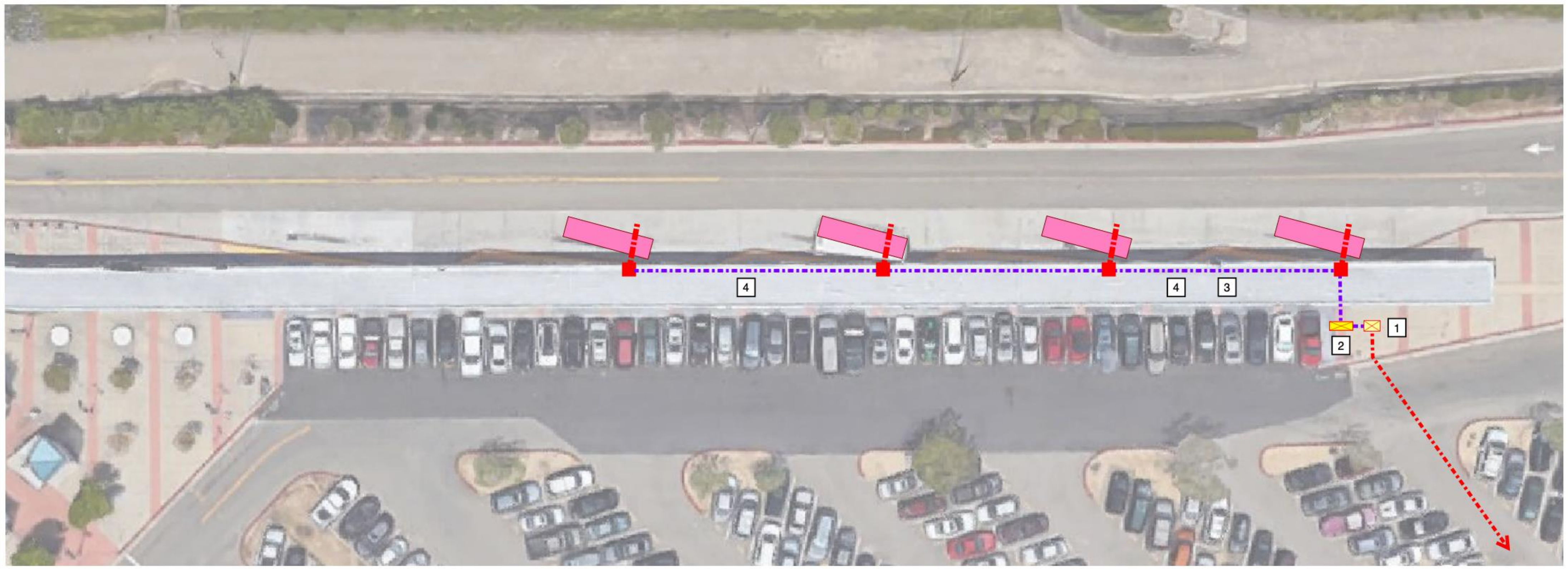


Appendix A7 – LAVTA Depot Site Plans, Mixed Fleet Scenario Phase 3 - 2035



Appendix A8 – LAVTA Depot Site Plans, FCEB Only Scenario Final - 2035





N

SITE PLAN

SCALE: 1" = 30'-0"

NOTES

1. PROPOSED NEW PAD MOUNTED TRANSFORMER, 500KVA, 480/277V SECONDARY (IN ENCLOSURE).
2. NEW 800A, 480/277V, 4W SWITCHBOARD "A", NEMA 3R (IN ENCLOSURE).
3. NEW UNDERGROUND CONDUIT DUCT BANK, CONCRETE ENCASED.
4. CHARGING CABINETS BETWEEN PANTOGRAPH COLUMN PAIRS (UNDER CANOPY).

0 30' 60'

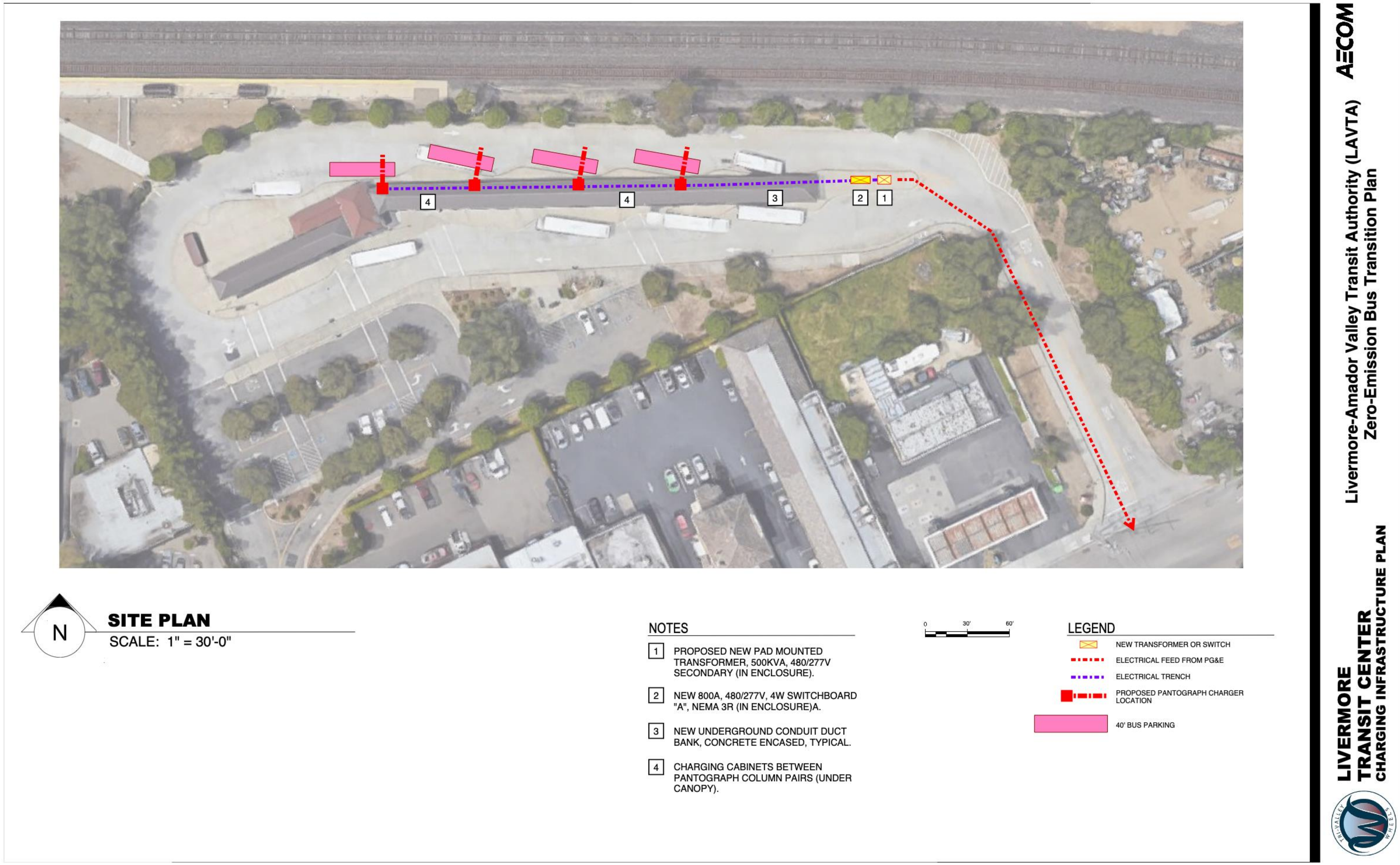
LEGEND

- NEW TRANSFORMER OR SWITCH
- ELECTRICAL FEED FROM PG&E
- ELECTRICAL TRENCH
- PROPOSED PANTOGRAPH CHARGER LOCATION
- 40' BUS PARKING

AECOM

BART TRANSIT CENTER
CHARGING INFRASTRUCTURE PLAN

Livermore-Amador Valley Transit Authority (LAVTA)
Zero-Emission Bus Transition Plan


4
4
3
2
1
N
SITE PLAN
SCALE: 1" = 30'-0"
NOTES
1 PROPOSED NEW PAD MOUNTED TRANSFORMER, 500KVA, 480/277V SECONDARY (IN ENCLOSURE).
2 NEW 800A, 480/277V, 4W SWITCHBOARD "A", NEMA 3R (IN ENCLOSURE)A.
3 NEW UNDERGROUND CONDUIT DUCT BANK, CONCRETE ENCASED, TYPICAL.
4 CHARGING CABINETS BETWEEN PANTOGRAPH COLUMN PAIRS (UNDER CANOPY).
0
30'
60'
LEGEND
NEW TRANSFORMER OR SWITCH
ELECTRICAL FEED FROM PG&E
ELECTRICAL TRENCH
PROPOSED PANTOGRAPH CHARGER LOCATION
40' BUS PARKING
AECOM
Livermore-Amador Valley Transit Authority (LAVTA)
Zero-Emission Bus Transition Plan
LIVERMORE
TRANSIT CENTER
CHARGING INFRASTRUCTURE PLAN

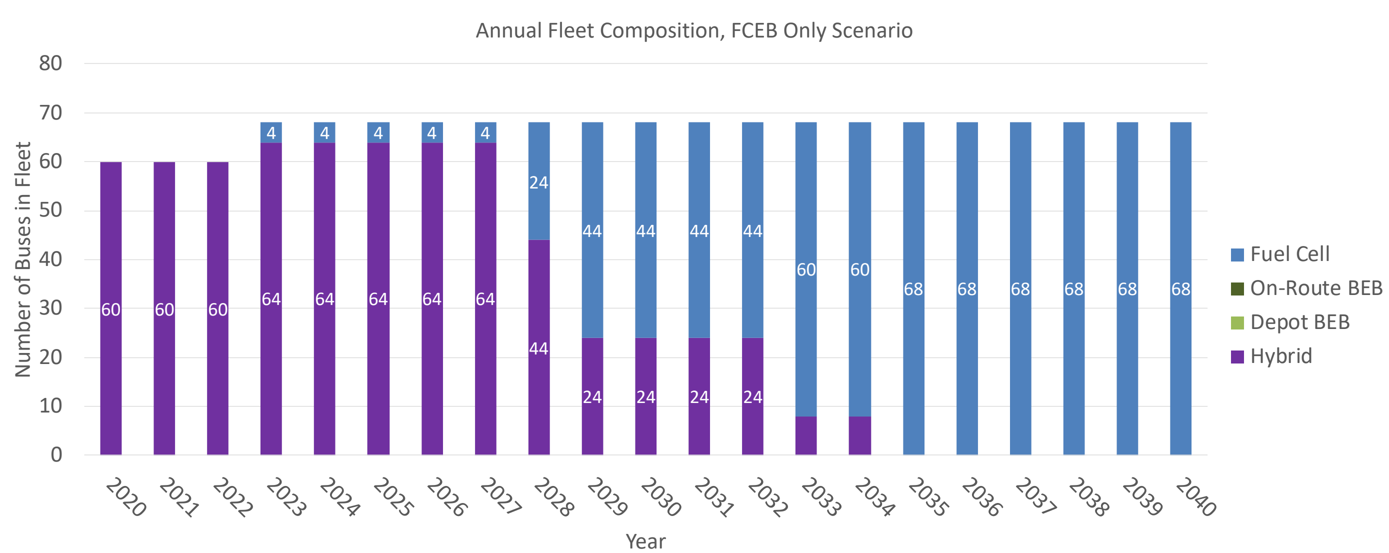
Addenda – Accelerated FCEB Purchase Cost Information

In the event that LAVTA chooses to purchase 12 FCEBs in 2023 rather than the previously projected 4 FCEBs and 8 Hybrids, additional costs would be incurred in 2023 for the capital cost of the bus purchases that year. Additionally, since there would be 8 additional FCEBs in the fleet from 2023-2035 compared to the original scenario (as demonstrated in **Addenda Figure 79:** Original Scenario (4 FCEB/8 Hybrid Purchased in 2023) Addenda Figure 1b: Accelerated 2023 FCEB Purchase Scenario (12 FCEB/0 Hybrid Purchased in 2023)**and 1b**), the maintenance and fuel costs would also differ from the 4 FCEB/8 Hybrid scenario since those additional FCEBs would be incurring slightly higher fuel and maintenance costs over their lifespan. However, since no additional infrastructure would be required by LAVTA if 4 or 12 FCEBs were purchased in 2023 due to the ability to easily scale the mobile fueler to accommodate and service 8 more FCEBs than modeled in the previous projections, there are no added infrastructure costs if 12 FCEBs are purchased in place of 4 FCEBs and 8 Hybrids.

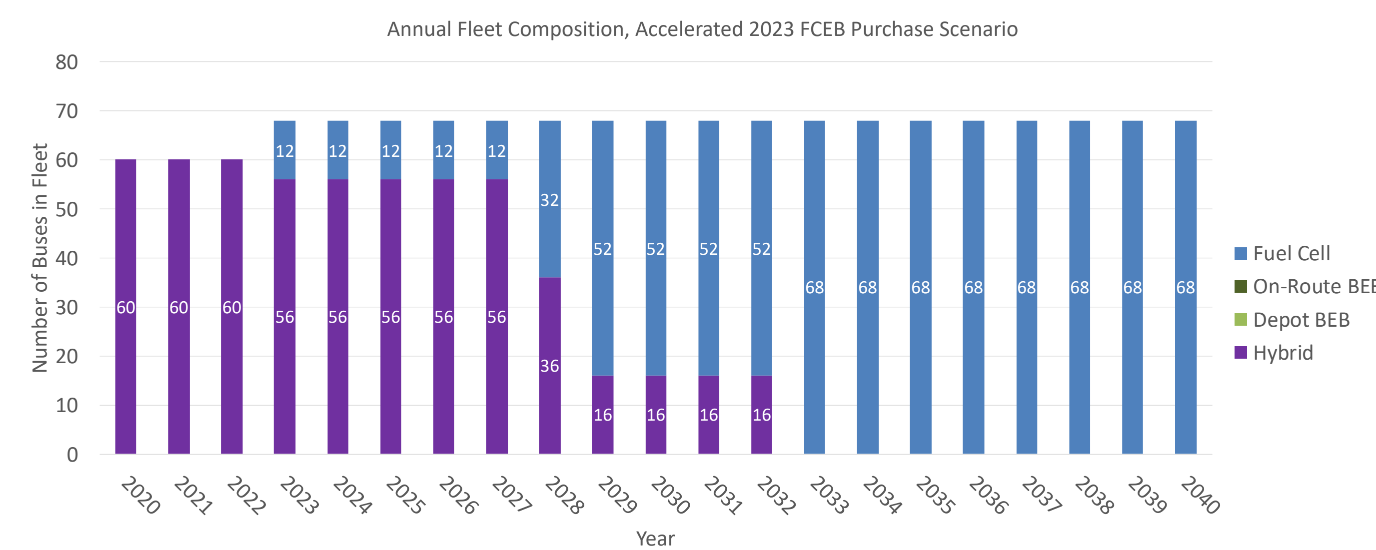
The additional costs that would be incurred by purchasing 12 FCEBs in 2023 as opposed to 4 FCEBs and 8 Hybrids are outlined below. Additional costs incurred are summarized as incremental relative to the original scenario and as the cumulative total for the accelerated 2023 FCEB Purchase Scenario:

	Costs incurred in 4 FCEB/8 Hybrid 2023 Purchase Scenario	Additional costs incurred 12 FCEB/0 Hybrid 2023 Purchase Scenario	Total Cumulative Costs Incurred 12 FCEB/0 Hybrid 2023 Purchase Scenario
Fleet	$150,188,000	$4,560,000	$154,748,000
Fuel	$30,399,000	$1,492,000	$31,890,000
Maintenance	$25,303,000	$617,000	$25,920,000
Facilities	$9,752,000	No additional cost	$9,752,000
TOTAL	**$215,642,000**	**$6,669,000**	**$222,310,000**

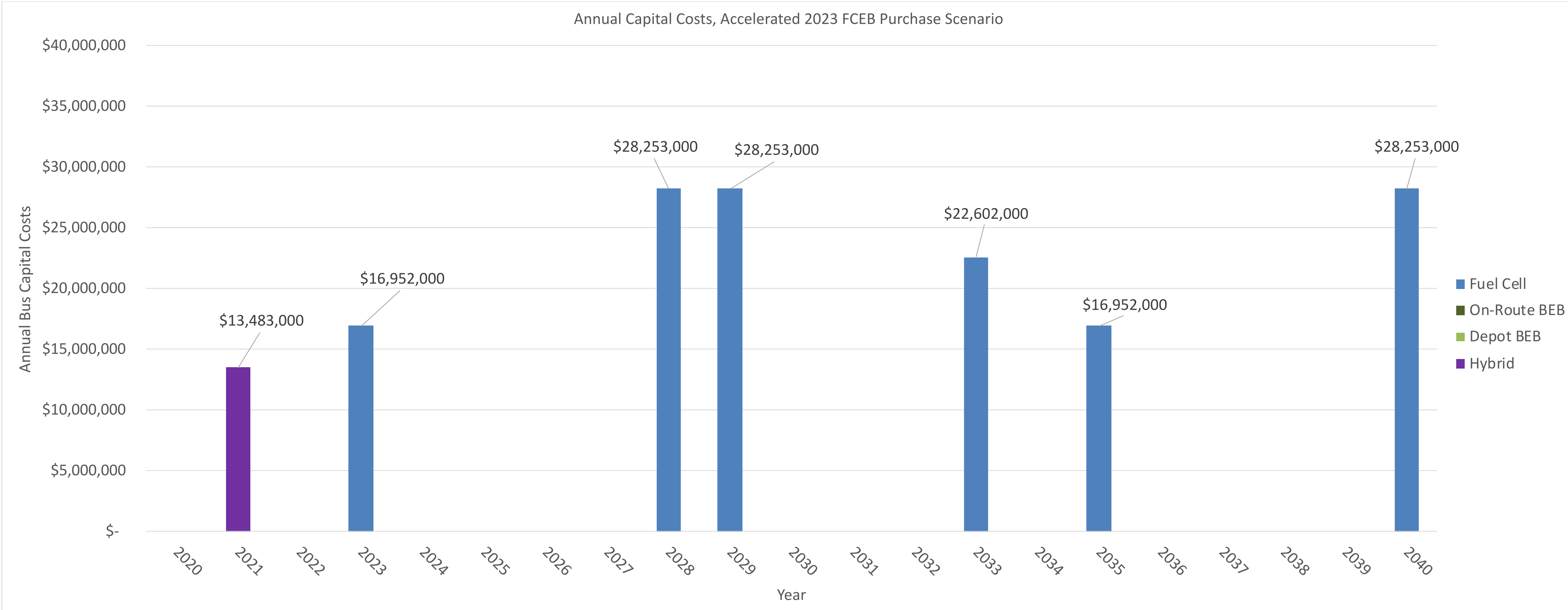
In summary, purchasing an additional 8 FCEBs instead of 8 hybrids in 2023, would incur an additional $6,669,000 over the lifetime of those vehicles.



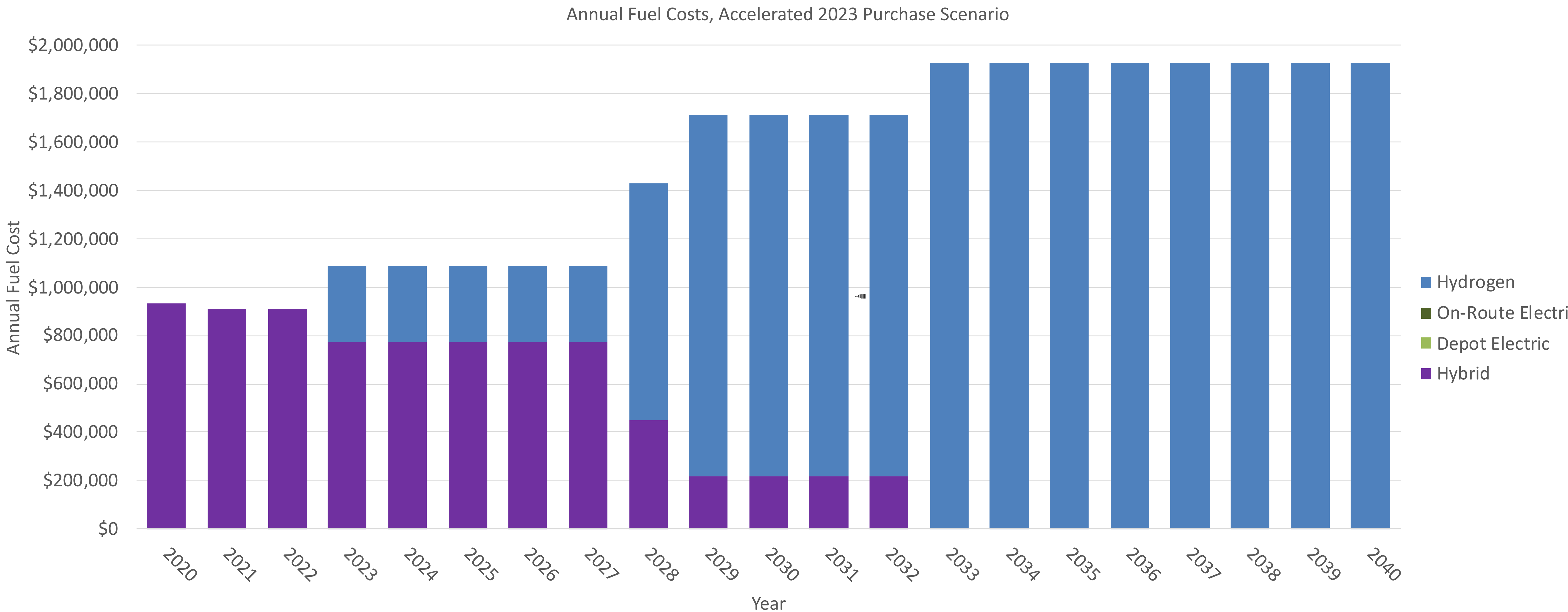
Addenda Figure 79: Original Scenario (4 FCEB/8 Hybrid Purchased in 2023)



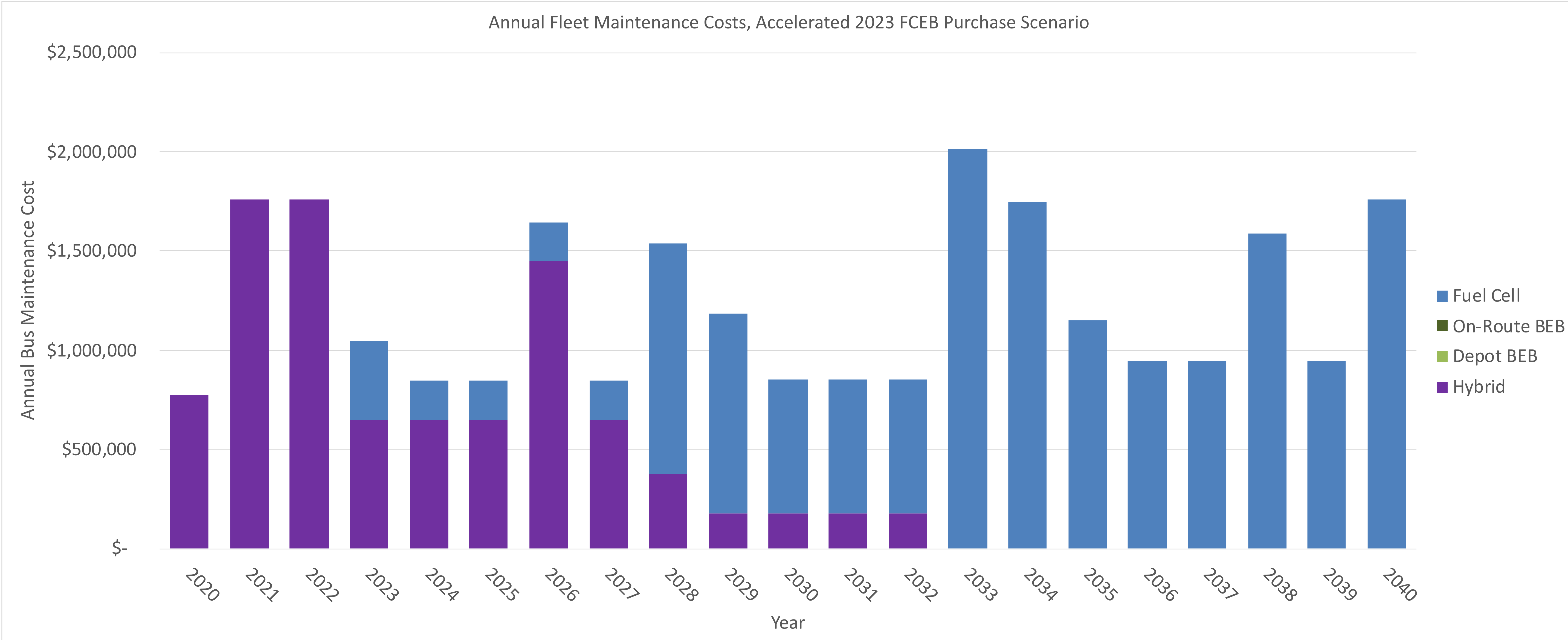
Addenda Figure 1b: Accelerated 2023 FCEB Purchase Scenario (12 FCEB/0 Hybrid Purchased in 2023)



Addenda Figure 2: Annual Bus Capital Costs, Accelerated 2023 FCEB Purchase Scenario



Addenda Figure 3: Annual Fuel Costs, Accelerated 2023 FCEB Purchase Scenario



Addenda Figure 4: Annual Bus Maintenance Costs, Accelerated 2023 FCEB Purchase Scenario