Comprehensive Review of California's Innovative Clean Transit Regulation: Phase I Summary Report

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List of Acronyms

AC Transit	Alameda–Contra Costa Transit District
APTA	America Public Transportation Association
APCD	air pollution control district
AQMD	air quality management district
BEB	battery-electric bus
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CCS	Combined Charging System
CEC	California Energy Commission
CNG	compressed natural gas
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EV	electric vehicle
EVSE	electric vehicle supply equipment
FCEB	fuel cell electric bus
FTA	Federal Transit Administration
FY	fiscal year
GDP	gross domestic product
GHG	greenhouse gas
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICT	Innovative Clean Transit
IMPLAN	Economic Impact Analysis for Planning
LCFS	Low Carbon Fuel Standard
LCTOP	Low Carbon Transit Operations Program
Low-No	Low or No Emission Vehicle
MBRC	miles between road calls
MD/HD	medium- and heavy-duty
mpdge	miles per diesel gallon equivalent
NPV	net present value
NREL	National Renewable Energy Laboratory
OCTA	Orange County Transportation Authority
OEM	original equipment manufacturer
PG&E	Pacific Gas and Electric Company
SCE	Southern California Edison
TIRCP	Transit and Intercity Rail Capital Program
TRL	technology readiness level
UCB	University of California, Berkeley
VICE	Vehicle and Infrastructure Cash-Flow Evaluation
VMT	vehicle miles traveled
ZEB	zero-emission bus
ZEV	zero-emission vehicle

Executive Summary

The Innovative Clean Transit (ICT) regulation requires California transit agencies to gradually transition to zero-emission vehicle technologies. It was adopted in 2018 to help the state reduce harmful vehicle emissions and meet its goals related to air quality and the environment. The ICT regulation is the first regulation in the United States that requires a vocational heavy-duty vehicle application to completely transition to zero-emission technologies over time. Zero-emission buses (ZEBs) serve as a foundation for transitioning the entire heavy-duty vehicle sector. Experience and lessons learned from ZEB demonstrations and deployments in transit can benefit other heavy-duty vehicle markets, such as school buses, as well as drayage, delivery, and yard trucks.

California leads the nation in developing and implementing programs designed to reduce harmful air pollutants from stationary and mobile sources. This includes a wide range of zero-emission vehicle (ZEV) regulations, such as for new passenger vehicles, transit buses, airport shuttles, trucks, ferries, locomotives, and off-road equipment. Transitioning away from fossil fuels and toward ZEV technology will help ensure there is clean air for all Californians, help protect the climate, and meet the goals set forth in Governor Newsom's Executive Order N-79-20.

The ICT regulation mandates an increasing percentage of new bus purchases to be ZEBs each year, including standard, articulated, double-decker, over-the-road, and cutaway buses. The purchase requirements begin in 2023 with 25% of new bus purchases for large transit agencies, expanding to small transit agencies in 2026, and increasing to a 100% ZEB purchase requirement beginning in 2029. This schedule is designed to achieve 100% ZEB fleets statewide by 2040 (Table ES-1). As part of the regulation, each transit agency is required to submit a ZEB rollout plan, approved by their governing board, that outlines the agency's plans to purchase ZEBs and deploy the charging and/or fueling infrastructure to comply with the regulation's ZEB purchase requirements. For large transit agencies, the ZEB rollout plans were due on June 30, 2020. All 21 large transit agencies have submitted their rollout plans which are posted on California Air Resources Board's (CARB's) website [1]. For small transit agencies, ZEB rollout plans are due on June 30, 2023.

Table ES-1. ICT Regulation, ZEB Purchase Requirements (percent of new buses purchased annually)

Date	Large Transit Agency [a]	Small Transit Agency [b]
2023–2025 (standard 40-ft buses only)	25%	—
2026–2028 (all bus types, if passed Altoona testing)	50%	25%
January 1, 2029, and thereafter	100%	100%

[a] A transit agency that either (a) operates more than 65 buses in annual maximum service in either the South Coast Air Basin or the San Joaquin Valley Air Basin, or (b) operates in an urbanized area with a population of at least 200,000 and at least 100 buses in annual maximum service.

[b] All other transit agencies.

As transit agencies deploy ZEBs in their daily operations and help advance the technologies, it is important they can continue to provide critical services to Californians, especially to transit-dependent riders. When CARB adopted the ICT regulation, they directed staff (Resolution 18-60) to conduct a comprehensive review of program readiness, with multiple metrics included such as costs, performance, and reliability of ZEBs and corresponding infrastructure, prior to initiating any purchase requirement [2,3].

To fulfil this commitment, a team led by the National Renewable Energy Laboratory (NREL) with the University of California, Berkeley (UCB) was awarded the contract (Agreement No. 19MSC005) by CARB to conduct the comprehensive review, which was divided into two phases. Phase I focuses on the "standard-length" (approximately 40-foot), low-floor-type transit buses. Phase II of the comprehensive review will provide an update to the standard 40-foot bus (from Phase I) and cover a wider variety of transit vehicle types, including articulated buses, over-the-road coaches, "cutaway" shuttle buses, and double-decker buses. This report represents the findings from Phase I of the review. The results for Phase II are planned to be delivered in 2024.

The objective of Phase I is to determine whether the currently available ZEB technologies in standard buses can be used by large transit agencies to meet the ZEB purchase requirement in 2023, while ensuring transit service or fares are not adversely impacted by the transition. The review also aims to identify the remaining needs for the full transition of the California transit bus fleets and determine what additional programs, resources, or support are needed by transit agencies. This review is intended to inform and improve policies to advance heavy-duty zero-emission technologies and inform funding strategies related to zero-emission buses and infrastructure.

This executive summary provides an overview of topics covered in more detail in the body of the comprehensive review:

- ZEB deployment status.
- Available ZEB models and related infrastructure.
- Cost, performance, reliability, and barriers to deploying ZEB technologies.
- Incentive funding programs.
- Workforce training for operating and maintaining ZEBs.
- Job creation and estimated economic impact of the ZEB transition in California.
- Lessons learned and remaining challenges.

The overall approach for the comprehensive review includes:

- Conduct a literature review for the latest information on ZEBs, including results of pilot and demonstration projects, incentive funding programs, and available ZEB models and infrastructure.
- Interview ZEB stakeholders—transit agencies, original equipment manufacturers (OEMs) and technology providers, utilities, and fuel providers.
- Combine analyzed data from detailed NREL fleet evaluations and other published ZEB studies.
- Utilize modeling tools to compare economics of ZEBs to conventional bus purchases and to estimate the economic impact of the ZEB transition in California.

Since the adoption of the ICT regulation in 2018, many improvements have been made in the market to support the transition to ZEBs, as described in the following sections.

Increased number of Altoona-tested ZEB models

Bus testing at Pennsylvania State University's Altoona Bus Research and Testing Center is part of the Federal Transit Administration's (FTA) Bus Testing Program. It evaluates how well the buses perform under the demanding conditions found in transit service. Vehicle categories that are assessed include maintainability, reliability, safety, performance, vehicle structure, noise, and fuel economy. In recent years, there has been an increase in the number of ZEB models that have completed Altoona testing. From 2001 to the end of 2018, eight ZEB manufacturers successfully passed Altoona testing for their battery and fuel cell electric bus (FCEB) models, and a total of 15 bus testing reports were generated (9 complete and 6 partial tests). In comparison, during the much shorter period from the beginning of 2019 until April 2022, 13 bus testing reports were generated (5 complete and 8 partial tests). These reports were related to battery-electric bus (BEB) models manufactured by seven OEMs: Proterra, BYD, New Flyer, Gillig, ENC, GreenPower, and Motor Coach Industries.

Increased number of commercially available ZEB models

A variety of ZEBs are now commercially available. As of May 2022, there are 56 models of heavy- and medium-duty ZEBs on California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) list of eligible vehicles. The list of manufacturers includes those with California-based manufacturing facilities: BYD Motors (Lancaster), Proterra (City of Industry), El Dorado National-California (Riverside), Gillig (Hayward), GreenPower Motor Company (Porterville), Motor Coach Industries (Hayward), Motiv Power Systems (Hayward), and Phoenix Motor Cars (Anaheim); as well as others with manufacturing throughout the United States: Van Hool, Nova Bus, New Flyer, Lightning eMotors, Lion Electric, ARBOC Specialty Vehicles, and Optimal-Electric Vehicle. In addition, SEA Electric and Alpha Mobility have headquarters in Torrance and San Diego, California, respectively.

Increased legislation and enhanced policy supporting ZEB deployment

The California Legislature has continued to provide policy incentives for the purchase of ZEBs. Assembly Bill 784 enacts a partial state sales and use tax exemption for the purchase of specified zero-emission technology transit buses by California transit agencies through January 1, 2024 [4]. Assembly Bill 2622 was introduced in February 2022, and, if passed by the legislature, will extend the exemption for specified zero-emission technology transit buses from state sales and use tax until January 1, 2026 [5]. In addition, Assembly Bill 841 helps streamline the process of installing electric vehicle charging infrastructure [6]. Senate Bill 350 comprises many grid- and electrical utility-related elements that benefit the deployment of medium- and heavy-duty (MD/HD) infrastructure projects to support transportation electrification [7]. Senate Bill 1000 further requires the California Public Utilities Commission to explore more targeted rate design strategies for commercial electric vehicle (EV) customers and fleets and to deploy charging stations where there is existing excess grid capacity [8]. Senate Bill 288 accelerates various transportation projects, such as charging infrastructure for ZEBs and new rapid transit, bus, or light rail service, by temporarily exempting them from the California Environmental Quality Act until 2023 [9]. Senate Bill 922 was introduced in February 2022 to amend Sections 21080.20 and 21080.25 of the Public Resources Code, relating to environmental quality. If passed, it will extend the California Environmental Quality Act exemption to January 1, 2030 [10].

Increased state funding for ZEBs and ZEB infrastructure

There was a significant increase in the fiscal year (FY) 2021 and FY 2022 dedicated funds to support deployment of zero-emission vehicles. Governor Newsom’s recent May Revision Budget Proposal adds $6.1 billion in new zero-emission transportation investments over 4 years to increase access to clean transportation, reduce air pollution, and support disadvantaged and low-income communities, including tribal communities [11]. This proposal builds upon the $3.9 billion approved in the 2021 Budget Act that aimed to put 1,000 zero-emission drayage trucks, 1,000 zero-emission school buses, and 1,000 zero-emission transit buses, as well as the necessary infrastructure, on California roads while prioritizing projects that benefit disadvantaged communities. Recognizing the importance of transitioning public transit buses to zero emissions, the proposed budget adds $320 million in dedicated funding for zero-emission public transit buses, with additional funding available for infrastructure. These proposed funds build upon the $200 million included in last year’s ZEV acceleration package, for a total of $520 million for zero-emission transit buses over the course of 5 years.

Increased group procurement opportunities on ZEBs

Group bus procurement has been utilized to reduce cost and improve efficiency. This becomes more important for ZEBs when more specifications are expected to be identified in each ZEB procurement. California’s Department of General Services has secured a statewide contract for ZEB procurements that covers multiple manufacturers, fuel types, and models [12]. This contract also meets FTA’s bus procurement criteria. In addition, transit agencies have also been putting out joint procurement solicitation for transit buses to relieve the procurement burden for many of the participating agencies. For example, in February 2021, Morongo Basin Transit Authority, on behalf of the California Association for Coordinated Transportation member agencies, issued a request for proposals (RFP-20-01) of a joint procurement for the manufacture and delivery of accessible transit/paratransit vehicles, which also included BEBs [13]. This solicitation is a joint procurement for the manufacture and delivery of accessible transit/paratransit vehicles that may be ordered by the California Department of Transportation (Caltrans), its subrecipients, and/or members of the California Association for Coordinated Transportation that have specifically entered into this joint procurement.

Increased state funding for workforce training

In 2021, the California Energy Commission (CEC) and CARB jointly allocated up to $6.8 million in grant funds for projects that will provide workforce training and development that support ZEVs, ZEV infrastructure, and ZEV-related commercial technologies in California [14]. Eight entities received awards under this program, including SunLine Transit Agency, Kern Community College District, Fresno City College, Los Angeles Pierce College, and California State University, Long Beach. In addition, CARB has instructed CALSTART, who administers the HVIP program, to allocate $250,000 of the HVIP outreach funding to support SunLine's training program at its West Coast Center of Excellence in Zero-Emission Technology. This training program focuses on maintaining and operating ZEBs in public fleets. Public and private organizations, including transit agencies, colleges, private industry, and government agencies, are collaborating with SunLine to develop training and resources for ZEB maintenance that include various types of alternative and emerging energy technologies [15].

Increased electric charging and hydrogen fueling standardization

ZEB charging and fueling interoperability topics have been investigated and worked on by various stakeholders, including industry associations and standardization groups, transit agencies (via joint procurements), and state contract work. The recent San Francisco Municipal Transportation Agency BEB pilot program is a good example that requires all four OEMs to use the same overhead chargers [16]. CARB also contracted with University of California, Irvine (Agreement No. 20MSC006) in 2021 to conduct a 2-year study on the status, implementation gaps, and future directions of electric charging and hydrogen fueling standardization.

Various electric charging standards have been developed by SAE International. SAE J1772 specifies the North American standard for electrical connectors used in plug-in charging. In 2011, SAE developed a J1772/CCS Combo Coupler to support the Combined Charging System (CCS) standard for DC fast charging up to 350 kW. SAE J3105/2, issued in 2020, specifies overhead conductive charging and provides a charging strategy for on-route charging and space-constrained depot charging [17]. SAE J2954/2 WIP, released in December 2020, establishes an industrywide specification guideline for high-power wireless charging of BEBs and other heavy-duty electric vehicles [18].

For fuel cell electric vehicle fueling, a major focus of the international community is on the development of a refueling standard for high-flow, 700-bar hydrogen dispensing for heavy-duty vehicles (H70) within the International Organization for Standardization. SAE International has released a guidance document for MD/HD vehicle fueling: SAE J2601/2, "Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles" [19].

Increased clean energy sector jobs

The increase in investment in the clean energy transportation sector has positively influenced jobs across multiple sectors. Clean energy is a major part of California's economy. Across the United States, California is ranked first in the total jobs that are held in five of the main clean energy sectors: energy efficiency, renewable generation, energy storage and the electric grid, clean vehicles, and clean fuels. Investing in clean energy is setting the foundation for job growth and a cleaner, sustainable, and more resilient economy. The Economic Impact Analysis for Planning (IMPLAN) framework was applied to estimate the impacts on jobs, gross domestic product (GDP), income, and industrial output resulting from the investments in new ZEBs and infrastructure, as well as annual operation and maintenance of the ZEB fleets. Purchases of new ZEBs and construction of the necessary infrastructure could add $2.1 billion to California's GDP and generate $240 million in state/county taxes and $3.8 billion in additional industrial output from 2019–2040. Most of these impacts are due to ZEB manufacturing; therefore, choice of bus manufacturer has a significant effect on the total impacts in California. On average, 611 jobs per year could be created in California due to ZEB investments between 2019–2040, half of which are due to indirect/induced effects. More than one-third of jobs do not require advanced skills (i.e., require a high school diploma or less), and this share is slightly higher for construction-induced jobs than ZEB manufacturing-induced jobs. Almost a quarter of jobs require no previous experience, and average salaries range between $50,000 and $60,000 per year, with median wage distribution higher than those from California in 2019. By 2040, around 789 jobs per year could be sustained by the ICT regulation in California.

Based on the information collected and evaluated under this comprehensive review, it appears that the California transit industry is well positioned to proceed with the 2023 requirement of 25% of new bus purchases being ZEBs for large transit agencies. This is supported by large transit agencies' ZEB rollout plans, momentum developed from over a decade of ZEB demonstrations and deployments, continued product development and refinement led by the transit industry, a supportive environment for ZEBs as already described, and successful partnership and collaboration of California transit agencies, vehicle manufacturers, charging and fuel equipment suppliers, utility providers, and others.

To achieve a successful transition to 100% ZEB transit fleets in the coming years, additional coordination, focus, and resources may be necessary. Areas of focus include:

- Sustained progress from the vehicle, equipment, and infrastructure manufacturing base to continue driving down costs, improving reliability, and optimizing performance.
- Expansion of charging and fueling infrastructure via coordinated efforts and forward-looking planning by transit agencies, utilities, and developers.
- Comprehensive and standardized training programs to develop a highly skilled workforce to improve the efficiency and cost of maintaining ZEB equipment while creating new jobs and ensuring safety.
- Financial support for purchasing ZEBs and installing the related fueling/charging equipment, especially in the early years.

Key findings of the comprehensive review follow and are covered in more detail in the body of the report:

- California transit agencies have been national leaders in deploying low- and no-emission vehicles for decades. The California transit industry was already a leader in the ZEB transition prior to the ICT regulation, but the regulation has accelerated plans to electrify transit and ensures the state continues on its path to achieve 100% zero-emission transit fleets. Analysis of the rollout plans and transit press releases shows five California transit agencies are planning to fully transition to ZEBs by 2030—Los Angeles Department of Transportation, Los Angeles County Metropolitan Transportation Authority, Foothill Transit, Long Beach Transit, and Santa Monica's Big Blue Bus. An additional two agencies expect to complete their ZEB transition by 2035. The annual progress of transit ZEB deployment in California has been tracked for the ICT regulation using CARB's Innovative Clean Transit Reporting Tool. Public transit agencies in California have reported that 336 ZEBs (46 FCEBs and 290 BEBs) were in service and another 318 ZEBs (30 FCEBs and 288 BEBs) were on order as of December 31, 2020, for a total of 654 ZEBs. Early adoption of ZEBs throughout California has already had numerous positive impacts on California's economy, job creation and growth in the clean transportation industry, and emissions reduction and local air quality improvements. The deployment of ZEBs in low-income and disadvantaged communities reduces local tailpipe emissions, particulate matter associated with brake wear, petroleum use, and energy consumption.

- One significant and unexpected event that has impacted the transit industry's transition to ZEBs is the COVID-19 pandemic. When the pandemic hit the United States in early 2020, transit agencies experienced a sudden and drastic decrease in ridership, which affected numerous aspects of the transit industry. Transit agencies had to quickly adapt to constantly changing service levels and public health requirements. Staff time and attention were focused on providing transit service as safely as possible in an uncertain environment. As a result, many transit agencies were unable to allocate resources toward ZEB transition efforts. As noted in Section 2, this caused some transit agencies to temporarily delay planning and deployment activities for their ZEB transition.

- All combined, the rollout plans indicate that California transit agencies plan to acquire approximately 8,000 standard ZEBs in the next 2 decades (Figure ES-1). This will be a tremendous accomplishment for the state of California, the California transit industry, transit riders, and communities. FCEB purchases account for approximately 1,200 of the buses, BEBs account for 5,250 of the buses, and the remaining 1,550 buses are still to be determined (TBD) [1].

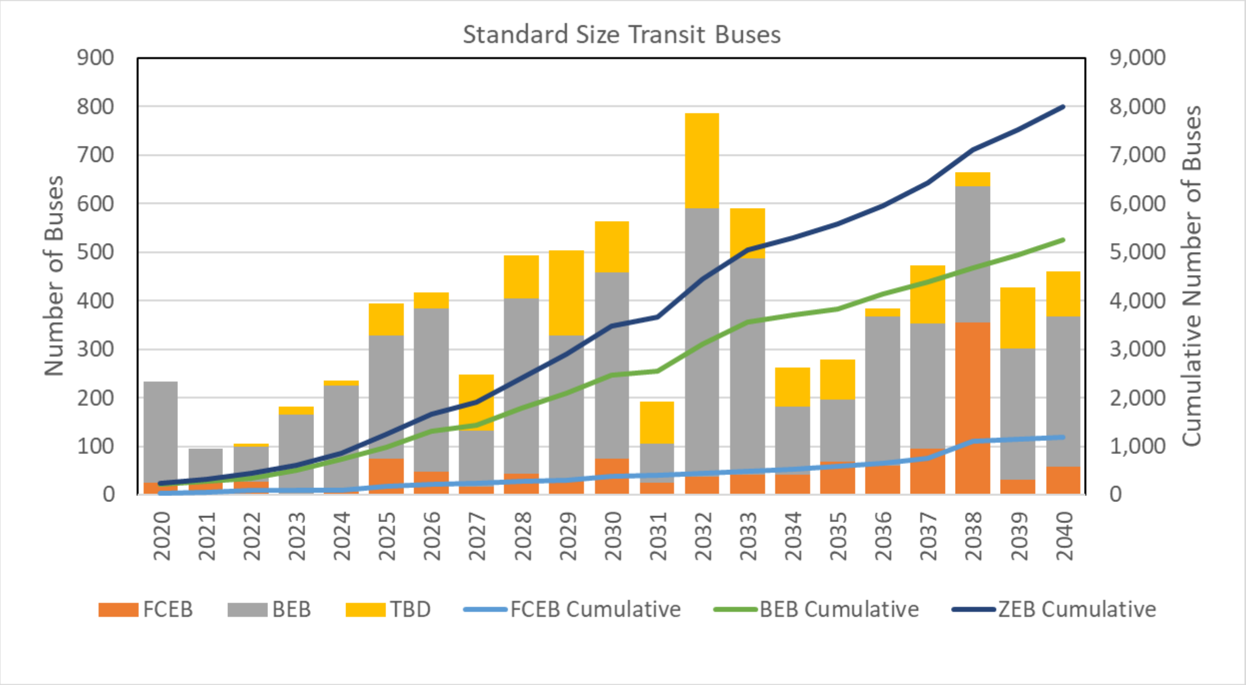

Figure ES-1. Planned purchases of standard-size (~40-foot) ZEBs from rollout plans

California transit rollout plans indicate that transit agencies are receptive to both ZEB technologies. Most agencies have plans to adopt some mix of BEBs and FCEBs or are considering both options for their yet-to-be-determined ZEB purchases; only a few agencies have chosen to wholly pursue one technology over the other. Many transit agencies are selecting BEBs for the initial ZEB deployments. However, based on early experience, some transit agencies have voiced concerns regarding range limitations and infrastructure scaling for current BEB technology. Therefore, the balance of purchases between the two technologies may shift depending on the pace of technology advancements for BEBs vs. FCEBs and future costs of the vehicles, infrastructure, and energy sources (electricity or hydrogen).

The initial ZEB purchase plans in the submitted rollout plans are primarily based on the one-to-one replacement schedules for existing buses at the end of the bus's useful life. However, some factors such as accidents, funding availability, infrastructure timeline, economy, transit agency policy, and status of the ZEB technology development may impact the actual ZEB purchase timeline.

- Zero-emission technologies for standard transit buses are commercially available, with manufacturers continuously improving their early models. As noted in this report, Vehicle and Infrastructure Cash-Flow Evaluation (VICE) modeling shows there is potential for BEBs to achieve a positive return on investment over the 12-year expected vehicle lifetime with incentives in early-stage and continued progress on reduced vehicle and infrastructure capital costs, enhanced workforce training, and utility infrastructure programs. The latest review of technology readiness levels (TRLs) for BEBs and FCEBs was noted in CARB's *Proposed Fiscal Year 2021-22 Funding Plan for Clean Transportation Incentives*, which identified both BEBs and FCEBs at a TRL of 9 for transit buses when compared to other on-road vocational applications [20]. A TRL of 9 indicates that the technology is in its final form (deployment marketing) and support is available for commercial products. There are now at least 10 OEMs that offer BEBs or FCEBs in various sizes and bus designs in the United States. Substantial progress has also been made in the electrical vehicle supply equipment (EVSE) industry, and a variety of charging technologies have been successfully demonstrated. A variety of charge management options are available from bus OEMs, EVSE vendors, and third-party providers. There are also numerous companies offering commercial services to design, engineer, construct, and operate hydrogen fueling stations for FCEB fueling and EVSE for BEB charging.

- Evaluations of early deployments have demonstrated the successful operation of ZEBs and indicated that ZEBs are indeed capable of meeting most transit service requirements. These early demonstrations have also highlighted some current limitations regarding bus availability and reliability, replacement parts availability, and driving range. The technologies are continuously improving to increase availability and range. Additional near-term progress is expected to help transit agencies achieve a full transition to ZEBs in the coming years.

- ZEBs have a significant fuel efficiency advantage when compared to conventional buses. BEBs can achieve 3–5 times as many miles per unit of energy as their conventional counterparts. This efficiency improvement has been demonstrated in revenue service over multiple years by transit agencies (see Section 7, "ZEB Performance"). However, BEB energy efficiency has been shown to be sensitive to external factors, such as heating and air-conditioning loads, driving conditions, vehicle weight, duty cycle, topography, and operator behavior. The resulting variability in daily driving range may pose a near-term planning challenge for some transit agencies, which will diminish as battery energy density and driving ranges increase over time. Operationally, transit agencies may initially choose BEBs for less-demanding routes and may expand driver training. Technically, transit agencies may choose bus models with larger battery packs (extended range), incorporate intermediate fast charging along some routes, and/or choose FCEBs.

- Bus availability is a measure of the percentage of time a bus is ready for revenue service compared to the time it is planned for service. While urban transit agencies are subject to a 20% spare ratio, it is important that ZEBs achieve a bus availability rate of 85% to maintain the service level [21]. Not all of the early ZEBs are achieving this benchmark. Some of the early ZEB downtimes may be attributed to troubleshooting issues and training maintenance staff to make repairs on the new technology buses. Availability is generally expected to improve as ZEB technologies continue to mature and operators gain more experience with the technologies. The reliability of ZEBs in early deployments, measured by the miles between road calls (MBRC), also highlights the need for improvements in durability/reliability for BEBs and FCEBs before they are on par with conventional buses.

  It often takes maintenance staff more time to diagnose, repair, and train other staff in the early years of a ZEB deployment due to less familiarity. A meta-analysis of maintenance costs from early ZEB deployments shows high variability in costs between individual buses for all propulsion types (BEB, compressed natural gas [CNG], diesel, and FCEB) but indicates that when aggregated by powertrain type, the combined cumulative maintenance cost per mile was relatively similar for all types after 4–6 years. In some cases, the propulsion systems for the ZEBs were less expensive to maintain, but the real-world maintenance costs from this limited data set are still highly dependent on the specific circumstances of these early deployments, such as route/service requirements, bus type and technology generation, maintenance and training practices, and level of support from the OEM. Maintenance costs are expected to decrease as transit agencies gain familiarity with maintaining and repairing ZEBs and as replacement parts for propulsion systems become less expensive and more readily available from OEMs and other suppliers.

- To date, the capital costs for BEBs and FCEBs are still higher than those of conventional buses. However, the capital costs, particularly for FCEBs, have decreased significantly. In the early 2000s, it cost more than $2.5 million per bus for precommercial demonstration vehicles, and recently the price has dropped to approximately $1.1 million per bus for the latest generation of FCEBs. Based on transit estimates in the rollout plans, transit agencies are expecting to pay between $850,000 and $1,300,000 per bus for future FCEB purchases and between $720,000 and $1,200,000 per bus for future BEB purchases. However, it is unclear if these prices include tax, training, inflation, or equipment like telematics devices that are normally not installed on conventional buses. For BEBs, the range design can also affect the cost for the same transit agency and same bus model. In 2020, the highest reported delivered bus price from the HVIP vouchers was for a Proterra BEB with an extended-range, 660-kWh battery pack capable of 300 miles. Comparable conventional internal combustion engine buses are expected to cost $410,000–$500,000 per bus for diesel and $540,000–$690,000 per bus for CNG.

- Transit agencies cite the cost of electricity and hydrogen fuel, as well as uncertainties regarding future fuel pricing, as major challenges to cost-effectively operate a fleet of ZEBs. However, conventional fuel costs can also fluctuate and are affected by the market (e.g., crude oil price, production costs and profits, distribution and marketing cost, taxes), contract length and type, and other factors. Having long-term fuel cost certainty helps transit agencies plan and budget their operational costs. The Low Carbon Fuel Standard (LCFS) regulation implemented in California is a market-based mechanism that is helping to reduce the effective cost of low-carbon fuels, including electricity and hydrogen, by allowing transit agencies to earn credits for the use of those fuels in ZEBs. With credits earned through LCFS, lower effective costs for hydrogen and electricity are reducing fuel costs for ZEBs relative to conventional buses, but with some fluctuations in LCFS credit prices that complicate long-term planning.

- One of the barriers to deploying ZEBs is the need for new infrastructure to supply the energy required to operate the bus fleet. Depending on the technology and the level of total power or system upgrades needed, the upfront costs associated with new ZEB infrastructure can be high for transit agencies, yet it is an essential part of transitioning to ZEBs. Transit agencies may face new challenges with infrastructure regarding space limitations at depots and adapting to charging schedules for BEBs. Federal and state funding, along with utility-based incentives to support the expansion of electric charging or hydrogen fueling infrastructure, will be instrumental to achieving a successful transition to 100% ZEB fleets.

- Although there are significant funding resources available to transit agencies, the agencies stated that more and continued funding is necessary to assist with the capital cost of new ZEBs, infrastructure, and other support such as workforce development. In addition, there is a need to improve the application processes and timelines to make it easier for transit agencies to combine funding awards from multiple incentive programs. ZEB financial incentive programs are available to California transit agencies through federal sources, especially the U.S. Department of Transportation (DOT) and U.S. Department of Energy (DOE); statewide funding sources in California such as CARB and CEC; and regional funding sources, such as those operated by air quality agencies. Particularly important programs for ZEB deployments include the Low or No Emission Vehicle (Low-No) Program at the federal level and HVIP at the state level.

  Many of the interviewed agencies planning for ZEB transition have taken advantage of the HVIP and/or Low-No programs and are planning to do so again with their next ZEB procurements. Other programs that were also used (but to a lesser extent) among the agencies interviewed include the Carl Moyer Program; the Transit and Intercity Rail Capital Program (TIRCP); the Low Carbon Transit Operations Program (LCTOP); CEC programs for supporting infrastructure; regional programs provided by local air quality agencies; the Volkswagen Environmental Mitigation Trust program; and electric utility "make-ready" infrastructure programs. Transit agencies planning for ZEB transition cite funding assistance as one of their most significant needs to comply with upcoming ICT ZEB purchase requirements.

These funding programs can significantly offset the upfront cost of ZEBs at this early stage, and the LCFS program will provide continued monetary returns for operating ZEBs without a sunset date. With improved technologies, installed infrastructure, and a trained workforce, it is reasonable to anticipate declining capital costs and operational costs that are expected to lead to a substantially beneficial cost of ownership for ZEBs.

- Another important topic for ZEB implementation is the workforce development and human operations and resources aspect that is needed to support the physical transition to the new generations of bus technology. It is challenging to find experienced staff, but it also serves as an opportunity for workforce development. Transit agencies have employed various strategies to achieve their training goals. They work closely with bus OEMs, BEB charger manufacturers, hydrogen fuel providers, hydrogen station developers, and established training programs for operators, mechanics, and maintenance workers. Many transit agencies also work proactively with fire safety officials for first responder training. The transit agencies interviewed had a wide range of plans and experiences around operator and mechanic training. The larger transit agencies tended to have more established and more extensive internal training programs, while the smaller agencies were more likely to rely on assistance from bus OEMs and charger manufacturers and other established programs.

- Given the continuing evolution of ZEB and infrastructure technology performance and cost, there is a critical need to have an active program to collect up-to-date data and facilitate communications between key stakeholders, including the state, transit agencies, utilities, and the vehicle and infrastructure manufacturing industry. This information base will help inform manufacturers on where to focus improvements, support data-driven purchase and deployment decisions by the transit industry, help the state assess and adapt policies, and inform the research community on where to invest funding to accelerate technology development.

The following report provides details of the comprehensive review conducted for implementation of the ICT regulation and deployment of zero-emission transit buses in California. The Phase I study focuses on implementation progress, status of standard-size (approximately 40-foot) transit buses, and the California transit industry’s readiness to meet the 2023 ICT purchase requirements. Additional ZEB market segments, including smaller cutaway buses, larger articulated buses, commuter buses, and double-decker buses, will be included in an updated assessment in Phase II. This will include assessments of their commercial readiness, performance/fuel economy, refueling infrastructure, workforce development, and additional aspects related to their implementation under the ICT regulation.

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1. Introduction

Zero-emission buses (ZEBs) serve as a foundation for transitioning the entire heavy-duty vehicle sector. They have the potential to provide significant support for the state of California's goal of fully transitioning the heavy-duty transportation sector to zero-emission technologies to achieve mid- and long-term greenhouse gas (GHG) reduction targets, protect public health, and address the environmental impacts of climate change. In 2000, the California Air Resources Board (CARB) adopted (and amended in 2004 and 2006) the Fleet Rule for Transit Agencies, which set more stringent emission standards for new urban bus engines and promoted advances in the cleanest technologies—specifically, ZEBs [22]. Following the rule, transit agencies launched ZEB demonstrations to help develop and demonstrate the technology in real-world applications and to determine the status of the technology toward meeting operational requirements. These demonstrations have advanced the technology significantly over the last decade. During that time, CARB has monitored the development and performance of ZEBs to determine the commercial readiness of the technology. In 2018, CARB adopted the Innovative Clean Transit (ICT) regulation, which requires all California transit agencies to begin transitioning to zero-emission vehicle technologies. The regulation requires a percentage of new bus purchases each year to be ZEBs, with the percentage increasing over time. The ZEB purchase requirements begin in 2023 for large transit agencies and in 2026 for small transit agencies. Beginning in 2023, 25% of large transit agencies' total annual new bus purchases must be ZEBs. Starting in 2029, 100% of transit agencies' bus purchases must be ZEBs to achieve the goal of full transition to zero-emission technologies by 2040 [23].

When CARB adopted the ICT regulation, they directed staff (Resolution 18-60) to conduct a comprehensive review of program readiness, with multiple metrics included such as costs, performance, and reliability of ZEBs and corresponding infrastructure, prior to initiating any purchase requirement [2,3].

To fulfil this commitment, a team led by the National Renewable Energy Laboratory (NREL) with the University of California, Berkeley (UCB) was awarded a contract (Agreement No. 19MSC005) by CARB to conduct the comprehensive review, which was divided into two phases. Phase I focuses on the "standard-length" (approximately 40-foot), low-floor-type transit buses. Phase II will provide an update to the standard 40-foot bus (from Phase I) and cover a wider variety of transit vehicle types, including articulated buses, over-the-road coaches, "cutaway" shuttle buses, and double-decker buses. This report represents the findings from Phase I of the review. The results for Phase II are planned for delivery in 2024.

The objective of Phase I is to determine whether the currently available ZEB technologies in standard buses can be used by large transit agencies to meet the ZEB purchase requirement in 2023, while ensuring transit service or fares are not adversely impacted by the transition. The review also aims to identify remaining needs for the full transition of the California transit bus fleets and determine what additional programs, resources, or support are needed by transit agencies. This review is intended to inform and improve policies to advance heavy-duty zero-emission technologies and inform funding strategies related to zero-emission buses and infrastructure.

1.1 Innovative Clean Transit Regulation

CARB has a long history of developing and implementing programs designed to help California meet its air quality and climate goals by reducing mobile-source GHG and particulate matter emissions [24]. Beginning over 20 years ago, the Fleet Rule for Transit Agencies required transit agencies operating urban bus fleets to upgrade diesel buses with diesel particulate filters or commit to transitioning a large fraction of their fleet to alternatively fueled buses that produce lower emissions [22]. Amendments to the rule made in 2006 included a 15% ZEB purchase requirement for larger transit agencies (that would sunset in 2027) and initiated an advanced demonstration of 12 fuel cell electric buses (FCEBs) in the San Francisco Bay Area [25]. In 2009, CARB evaluated overall ZEB technology readiness and determined ZEBs were not yet commercially ready, delaying enforcement of the ZEB purchase requirement until ZEB technologies could advance further. In 2015, comprehensive evaluations of battery- and fuel cell electric bus technologies by CARB indicated they were in an early commercialization stage, leading to the process of reinstating and revising the ZEB purchase requirement for transit agencies [26–28].

The ICT regulation, adopted in December 2018 and effective since October 2019, is a result of the public process that expanded ZEB purchase requirements and defined the pathway to achieve 100% ZEB fleets in California by 2040. The ICT regulation is the first regulation in the United States that requires a vocational heavy-duty vehicle application to completely transition to zero-emission technologies over time. This regulation requires transit agencies to gradually transition their fleets to all ZEBs by defining an increasing percentage of new bus purchases that must be ZEB each year. It applies to all public transit agencies in California that own and operate buses with a gross vehicle weight rating greater than 14,000 pounds and covers standard, articulated, double-decker, over-the-road, and cutaway buses. The purchase requirements begin in 2023, but the timeline varies slightly for large and small transit agencies, as shown in Table 1. Considering the 12-year expected lifetime of transit buses, the 100% ZEB purchase requirement beginning in 2029 is designed to result in 100% ZEB fleets by 2040.

Table 1. ICT Regulation, ZEB Purchase Requirements (percent of new buses purchased annually)

Date	Large Transit Agency [a]	Small Transit Agency [b]
2023–2025 (standard 40-ft buses only)	25%	—
2026–2028 (all bus types, if passed Altoona testing)	50%	25%
January 1, 2029, and thereafter	100%	100%

[a] A transit agency that either (a) operates more than 65 buses in annual maximum service in either the South Coast Air Basin or the San Joaquin Valley Air Basin, or (b) operates in an urbanized area with a population of at least 200,000 and at least 100 buses in annual maximum service.

[b] All other transit agencies.

CARB included provisions in the regulation to delay the ZEB purchase requirements in the event of early ZEB adoption by the broader transit industry. The first discharge provision stated that if transit agencies in California collectively had 850 or more ZEBs in service or on order before the end of the calendar year 2020, the 2023 purchase requirement would be waived. Similarly, if 1,150 or more ZEBs were in service or on order before December 31, 2021, purchase requirements otherwise effective in 2024 would be waived. The second discharge would be considered only if the first discharge provision was met. According to information reported to CARB, California transit agencies collectively had 654 ZEBs in service or on order by December 31, 2020. Therefore, the threshold to discharge the first ZEB purchase requirement was not met, and the 2023 purchase requirement remains in place for January 1, 2023 [29]. As discussed in Section 2.4, the COVID-19 pandemic has had a big impact in slowing the initial transition to ZEBs.

As part of the ICT regulation, each transit agency is required to submit a ZEB rollout plan, approved by their governing board, that outlines the agency's plans to purchase ZEBs and required charging and/or fueling infrastructure to comply with the regulation's ZEB purchase requirements. For large transit agencies, the ZEB rollout plans were due on June 30, 2020. All 21 large transit agencies have submitted rollout plans, which are posted on CARB's website [1]. For small transit agencies, ZEB rollout plans will be due on June 30, 2023. In addition, the ICT regulation requires annual reporting by the transit agencies, starting in 2021. Among many utilizations of the reporting data, the data will help CARB track the overall progress of ZEB transitions.

ZEBs serve as a foundation for electrification of the heavy-duty vehicle sector. Experience from using zero-emission technologies in transit buses and demonstrating their viability will benefit the market for the same technologies to be used in other heavy-duty vehicle applications, such as school buses, as well as drayage, delivery, and yard trucks. The ICT regulation sets the stage for the development and adoption of the Advanced Clean Trucks and Advanced Clean Fleets regulations, which accelerate large-scale transition of medium- and heavy-duty (MD/HD) trucks and buses from Class 2b to Class 8 to zero-emission technologies. The Advanced Clean Trucks regulation (effective since March 15, 2021) requires manufacturers who certify Class 2b–8 chassis or complete vehicles with combustion engines to sell zero-emission trucks as an increasing percentage of their annual California sales from 2024 to 2035. By 2035, zero-emission truck/chassis sales need to be 55% of Class 2b–3 truck sales, 75% of Class 4–8 straight truck sales, and 40% of Class 8 tractor sales [30]. CARB is currently developing the Advanced Clean Fleets regulation with the goal of accelerating the purchase of zero-emission trucks and buses to achieve the complete transition to zero-emission technologies by 2045 everywhere feasible, and significantly earlier for certain market segments such as last-mile delivery and drayage applications [31].

In addition, CARB recently adopted several zero-emission regulations that apply to off-road equipment for the movement of freight and goods in California. Requirements for zero-emission technologies apply to or will apply to locomotives, oceangoing vessels at berth, commercial harbor craft, transportation refrigeration units, cargo handling equipment, small off-road engines, and more. Transitioning away from fossil fuels and toward zero-emission technologies will help CARB deliver clean air to all Californians while also satisfying Governor Newsom's Executive Order N-79-20 [32].

1.2 Comprehensive Review Objectives

As transit agencies deploy ZEBs in their daily operations and help advance the technologies, it is important to ensure they can continue providing their critical services to Californians, especially to transit-dependent riders. When CARB adopted the ICT regulation, they directed staff

(Resolution 18-60) to conduct a comprehensive review of program readiness, with multiple metrics included such as costs, performance, and reliability of ZEBs and corresponding infrastructure, prior to initiating any purchase requirement [3].

The initial plan was for this comprehensive review to be conducted from 2020 to 2022 and cover all bus types. The ZEB market trends in early 2020 indicated a strong probability of meeting the first discharge provision of the ICT regulation. Due, in part, to the unexpected impact of the COVID-19 pandemic, the plan was revised by CARB, with agreement by the California Transit Association, to separate the assessment into two phases. The California Transit Association also requested the inclusion of the impact of the pandemic on ZEB transitions. Phase I of the comprehensive review focuses on the “standard-length” (approximately 40-foot), low-floor-type transit buses. Phase II of the comprehensive review will provide an update to the standard 40-foot bus (from Phase I) and cover a wider variety of transit vehicle types, including articulated buses, over-the-road coaches, “cutaway” shuttle buses, and double-decker buses. This report represents the findings from Phase I of the review. The results for Phase II are planned for delivery in 2024.

This comprehensive review provides an overview of the following topics in detail:

- ZEB deployment status.
- Available ZEB models and related infrastructure.
- Cost, performance, reliability, and barriers to deploying ZEB technologies.
- Incentive funding programs.
- Workforce training for operating and maintaining ZEBs.
- Job creation and estimated economic impact of the ZEB transition in California.
- Lessons learned and remaining challenges.

The objective of Phase I is to determine whether the currently available ZEB technologies in standard buses can be used by large transit agencies to meet the ZEB purchase requirement in 2023, while ensuring transit service or fares are not adversely impacted by the transition. The review also aims to identify remaining needs for the full transition of the California transit bus fleets and determine what additional programs, resources, or support are needed by transit agencies. This review is intended to inform and improve policies to advance heavy-duty zero-emission technologies and inform funding strategies related to zero-emission buses and infrastructure.

1.3 Project Partners

NREL, with UCB, was awarded a contract (Agreement No. 19MSC005) by CARB through a request for information process to conduct the comprehensive review in June 2020. NREL has extensive experience evaluating alternative fuels and new propulsion technologies in transit operation. Detailed fleet evaluations have been conducted for various gasoline- and diesel-hybrid vehicle designs and multiple generations of battery-electric buses (BEBs) and FCEBs. NREL evaluated demonstrations of early-generation fuel cell electric transit buses as part of the American Fuel Cell Bus program, as well as early pilot deployments of BEBs operating in revenue service in the United States and Canada. UCB researchers have extensive experience with ZEB technology through the Transportation Sustainability Research Center, part of the Institute of Transportation Studies. UCB has conducted ZEB analysis projects including real-world performance studies, simulation modeling, implementation analysis, and surveys of ZEB driver impressions and experiences.

The NREL/UCB team offers a unique combination of expertise and experience in all major aspects of ZEB and infrastructure technologies; transit and energy industry relationships; and existing data, knowledge, and analysis tools. The NREL team, with its long, successful history of partnering with the transit industry, offers world-class tools as well as expertise in data monitoring, collection, and analysis methods. NREL's Center for Integrated Mobility Sciences has active research programs in commercial vehicles, mobility systems, energy storage, electric vehicle charging, grid integration, fuel cell vehicles, and hydrogen infrastructure. NREL has worked with many California transit agencies to evaluate ZEBs in comparison to conventional technology buses, collecting a wealth of performance and cost data and conducting associated analyses. Building on this solid base of data and knowledge, the team has also conducted a thorough literature review. The data gathered from existing evaluations and the literature reviews are supplemented with data from additional transit agencies and manufacturers. The project team has compiled and analyzed data to assess the current status of ZEB technology and infrastructure performance, identified the 2023 program readiness along with remaining challenges and needs for the full transition of the California transit fleet, and recommended solutions for a smooth complete transition to ZEBs.

The overall approach for the comprehensive review includes the following elements:

- Conduct literature reviews for the latest information on ZEBs, including results of pilot and demonstration projects, incentive funding programs, and available ZEB models and infrastructure.
- Interview ZEB stakeholders—transit agencies, original equipment manufacturers (OEMs) and technology providers, utilities, and fuel providers.
- Combine analyzed data from detailed NREL fleet evaluations and other published ZEB studies.
- Utilize modeling tools to compare the economics of ZEBs to conventional bus purchases and estimate the economic impact of the ZEB transition in California.

2. Deployment Status of ZEBs

2.1 Current ZEB Deployments

The *2021 Public Transportation Fact Book*, published annually by the American Public Transportation Association (APTA), shows that despite a gradual and continuous shift away from diesel fuel to alternative fuels for transit bus operation over the past 20 years (primarily toward compressed natural gas [CNG] and hybrid vehicles), the national share of battery-electric and hydrogen-fueled buses is still small (less than 2%). There is also a large disparity in ZEB adoption between states [33].

The APTA fact book lists the top 50 urbanized areas in the United States that have the most transit travel, ranked by unlinked passenger trips. The list is based on data reported to the Federal Transit Administration (FTA) in the National Transit Database for fiscal year (FY) 2019. As seen in Table 2, this ranking shows that California has seven urbanized areas in the top 50 in the United States, and two in the top five.

Table 2. California Urbanized Areas Ranking Among Top 50 With Most Transit Travel in the United States [33]

Rank	Urbanized Area	Population (2010 Census)	2019 Unlinked Passenger Trips (thousands)	2019 Passenger Miles (thousands)
3	Los Angeles–Long Beach–Anaheim	12,150,996	538,864.0	2,947,725.2
5	San Francisco–Oakland	3,281,212	406,960.7	2,461,068.1
13	San Diego	2,956,746	96,911.8	587,874.1
22	San Jose	1,664,496	42,801.7	328,015.0
27	Concord	615,968	32,879.5	424,582.5
34	Sacramento	1,723,634	22,695.9	125,229.5
43	Riverside–San Bernardino	1,932,666	17,203.5	141,373.4

The fact book also ranks the size of U.S. transit agencies by the number of unlinked passenger trips. Of the top 50 bus transit agencies, California claims eight, which are listed in Table 3 according to their overall rankings.

Table 3. California Bus Transit Agencies Ranking Among 50 Largest in the United States [33]

Rank	Transit Agency	Urbanized Area	2019 Unlinked Passenger Trips (thousands)	2019 Passenger Miles (thousands)
2	Los Angeles County Metropolitan Transportation Authority	Los Angeles	266,887.6	1,103,847.5
8	San Francisco Municipal Railway (Muni)	San Francisco	110,803.0	225,220.9
20	Alameda–Contra Costa Transit District (AC Transit)	Oakland	50,484.4	171,068.0
22	San Diego Metropolitan Transit System	San Diego	47,205.8	182,741.0
25	Orange County Transportation Authority (OCTA)	Orange	37,642.8	140,082.2
29	Santa Clara Valley Transportation Authority	San Jose	27,472.1	137,216.1
34	Long Beach Transit	Los Angeles	23,210.0	75,502.2
43	Los Angeles Department of Transportation	Los Angeles	17,467.1	30,643.6

CALSTART tracks ZEB deployments throughout the United States and Canada and publishes an annual inventory report called *Zeroing in on ZEBs: The Advanced Technology Transit Bus Index* [34–36]. This inventory includes ZEBs from transit agencies as well as other public and private entities, such as universities and airports. Currently, there is no other centralized database or accounting system for all publicly and privately operated ZEBs that accurately indicates the number of buses in service, on order, or planned, as the ZEB market is still relatively young.

According to CALSTART's 2021 report, ZEB deployments in the United States have increased by 27% since the previous count in 2020. California is the state with the most ZEBs, with 1,244 BEBs and 127 FCEBs in service or on order at all public and private institutions, including but not limited to transit agencies, such as those shown in Figure 1 (from CALSTART's 2020 report). This represents nearly 40% of ZEBs in the United States (75% of all FCEBs), placing California far ahead of the states with the next largest deployments. The 2021 report highlights that California also has the largest ZEB fleet sizes per transit agency, emphasizing that California is the clear leader in the ZEB transition, nationally. However, most transit agencies have fewer than 10 ZEBs per property, so California transit agencies still require a lot of scaling up to achieve all-ZEB fleets.

The 2020 report provided a detailed list of ZEBs by transit operators. Of the 229 agencies in the United States and Canada listed in that report as having deployed or purchased ZEBs, 57 (25%) are in California. The active ZEBs in California were distributed between 27 different organizations (e.g., transit agencies, universities), listed in Appendix A.1. The 2021 report did not provide a detailed update of ZEB deployments by transit agency.

Figure 1. Map of ZEB locations in California [35]

California was already a leader in the ZEB transition prior to the ICT regulation, but the regulation has served to accelerate plans to electrify transit fleets. CARB's Innovative Clean Transit Reporting Tool is being used to track ZEB deployments for the ICT regulation. Public transit agencies in California have reported that 336 ZEBs (46 FCEBs vs. 290 BEBs) were in service and another 318 ZEBs (30 FCEBs vs. 288 BEBs) were on order, for a total of 654 purchased ZEBs, as of December 31, 2020 [29]. Updated totals for ZEB deployments in calendar year 2021 are not yet available.

California has recently celebrated its first transit agency that became a fully zero-emission bus fleet. Antelope Valley Transit Authority announced in March 2022 that it was the first 100% zero-emission transit fleet in North America, consisting of standard buses for local routes, microtransit vans, and commuter coaches [37]. Following their lead, Anaheim Transportation Network, currently with 59 BEBs in service and 4 on order, is on a path to reach its goal of a fully electric bus fleet by 2025 [38]. Many other transit agencies have also initiated ZEB deployments. Some of the major deployments are summarized below:

- AC Transit has been a leader in advancing zero-emission technologies for more than 20 years. In 2018, four FCEBs operated by AC Transit surpassed the 25,000-hour milestone, which is the ultimate target set by the U.S. Department of Energy (DOE) and FTA [25]. AC Transit currently has 36 FCEBs and 7 BEBs in service, as well as 21 BEBs on order. In 2019, AC Transit initiated a side-by-side comparison study by operating hydrogen and battery-electric vehicles in identical service as the conventional buses to collect real-world performance data and determine which technology performs better to meet their service needs [39]. Experience learned from this project will be instrumental for the whole transit industry.

- Foothill Transit, in 2021, made the largest FCEB purchase in North America for 33 FCEBs [40]. Foothill Transit also currently has 36 BEBs in service.
- Long Beach Transit currently has 10 BEBs in service and received authorization from its board to purchase 20 additional BEBs [41].
- Los Angeles County Metropolitan Transportation Authority has completely electrified the popular Metro G line (Orange) with 40 60-foot articulated BEBs and expects delivery of 100 more 60-foot articulated BEBs to electrify the J line (Silver) [42,43]. Their goal is to complete the transition to ZEBs by 2030.
- Los Angeles Department of Transportation is planning to install 104 electric vehicle (EV) chargers—one of the largest EV fleet charging systems in the United States powered by a solar photovoltaic and battery storage microgrid. This charging system will support the agency's transition to a fully electric bus fleet by 2028. The department currently operates 29 BEBs and expects to have 30 additional BEBs in operation by summer 2022 [44]. In 2019, they ordered 130 BEBs, which is the largest single order of battery-electric buses to date in the United States [45].
- Orange County Transportation Authority (OCTA) has the largest transit-operated liquid hydrogen fueling station in the United States. This station has a fuel capacity of 18,000 gallons to serve 40–50 buses [46]. OCTA currently has 10 FCEBs in service.
- Porterville Transit has electrified approximately half of its bus fleet. They currently have 10 BEBs and 12 battery-electric vans in operation and 3 additional BEBs on order. This agency is only 10 BEBs short of transitioning its entire fleet to BEBs by 2024 [47].
- Sacramento Regional Transit District has 18 BEBs in service and has completely electrified its airport express bus (route 142) between downtown Sacramento and Sacramento International Airport, with easy access to light rail stations [48].
- San Diego Metropolitan Transit System has been piloting 13 ZEBs and recently started construction of an overhead charging system that offers a quicker and safer hands-free electric vehicle charge. The new charging system is a depot charging pantograph that allows buses to be docked in seconds and provides high-power charging. The overhead gantry charging system is capable of charging 24 battery-electric buses at a time, and it is expandable to add more charging capacity as the fleet transitions to all-electric over the coming years [49].
- San Francisco Municipal Transportation Agency had ordered 12 BEBs, three each from four different manufacturers—New Flyer, BYD USA, Proterra, and Nova Bus—for an 18-month tryout. Five BEBs have arrived already, and the remaining seven will be delivered by the end of 2022. The agency plans to operate one bus from each manufacturer on the same line each day using the same chargers to gather data on how the buses respond to the agency's operational needs [50].
- With 17 BEBs currently in service, San Joaquin Regional Transit District was the first transit agency in the nation to electrify its bus rapid transit in 2017 [51]. They placed their first BEB in service in 2013 [52].
- Santa Clara Valley Transportation Authority currently has 10 BEBs in service. In partnership with Proterra and Scale Microgrid Solutions, they are installing solar photovoltaic and battery storage microgrid and EV fleet charging for their BEBs. The microgrid will enable

them to operate electric buses during power outages and deliver savings on electricity costs [53].
- SunLine Transit has the largest on-site hydrogen production station dedicated to transit use in the United States. Operation of a proton exchange membrane hydrogen electrolyzer allows this agency to produce its own hydrogen. SunLine currently has 15 FCEBs and 7 BEBs in service and 5 FCEBs on order, and is on track to transition all its buses to zero emissions by 2035 [54].

Initial ZEB deployments, in California and throughout the United States, have been heavily weighted toward BEBs. This is due to several factors, including capital costs, availability of bus models, infrastructure requirements for small deployments, and perception of the technologies. For BEBs, initial deployments also tend to service shorter routes/blocks, in part due to energy storage limitations that reduce daily driving range relative to conventional buses. As agencies continue to scale up their ZEB fleets, new BEB models with increasing energy density in the future are anticipated to provide service to longer transit routes. However, it is also expected that FCEBs will comprise an increasing fraction of ZEB purchases, enabling transit agencies to service their longest route/blocks and providing greater operational flexibility.

Since the adoption of the ICT regulation in 2018, there has been an increase in group procurement opportunities for ZEBs. This development has resulted in greater price transparency, stronger buying power, and an enormous savings in time and energy for transit agencies attempting to purchase vehicles.

California's Department of General Services has secured a statewide ZEB contract that covers multiple manufacturers, fuel types, and models [12]. This contract also meets FTA's bus procurement criteria. With a zero-emission statewide contract, purchasing agencies are free to select a bus from a menu of vehicles and proceed with the vehicle purchase without the process of procurement and contract negotiations. Necessary but time-consuming work (e.g., research, request for proposal, proposal evaluation, and negotiations) that leads up to a purchase agreement is completed by the state contracting agency, relieving transit agencies of this burden. Even though transit agencies were not part of the preliminary process of developing the specifications and request for proposal and awarding OEMs, they can still customize the vehicles with a transparent base price of the vehicle. In addition to California, similar statewide contracts for ZEB procurements have been released or are underway by other states such as the state of Washington's Department of Enterprise Services, Georgia's Department of Administrative Services, and Virginia's Department of General Services [55]. While California, Georgia, and Virginia involved their state departments of transportations and general services, Washington went a step beyond. Washington's Department of Enterprise Services formed a coalition of transit agencies (about 15–16 agencies of various sizes), OEMs, Washington State Department of Transportation, and departments of transportation from surrounding states. This gave the state of Washington the ability to include various specifications, should they choose to do so, that may make the contract more applicable and attractive to regional partners. Further, transit agencies have also been putting out joint procurement solicitations for transit buses to relieve the procurement burden for many of the participating agencies. For example, in February 2021, Morongo Basin Transit Authority, on behalf of the California Association for Coordinated Transportation member agencies, issued a request for proposal (RFP-20-01) of a joint procurement for the manufacture and delivery of accessible transit/paratransit vehicles, including some BEBs [56].

2.2 Anticipated ZEB Deployments From Rollout Plans

One of the requirements of the ICT regulation is for transit agencies to prepare and submit a ZEB rollout plan (adopted by the transit agency's board or governing body) detailing how they intend to comply with the regulation's ZEB purchase requirements leading up to full fleet transition by 2040. This is intended to help transit agencies get started with the planning necessary for full fleet transition and to allow all stakeholders in the ZEB market to better understand the anticipated demand for ZEBs, infrastructure, and fuel. The plans will also help state officials with policy and funding decisions related to ZEBs.

CARB provided a guidance document in January 2020 outlining expectations for the rollout plans [57]. The plans are intended to be "living documents" that can and should be updated as transit agencies' plans evolve throughout the planning and implementation stages. The guidance document lists the ICT regulation requirements and contains nine sections—including Current Bus Fleet Composition and Future Bus Purchases, Workforce Training, and Potential Funding Sources—and specifies what information is required and which items are optional (but recommended) as supplementary information that should be included in the plans.

The ICT regulation applies to all transit buses with gross vehicle weight rating greater than 14,000 pounds, including articulated, over-the-road coaches, cutaway, and double-decker-style buses. Thus, the rollout plans include transit agencies' plans to replace all of these transit buses according to the ICT purchase requirements. However, Phase I of this comprehensive review will focus only on anticipated replacement of standard transit buses.

All 21 large transit agencies and one small transit agency have submitted ZEB rollout plans to CARB before the end of 2021 [1]. This list of transit agencies is provided in Appendix A.2. Other ZEB deployment plans that have been published recently, such as Eastern Contra Costa Transit Authority's *Short Range Transit Plan* and the *San Bernardino Countywide Zero-Emission Bus Study Master Plan*, are also incorporated into this comprehensive review [57,58]. The deadline for small transit agencies to submit a rollout plan is June 30, 2023, and some of them are currently in the process of developing a rollout plan or in the stage of coordination with their city or county.

NREL analyzed the rollout plans and other ZEB deployment plans and tracked the planned purchases between 2020 and 2040 that were reported by each transit agency. In most cases, the plans that specified purchases by bus type and fuel/propulsion type mapped a clear schedule. Several agencies are waiting for the results of their own initial ZEB deployments to help inform their future purchase decisions; therefore, their long-term ZEB purchase timelines were less clearly defined. In a few cases, it was necessary for NREL to make assumptions about the exact timing of future purchases or the division between standard and articulated buses (which were based on those agencies' current fleets) in order to plot the totals. Figure 2 shows the projected number of buses expected to be purchased each year, as well as the cumulative totals for FCEBs, BEBs, and propulsion types to be determined (labeled TBD). FCEBs are shown as the bottom columns and lowest trend line, the BEBs are in the middle, and the top columns and the trend line are the TBD purchases and the cumulative total ZEBs, respectively.

The rollout plans indicate that most California transit agencies are receptive to both ZEB technologies. Most agencies have plans to adopt both BEBs and FCEBs or are considering both options for their TBD bus purchases; only a few agencies have chosen to wholly pursue one technology over the other. The majority of ZEBs currently in service, on order, or planned in the near future are heavily weighted toward BEB technology. This is not surprising for ZEB pilot fleets. Given the current capital costs and infrastructure requirements, BEBs are generally considered simpler and more cost-effective to operate in small pilot deployments than FCEBs. For small fleets of BEBs, specific routes/blocks are often selected to match the available BEB range. FCEBs are normally dispatched more similarly to their diesel or CNG counterparts, although dispatching practices vary by transit agency.

Thus, many transit agencies are selecting BEBs for small, initial ZEB deployments. However, based on early experience, there are continuing concerns regarding range limitations and infrastructure scaling for current BEB technology. Therefore, the balance of purchases between the two technologies may shift depending on the pace of technology advancements for BEBs vs. FCEBs and future costs of the vehicles, infrastructure, and energy type used (electricity or hydrogen).

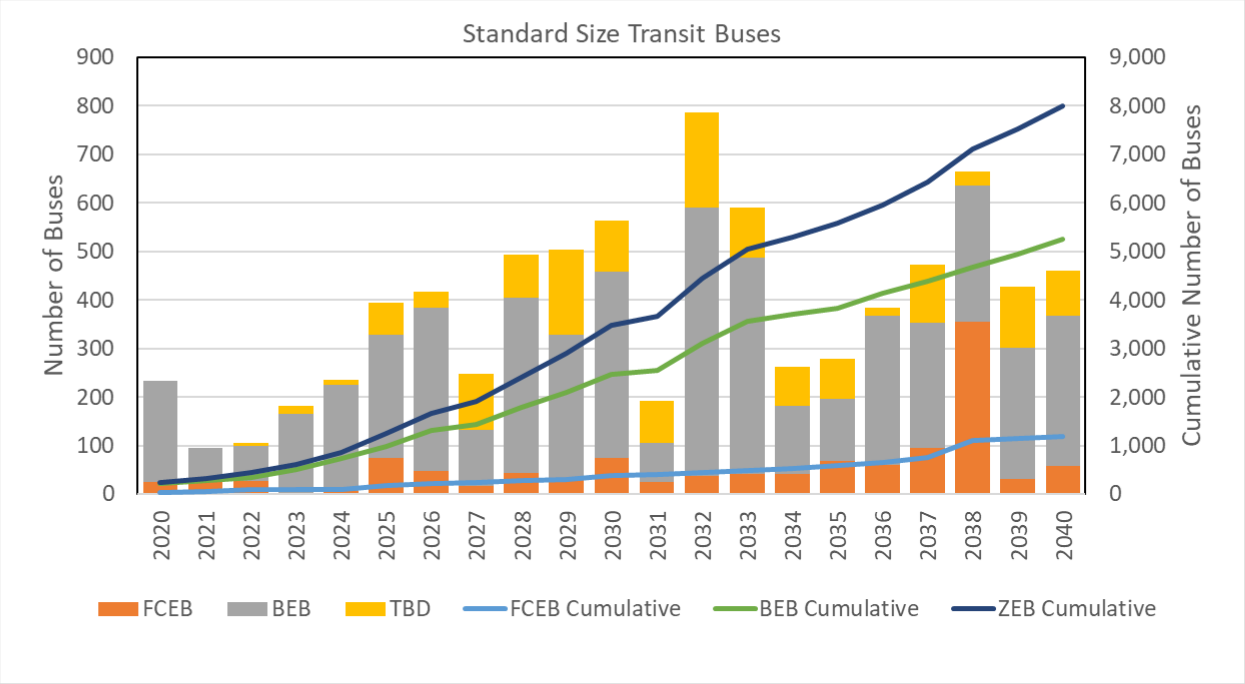


Figure 2. Planned purchases of standard-size (~40-foot) ZEBs from rollout plans.

Data from ZEB rollout plans [1]

Even though the ICT regulation does not require a complete transition to zero-emission technologies until 2040, the rollout plans indicate that some transit agencies anticipate reaching 100% ZEB status ahead of the target date. Analysis of rollout plans and transit press releases shows five California transit agencies are planning to fully transition to ZEBs by 2030: Los Angeles Department of Transportation, Los Angeles County Metropolitan Transportation Authority, Foothill Transit, Long Beach Transit, and Santa Monica's Big Blue Bus. Of the transit agencies that submitted rollout plans, an additional two agencies expect to complete their ZEB transition by 2035 [60].

All combined, the reviewed rollout plans indicate that California transit agencies plan to acquire approximately 8,000 standard ZEBs in the next 2 decades. FCEB purchases account for approximately 1,200 of the buses, BEBs account for 5,250 of the buses, and the remaining 1,550 buses are still to be determined. Nearly half of the planned BEBs are from the Los Angeles County Metropolitan Transportation Authority, who also plans to convert more than 750 buses to zero-emission by retrofitting CNG buses to BEBs at midlife [61]. Four other transit agencies are each planning to purchase 300–500 BEBs: Los Angeles Department of Transportation, SamTrans, San Diego Metropolitan Transit System, and San Francisco Municipal Transportation Agency. For FCEBs, two agencies (AC Transit and Orange County Transportation Authority) currently plan to purchase more than 300 FCEBs. Two other transit agencies (Long Beach Transit and Riverside Transit Agency) are planning to purchase more than 150 FCEBs each, while all others expect to have fewer than 100 FCEBs each [1].

When including all other bus types specified in the rollout plans (coaches, cutaways, double-decker, and articulated buses), the total number of ZEBs expected to be purchased by 2040 is approximately 12,000 buses.

The initial ZEB purchase plans in the submitted rollout plans are primarily on a one-for-one basis based on replacement schedules for existing buses at the end of the bus's useful life. However, some factors such as accidents, funding availability, infrastructure timeline, economy, transit agency policy, and status of the ZEB technology development may impact the actual ZEB purchase timeline.

2.3 Environmental Justice and Social Equity

Transit agencies play a pivotal role in promoting environmental justice and providing clean transportation for all Californians, especially disadvantaged communities and low-income residents. While many low-income residents may not have access to zero-emission passenger vehicles due to high costs and/or infrastructure access, ZEBs provide affordable access to zero-emission transportation to everyone. One of the requirements for the ICT rollout plans is for transit agencies to specify how they intend to deploy ZEBs in disadvantaged communities within their service territory, as designated in CalEnviroScreen [62].

ZEB adoptions in low-income and disadvantaged communities will be an important part of the solution in achieving GHG emissions reduction and air quality goals. Due to the elimination of tailpipe emissions and the energy efficiency benefit of ZEBs over conventional internal combustion engine buses, ZEBs are among the most effective technologies in reducing transportation energy consumption and combustion-related emissions. The deployment of ZEBs in low-income and disadvantaged communities reduces local tailpipe emissions, particulate matter associated with brake wear, petroleum use, and energy consumption.

In addition to emissions reduction, the ICT regulation is expected to attract ZEB industries to California. These new equipment manufacturers bring high-quality job opportunities to California and support employment in disadvantaged communities. As the demand and corresponding production of ZEBs increases, so will the number of ZEB manufacturing, operation, and maintenance-related jobs in California. For example, BYD, located in Lancaster, California, has a community benefits agreement with Jobs to Move America. Through deep investments in apprenticeship and training programs, Jobs to Move America will support the creation of a robust jobs program. Twenty people have graduated so far from the apprenticeship program, with 25 more in the pipeline. BYD also recruits 40% of its employees from priority populations, such as veterans and returning citizens who face significant barriers to employment. In addition, the community benefits agreement plans to target populations that have historically been underrepresented in the manufacturing industry, such as women and minority groups. In addition to BYD, Proterra also entered into a similar agreement. Proterra commits to hiring 50 new employees from harder-to-employ groups, including veterans, the previously incarcerated, and single parents. Proterra is also in discussions with its union to establish an apprenticeship program similar to BYD's, going beyond the pre-employment training it has offered since 2020 [24,35,63].

2.4 Pandemic Impacts on the ZEB Transition

When the COVID-19 pandemic hit the United States in early 2020, transit agencies across the nation experienced a sudden and drastic decrease in ridership. This unexpected impact is shown clearly by the trends in Figure 3, which displays the estimated weekly ridership between January 2020 and September 2021. The chart shows trends for the United States at a national level and for the Pacific region, which includes California, subdivided into three transit agency size groupings by servicing populations (>2 million, 500,000–2 million, and <500,000). The weekly ridership percentages for 2020 and 2021 were calculated relative to 2019 ridership values for the corresponding month and week of the year; 2019 ridership was treated as the typical pre-pandemic level. The underlying ridership data for these trends were obtained from APTA and the Transit app, who partnered to combine reported ridership data from transit agencies with Transit app user activity data ("transit demand") to estimate the weekly ridership at individual agency levels and at aggregated levels for different regions of the United States [64].

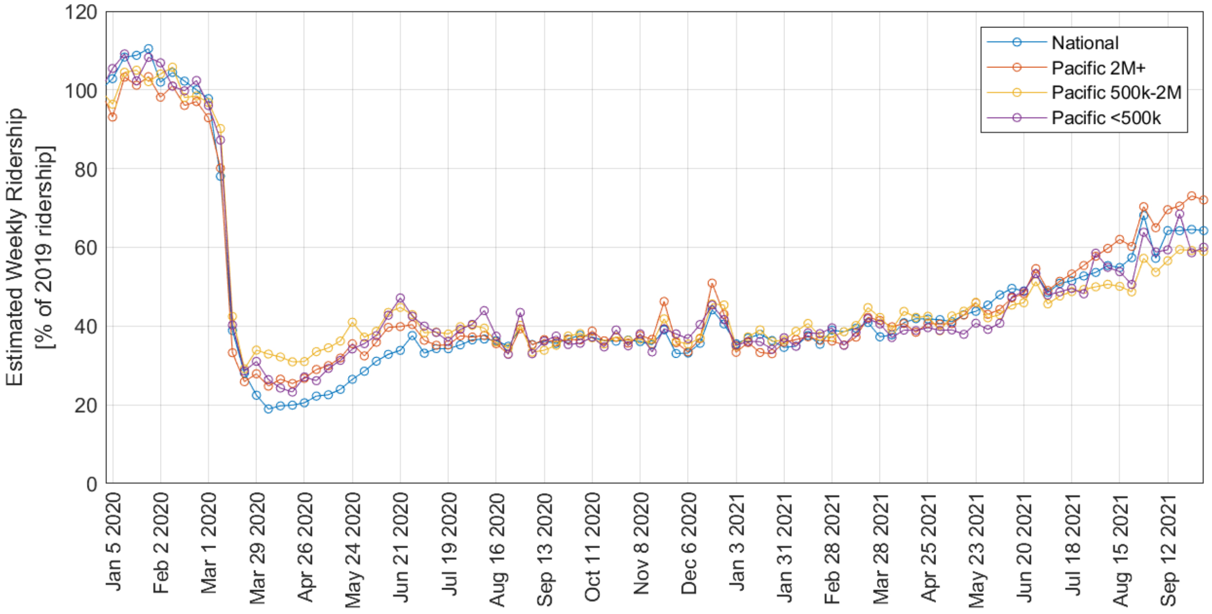


Figure 3. Impact of the COVID-19 pandemic on transit ridership.

Estimated ridership data from APTA and the Transit app [64]

Similar to the national trend, transit agencies of all sizes in the Pacific region experienced a 60%–80% drop in ridership in a span of only 2–3 weeks in March 2020. Not only was the decrease in ridership sudden and extreme, but it has also been long-lasting. Transit ridership rebounded slightly (10%–20%) in the first few months after the initial decline but then held steady at approximately 40% of typical (2019 levels) for 10 months. After the initial decline, ridership had climbed back to only 60%–70% of pre-pandemic levels by September 2021. The slow ramp-up in 2021 corresponded to increases in COVID-19 vaccination rates and loosening of restrictions on businesses and public spaces as infection and transmission rates decreased, but there have been multiple waves of increased transmission rates during the prolonged pandemic, slowing the ridership recovery. Ridership increases are expected to continue as the pandemic subsides. However, it is still uncertain when—and to what extent—transit ridership will return to pre-pandemic levels. The willingness of individuals to return to transit seems to be lagging behind the return to other public events, businesses/services, and modes of transportation. It is yet to be seen what percentage of transit commuters that switched to telecommuting (remote work) during the pandemic will return to normal office commutes and what percentage will remain as telecommuting following the pandemic. The decline in the unemployment rate as individuals go back to work is also expected to have an impact on transit ridership trends, but the timing and magnitude of the impact are still unclear. These factors could have disproportionate effects on ridership in different regions, transit agencies, and modes of public transportation.

The COVID-19 pandemic has had a significant impact on numerous aspects of the transit industry. In addition to the impacts on day-to-day operations as transit agencies adapted to constantly changing service levels and public health requirements, the most notable impact was on transit agencies' financial conditions. The pandemic had a compounding effect of decreasing transit revenue generation while increasing expenses. The additional expenses incurred were generally in the form of costs for personal protective equipment, labor and supplies for increased cleaning practices, and training. The revenue losses came in several forms. Most importantly, the drastic and persistent decrease in ridership led to significant decreases in revenue generated from fareboxes. In May 2020, it was reported by EBP US Inc. that ridership was down 73% nationally in April 2020 compared to the previous year, while corresponding fare revenues were down 86% [65]. The losses in farebox revenue were larger than the losses in ridership, in part because many transit agencies suspended passenger fare collection during the pandemic to limit interactions between drivers and passengers (policies for passenger rear-door boarding and elimination of cash payments). Another reason was the disproportionate nature of ridership losses of different modes of transit service that have different fare structures. For example, commuter services, which experienced a larger decline in ridership, tend to have higher fares than short, local transit routes.

According to EBP, "While fares and other ridership-related funds are transit agencies' largest sources of revenues, accounting for almost 40% of annual budgets, other key sources are also forecast to decline significantly due to underlying economic conditions" [66]. These other important sources include revenue from state and local taxes, which were depressed by all the economic factors surrounding the pandemic, and revenue from motor fuel taxes, which decreased when personal vehicle travel was lower than normal. Despite two rounds of emergency funding (totaling ~$39 billion) from the federal government in 2020 and early 2021 to help fill the gaps in transit revenue, agencies are still projected to have large budget deficits in the coming years. EBP's analysis reported in January 2021 predicts national deficits in transit funding of $25.2 billion, $15.1 billion, and $13.0 billion for calendar years 2021, 2022, and 2023, respectively [66]. If funding needs are not met by additional federal and state financial aid, the shortfalls can result in reduced transit service and reduced capital spending, and many transit agencies may have to divert capital budgets (wherever it is allowed) to cover operating expenses. Any canceled and deferred capital spending will be at the expense of capital improvement projects such as facility upgrades, bus replacements, and maintenance/construction activities to maintain the state of good repair, some of which can affect the ZEB deployments.

NREL and UCB collected information from transit agencies to assess how the COVID-19 pandemic had impacted their ZEB deployments and planning activities. In some cases, where ZEB orders had already been funded and/or placed with the manufacturer, there was little to no impact and transit agencies were able to keep their ZEB deployment plans on track, despite the circumstances. But transit agencies that were already in the process of preparing for the ZEB deployments—such as site permitting, construction or facility modifications, and installation and commissioning of infrastructure—experienced delays in the project schedules during the pandemic. At least one ZEB manufacturer reported having to slow down the bus manufacturing line at times during the pandemic but was able to stay open and continue building buses. The slowdown in manufacturing may have caused some delays in the bus delivery schedules.

Significant time and effort are required for most transit agencies to properly research ZEB technologies and plan to transition their fleet to ZEBs. The unexpected pandemic required transit staff time to be diverted toward more urgent day-to-day operational issues focused on providing transit service as safely as possible in a very uncertain environment. As a result, in many cases, transit agencies put ZEB planning efforts temporarily on hold.

The pandemic caused transit agencies as a whole to not meet the first discharge requirement of the ICT regulation in 2020. According to CARB's unofficial discussions with transit bus OEMs in February 2020, a total of 800 ZEBs were already purchased or delivered. However, the pandemic caused many delayed and/or cancelled orders, which led to the transit industry falling short of the targeted 850 ZEBs needed by the end of 2020 to waive the 2023 purchase requirement.

A lot of uncertainty remains for agencies trying to plan for the ZEB transition in the wake of the pandemic's effects. Ridership levels are slowly increasing, but there is no clear indication of when, or if, ridership will fully return to pre-pandemic levels. The geographic and demographic mix of transit riders may also shift. Transit ridership demand has a direct impact on the size and makeup of bus fleets and the type of transit service offered. Some agencies expect they will need smaller bus fleets because they anticipate reduced service levels in the future. Shrinking fleets will require fewer replacement buses, which can reduce and delay ZEB purchases. Agencies may also shift to more on-demand service and fewer fixed-route and commuter options, which can lead to a higher fraction of shorter cutaway buses compared to standard buses, coaches, and articulated buses. Labor shortages across the industry—resulting from a combination of hiring freezes during the pandemic, higher-than-normal attrition, and difficulty attracting new transit staff—have made maintaining operations challenging for transit agencies, regardless of bus and powertrain type.

Above all, the most notable impact of the pandemic on transit agencies transitioning to ZEBs has been the strain on transit agencies' budgets. This unexpected event has led to even greater challenges in purchasing ZEBs and necessary infrastructure. It slowed down the purchase and deployment of ZEBs in the early years of the ICT implementation and weakened the ability of some transit agencies to purchase ZEBs early and ahead of the ICT ZEB purchase requirements. The significant increase in recent dedicated funds to support the ZEB deployment may allow transit agencies to regain the ZEB purchase momentum.

3. Available ZEBs and Related Infrastructure

3.1 Available ZEB Models

In recent years, an increased number of ZEB models have completed testing at Pennsylvania State University's Altoona Bus Research and Testing Center [67]. Altoona testing is part of the FTA's Bus Testing Program. It evaluates how well the buses perform under the demanding conditions found in transit service. Vehicle categories assessed include maintainability, reliability, safety, performance, vehicle structure, noise, and fuel economy. Between 2001 and 2018, 15 ZEB models from eight OEMs passed Altoona testing. These OEMs were E-Bus, Proterra, BYD, New Flyer, Nova Bus, Kiepe Electric, Gillig, and ENC. During a much shorter period, between 2019 and 2020, an additional 14 ZEB models from the OEMs mentioned previously and two additional OEMs (GreenPower and Motor Coach Industries) passed Altoona testing [67]. This indicates that OEMs have been launching a variety of new ZEB products at an accelerated pace and these ZEBs (both BEBs and FCEBs) are now available to transit agencies for purchasing and placing into revenue service.

Indeed, commercially available ZEB models have increased in number and variety. As of May 2022, there were 56 models of heavy- and medium-duty ZEBs on the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project's (HVIP's) list of eligible vehicles from the following manufacturers, with their U.S.-based manufacturing facilities listed in parentheses:

- ARBOC Specialty Vehicles (Middlebury, Indiana)
- BYD Motors (Lancaster, California)
- ENC (Riverside, California, and Salina, Arkansas)
- Gillig (Hayward, California)
- GreenPower Motor Company (Porterville, California)
- Lightning eMotors (Loveland, Colorado)
- Lion Electric (Joliet, Illinois)
- Motiv Power Systems (Hayward, California)
- Motor Coach Industries (Hayward, California)
- Phoenix Motor Cars (Anaheim, California)
- New Flyer (Anniston, Alabama; Crookston, Minnesota; St. Cloud, Minnesota; and Jamestown, Virginia)
- Nova Bus (Plattsburgh, New York)
- Optimal-Electric Vehicle (Elkhart, Indiana)
- Proterra (City of Industry, California)
- Van Hool (Morristown, Tennessee).

In addition, SEA Electric and Alpha Mobility have only headquarters in Torrance and San Diego, California, respectively. Micro Bird has its headquarters and production facility in Drummondville, Quebec, Canada, but its school bus manufacturing facility is in Fort Valley, Georgia [68].

There are now numerous OEMs that offer BEBs or FCEBs in various sizes and bus designs in the United States. Some of these OEMs are new bus manufacturers that build only ZEBs, whereas others offer new zero-emission powertrains for their existing transit bus platforms. Table 4 lists vehicle OEMs offering standard bus models with zero-emission powertrains as of 2022. This list is continually changing as OEMs enter the ZEB market and as new ZEB models and configurations are announced.

Table 4. OEMs Offering Standard Transit Bus Models with Zero-Emission Powertrain

OEM	Model	Nominal Length (ft)	BEB	FCEB	Max/Nominal Range (miles)
ARBOC [a]	Equess CHARGE	30	✓		210
	Equess CHARGE	35	✓		230
BYD [b]	K7M, K7MER	30	✓		158, 196
	K8M	35	✓		196
	K9M, K9MD	40	✓		157, 203
ENC [c, d]	Axess-BEB 32	32	✓		n/a
	Axess-BEB 35	35	✓		n/a
	Axess-BEB 40	40	✓		n/a
	Axess-FC 35	35		✓	260
	Axess-FC 40	40		✓	260
Gillig [e]	Low Floor	40	✓		150
GreenPower [f, g]	EV250	30	✓		150+
	EV350	40	✓		200+
New Flyer [h]	Xcelsior CHARGE NG	35	✓		179, 220
	Xcelsior CHARGE NG	40	✓		174, 213, 251
	Xcelsior CHARGE H2	40		✓	350
Nova [i, j]	LFSe, LFSe+	40	✓		n/a
Proterra [k]	ZX5, ZX5+	35	✓		125, 240
	ZX5, ZX5+, ZX5 MAX	40	✓		120, 232, 329

[a] https://arbocsv.com/models/equess-charge/
[b] https://en.byd.com/bus/
[c] https://www.eldorado-ca.com/electric-bus
[d] https://www.eldorado-ca.com/hydrogen-hybrid-bus
[e] http://www.gillig.com/battery-electric
[f] https://greenpowermotor.com/gp-products/ev250-bus/
[g] https://greenpowermotor.com/gp-products/ev350-bus/
[h] https://www.newflyer.com/new-flyer-buses-meet-the-xcelsior-family/
[i] https://us.novabus.com/blog/bus/lfse/
[j] https://us.novabus.com/blog/bus/lfse-plus/
[k] https://www.proterra.com/vehicles/zx5-electric-bus/.

These low-floor bus models are available in nominal lengths of 30 to 40 feet. BEB models often have multiple options for the size of the battery pack to be installed, which determines the onboard energy storage capacity. These options for onboard energy storage are reflected in the nominal driving range column of Table 4. It is worth noting the greater number of BEB models that are available compared to FCEBs. This could be related to early market demand for BEBs or the state of FCEB technology/industry. A more detailed table of available ZEB models is provided in Appendix A.3.

In addition to the bus OEMs building new ZEBs, the companies listed in Table 5 offer remanufacturing and repowering services to convert transit buses with conventionally fueled powertrains to zero-emission powertrains. The repowering option can extend the life of a used bus while eliminating the tailpipe emissions to help transit agencies comply with the ICT regulation and reach their GHG and air pollution reduction goals.

Table 5. Companies Offering Remanufacturing of Standard Transit Buses to Zero-Emission Powertrain

Company	BEB	FCEB
Complete Coach Works [a]	✓	✓
Lightning eMotors [b]	✓	

[a] https://completecoach.com/services-alternative-fuel-electric-conversions/
[b] https://lightningemotors.com/buses/.

3.2 Electric Charging Infrastructure

All BEBs, regardless of size and type, require electric charging infrastructure to replenish the energy stored in the onboard batteries. The charging infrastructure consists of utility assets (to-the-meter equipment) that deliver electricity from the grid to a customer's facility, and customer assets (behind-the-meter equipment), which enable charging of electric vehicles from the facility's electrical service. Behind-the-meter equipment includes electrical cabinets/switchgear and the charger/dispenser (also called electric vehicle supply equipment [EVSE]). Bus operating requirements and the energy storage capacity of electric bus batteries dictate the type of charging and EVSE needed to operate BEBs, and while many OEMs consider their BEB models to be charger-agnostic, the vehicles and compatible charging systems work as a combined system. They must be acquired and placed into service at the same time to ensure successful operation. The three primary categories of EVSE are plug-in (conductive), overhead (conductive), and wireless (inductive) charging [69–72].

Plug-in charging, sometimes called "slow" charging, occurs at the depot or bus parking location when the bus is not in service (e.g., overnight, between peak service periods). Plug-in EVSE traditionally provided lower-power AC charging, but the technology has quickly advanced to allow for higher-power DC charging (approximately 50–350 kW). This charging method uses a cord and plug that must be manually connected to the charging receptacle on the bus. Most plug-in charging systems in use today are between 60 and 200 kW, with some designs requiring a redundant cord and plug configuration to double the power level above 100 kW. At higher power levels, liquid cooling may be necessary for the cord and plug.

The connection interfaces for plug-in charging have also evolved in recent years to meet the needs of increasing power levels and improving interoperability. Although some proprietary plug interfaces have been developed, medium- and heavy-duty vehicles generally use one of a few standard interfaces. The least commonly used, due to the low power level (<20 kW), is the J1772 AC charging interface specified by the SAE International standard J1772. This standard provides functional requirements and best practices for plug-in charging with EVSE [73]. The Combined Charging System Type 1 (CCS-1)—which combines AC and DC connections—is used for power levels of approximately 20–350 kW (and 450 kW is proposed); alternatively, the CHAdeMO DC interface can be used for this power range. For higher-power plug-in connections, the CCS-1 DC interface is typically used, yet SAE’s new standard J3068 has updated the CCS interface to harmonize the North American and European versions [74].

DC charging dispensers come in several different forms depending on the power level, charging strategy, and design considerations by the manufacturers. The size and configuration of the equipment will have important implications for transit agencies installing EVSE in their bus depots, from space constraints and collision hazards to construction timelines and costs.

Overhead charging uses one of several automated methods for connecting the bus to EVSE. Some early generations of BEBs required proprietary charging equipment developed by the bus OEM to work specifically with their BEB models. As the BEB market has grown and calls for better interoperability between vehicles and chargers have increased, more charging standards have been formalized to guide manufacturers and improve the interoperability of buses and charging systems for transit agencies.

In January 2020, SAE published recommended practice J3105, which outlines requirements and best practices for transferring DC power to buses and heavy-duty vehicles with an automated charging device [75,76]. The three interfaces covered in the standard are infrastructure-mounted cross-rail connection, vehicle-mounted pantograph connection, and enclosed pin-and-socket connection. These interfaces for higher-power “fast” charging (typically 300–500 kW) were originally intended for frequent, on-route charging at scheduled layovers while a bus was in service. However, they can also be utilized at bus parking locations and/or maintenance facilities to quickly recharge a BEB. As more BEB models are developed with overhead charging and plug-in charging capability, some transit agencies are incorporating one or more overhead chargers at their facilities alongside plug-in chargers to increase their charging options. Some transit agencies are planning for charging “fast lanes” at their depots that use DC fast charging to improve the efficiency and resiliency of their operations. Overhead chargers can also be used at transit centers or other strategic locations along routes to provide additional energy to BEBs to extend their driving range for particularly long routes/blocks.

Wireless inductive charging is another type of automated charging that is typically used on route at scheduled bus layovers. This charging method transfers power from a transmitting coil installed under the road surface to a receiving coil mounted on the underside of a BEB when the bus is parked with the coils aligned. Inductive charging systems between 50–250 kW are available from multiple charger manufacturers. These systems require the receiving coil and other bus-side charging equipment to be retrofitted onto a BEB to enable wireless charging capability. The automated nature of the charging and reduction of equipment installed near the bus stop make the wireless charging method appealing for on-route charging, but the equipment and installation can be more costly than aboveground chargers and requires a significant amount of subsurface construction work.

The type and power level of the EVSE, along with the daily energy requirements of each bus, have a significant impact on the time required to “refuel” BEBs by one of these charging methods. In general, plug-in-style depot charging systems operate on the order of hours to recharge a bus, while on-route or DC fast charging systems (both overhead and wireless) operate on the order of minutes. Charging times can vary greatly from day to day and from bus to bus depending on the route requirements, the daily energy consumed by each bus, and the available charging power. As an example, Foothill Transit operates BEBs that primarily use plug-in chargers at the depot for overnight charging, but also use high-powered overhead charging on route to extend driving range. Figure 4 shows a distribution of the charging duration for both types of charging. The vast majority of on-route charges are less than 30 minutes in duration, while plug-in charging events at the depot can last for many hours [77].

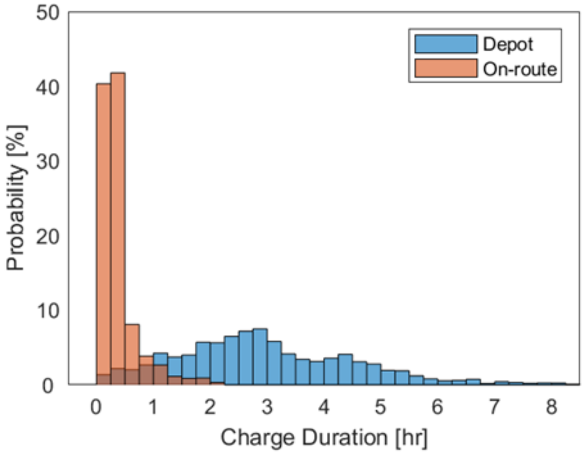


Figure 4. Example charging duration for plug-in (depot) and overhead (on-route) charging [77]

Another crucial component of BEB charging infrastructure is the software used to schedule and control charging activities. While this feature is not required—EVSE does not need separate software to initiate or manage bus charging when connected manually—transit agencies are finding this increasingly important as they deploy larger fleets of BEBs, as a means of minimizing charging costs (by scheduling and limiting the power delivered) and ensuring smooth/continuous operations (charging prioritization and error alerts). A variety of charge management options are available from bus OEMs, EVSE vendors, and third-party providers, but the communication protocols used in each case will determine which products and services are compatible. The options can range from a preset limit for the charging power up to real-time monitoring and remote control of numerous EVSE charging profiles.

3.3 Hydrogen Fueling Infrastructure

Hydrogen fueling infrastructure consists of hydrogen storage, compression, and dispensing equipment. Precooling may be added to this setup if faster dispensing times or a more complete fill is needed. Dispensing hydrogen into FCEBs has unique requirements that determine the type of fueling equipment and processes needed. The first consideration is how the hydrogen will be produced and supplied. While gaseous hydrogen is currently used by smaller demonstration fleets, the amount of hydrogen used by a fleet of FCEBs will quickly drive the storage and delivery requirements toward liquid hydrogen. On-site production of hydrogen by either water electrolysis or steam methane reforming is often used to supplement the delivered hydrogen. The decision for which method of on-site production will provide the most benefit will need to be made on a case-by-case basis depending on the resources available at each transit agency. A financial modeling tool called the Hydrogen Financial Analysis Scenario Tool (H2FAST) is available to determine the appropriate scenario for specific circumstances [78].

The level of compression needed at hydrogen fueling stations will depend on the pressure required by the FCEBs themselves. Currently, FCEB models available in the United States are pressurized to 35 MPa (5,000 psi), whereas some FCEBs outside the United States use 70-MPa (10,000-psi) pressurization. Higher pressure increases the amount of energy storage per unit volume, which allows for the onboard hydrogen to use less cargo space (for the same energy storage) but introduces an additional requirement for precooling and requires higher-pressure compressors. Lower delivery pressure allows for less compression at the station and removes the requirement to precool the dispensed gas but takes up more cargo space on the bus. It appears that most systems in the United States will stay with the 35-MPa pressure in the near future, but higher-pressure systems may begin to be introduced as other FCEB models begin to be available for purchase in the United States.

Dispensing hydrogen into FCEBs can be performed in a similar manner to how a current fueling bay functions for conventional fuels. Hydrogen dispensers can be installed in line with the cleaning and farebox systems for a similar experience to current operations. Current fueling rates are limited to the SAE J2601 requirements, which were developed for light-duty vehicle applications. Fast-flow standards for medium- and heavy-duty vehicles are still under development and will improve fueling rates and times once approved. Alternatively, lower-flow systems can be installed throughout a garage that would fuel individual buses as they are parked. These systems have been proposed but have not yet been implemented by any studied transit agency.

An additional consideration for hydrogen station capability is the bus fueling time. With most buses fueling to 35-MPa pressure, they can safely fuel a bus without the need to precool the gas. Fueling times have been reported to be 6.5 to 7.5 minutes without precooling, on average, and faster with precooling. Precooling is used in 70-MPa light-duty applications to avoid overheating the onboard storage tank during a fast fill. Although FCEBs do not require precooling, a fast fill without precooling has been found to result in elevated tank temperatures that ends with a lower fueling pressure after settling back to ambient temperature. To get a full tank and the expected driving range, transit agencies have either slowed the fueling process [79] or fueled a second time to “top off” the tank before dispatching the bus for service [80]. Both options could result in increased personnel time and more time for the bus to be at the dispenser. OCTA installed precooling in their dispenser to avoid these issues and increase throughput [81]. The cooling capacity of liquid hydrogen storage can be used in the precooling process, as proven in the recent station upgrade at AC Transit. During acceptance testing, the station upgrade was confirmed to be capable of fueling up to 130 buses, back to back, in a 10-hour window.

Fueling stations are as diverse as transit agencies themselves, and one method will not fit all the needs of every transit agency. The hydrogen fuel industry continues to develop from an industrial setting to a more commercial setting, and the limited number of installations makes advancement slow. As medium- and heavy-duty fueling standards are developed and implemented, the industry will continue to adapt and meet the specific needs of each transit agency [82].

3.4 Standardization on Electric Charging and Hydrogen Fueling

Given the short development and deployment timeline of zero-emission vehicles (ZEVs), along with the number of stakeholders involved, increases in scale and interoperability for electric charging and hydrogen fueling of MD/HD ZEVs are needed. Standardization will provide market certainty, protect state investments, streamline heavy-duty vehicle electrification, and support accelerated deployment. Ideally, standardization should take place early in the process to ensure mass market success and universal expansion on necessary timelines.

ZEB interoperability topics have been investigated and worked on by various stakeholders, including industry associations and standardization groups, transit agencies (via joint procurements), and state contract work. The recent San Francisco Municipal Transportation Agency BEB pilot program is a good example that requires all four BEB OEMs to use the same overhead chargers [83]. CARB also contracted with University of California, Irvine (Agreement No. 20MSC006) in 2021 to conduct a 2-year study on electric charging and hydrogen fueling standardization's status, implementation gaps, and future directions. Brief summaries on the status of both electric charging and hydrogen fueling standards are given in the following sections.

3.4.1 Protocols Relevant to BEB Electric Charging

Most chargers in the United States were first developed to support light-duty vehicle applications and have been adapted for MD/HD vehicle use cases in the current U.S. EV market. To support the deployment and operation of these chargers, a wide variety of EV charging standards have been developed or are under development. Among the various charging protocols, J1772/CCS1, SAE J3105, SAE J2954/2, and SAE J3271 (Megawatt Charging System) have been more commonly used or have more potential to be used for charging battery-electric transit buses in the United States.

The Combined Charging System, more commonly known as CCS, is the European standard plug-and-socket type used for connecting electric or plug-in hybrid cars to a DC fast charger. In 2011, SAE developed a J1772/CCS Combo Coupler to support the CCS standard for DC fast charging, which includes the standard five-pin J1772 connector along with two larger pins to support fast DC charging. This is commonly called CCS-1 and is mostly used in North America. CCS-1 accommodates charging at 200–920 V DC and up to 350 kW (450 kW is proposed) [84,85]. The combination coupler uses power-line communication technology to communicate between the vehicle, off-board charger, and smart grid.

SAE J3105 (January 2020)—"Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices"—is a recommended practice that covers the general physical, electrical, functional, testing, and performance requirements for vehicles using a conductive automated connection device connection capable of transferring DC power [75]. Three interfaces are covered in the standard, including infrastructure-mounted cross-rail connection (J3105/1), vehicle-mounted pantograph connection (J3105/2), and enclosed pin-and-socket connection (J3105/3). These high-power fast-charging interfaces are typically used for on-route charging but can also be utilized at bus depots. Particularly, SAE J3105/2 details the vehicle-mounted pantograph, or the "bus-up" connection (as opposed to the "bus-down" pantograph connection in J3105/1), providing a charging strategy for on-route charging and space-constrained depot charging.

SAE J2954/2—"Wireless Power Transfer & Alignment for Heavy Duty Applications"—was released in December 2020 as a "work in progress" [86]. It establishes an industrywide specification guideline that defines acceptable criteria for the interoperability, electromagnetic compatibility, minimum performance, safety, and testing for wireless power transfer for high-power wireless charging of heavy-duty EVs. J2954/2 is the MD/HD expansion of J2954 and will account for differences between light-duty EV and MD/HD EV charging requirements, including alignment methods, vehicle geometry considerations, vehicle suspension systems, electric utility feed (voltage, phase), and power levels (potentially between 50–500 kW) [87].

To facilitate the deployment of commercial vehicles with larger battery packs requiring higher charging rates with moderate dwell time, another primary charging standard in active development is the Megawatt Charging System. A contract between CARB and the University of California, Irvine (Agreement No. 20MSC006) identifies that with SAE under J3271, the Megawatt Charging System is currently a work in progress and its contents are being coordinated with the CharIN industry consortium [88,89]. The Megawatt Charging System is planned for DC high-powered charging to deliver 1,250 V and 3,000 A for up to 3.75 MW for a single conductive plug [90]. The current focus on the SAE J3271 Megawatt Charging Working Group is to develop a technical information report that describes the megawatt-level DC charging system requirements for couplers/inlets, cables, cooling, communications, and interoperability.

In addition to hardware compatibility, more standardization of charging software and management processes are also important for improving availability and performance of battery-electric vehicles and charging infrastructure [91]. ISO 15118 provides a standard vehicle-to-charger communication language, and the Open Charge Point Protocol provides a standard charger-to-network language.

ISO 15118 provides a common language for vehicles and chargers to exchange information about authentication, billing, and information to promote vehicle-grid integration. Many automakers and charging networks have publicly signaled their intention to adopt ISO 15118 as a more robust digital communications protocol between the vehicle and charger. While communication protocols such as ISO 15118 provide general guidelines for signaling between the EV and EVSE, currently there is sufficient design heterogeneity at the commercial product level that interoperability testing is required to ensure performance across multiple platforms and products [85]. The charging software needs to be developed in a way that ensures a good "handshake" between chargers and EVs, even if they are from different OEMs. Standardization of software also ensures that any update on charging software will not lead to equipment failures or service interruption.

The Open Charge Point Protocol is the global open communication protocol between EV charging stations and a central management system, also known as a charging station network. The protocol creates an open application protocol that allows EV charging stations and central management systems from different vendors to communicate with each other. This protocol handles the exchange of charging data and can trade information between EVs and the electricity grid. Through the back-end network management software, hosts can monitor charger status, connect chargers to signals for local electricity pricing and demand response, and even set up a reservation system to allocate time slots to users [91]. EV charging manufacturers that adhere to this protocol standard ensure that their products will work with competing brands, for the benefit of customers. Working with an open-network solution also makes it easier for charging station owners to protect their investment over the years.

3.4.2 Fuel Cell Electric Vehicle Hydrogen Refueling Protocols

SAE J2601 is currently the only standard for hydrogen fueling that the U.S. auto industry has developed and adopted for fuel cell electric vehicles, but it was harmonized for the European market as ISO 19880-1 and adapted for the Japanese market as JPEC-S 0003 [85,92–94].

SAE J2601 (May 2020)—"Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles"—establishes the protocol and process limits for hydrogen fueling of vehicles with total volume capacities greater than or equal to 49.7 L. The hydrogen fueling limits such as maximum fuel flow rate, pressure increase rate, and ending pressure are affected by various factors, including ambient temperature, fuel delivery temperature, and initial pressure in the onboard storage system. The J2601 fueling protocols are based on either a look-up table approach (table-based protocol) with a fixed pressure ramp rate or a formula-based approach (MC formula) utilizing a dynamic pressure ramp rate that is continuously calculated throughout the fueling process. The table-based protocol provides a fixed end-of-fill pressure target, whereas the MC formula-based protocol calculates the end-of-fill pressure target continuously during a fueling event.

Previous releases of SAE J2601 had a maximum onboard storage capacity of 10 kg, but the May 2020 release added Category D to establish boundaries for any onboard storage greater than 10 kg. As the market for hydrogen-powered heavy-duty transit buses expands, there is an industry need to establish more specific fueling guidelines for hydrogen-fueled transit buses and other heavy-duty vehicles.

SAE J2601/2 (September 2014)—"Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles"—is a short guidance document for MD/HD vehicle hydrogen fueling that provides performance requirements for hydrogen dispensing systems used for fueling 35-MPa (H35) heavy-duty hydrogen-fueled transit buses and vehicles [95]. Boundary conditions are established for safe heavy-duty hydrogen surface vehicle fueling, such as safety limits and performance requirements for gaseous hydrogen fuel dispensers used to fuel hydrogen transit buses. This fueling protocol is suitable for heavy-duty vehicles with a combined hydrogen storage system capacity more than 10 kg, aiming to support all practical capacities of transit buses. The current version of J2601/2 is not a comprehensive fueling protocol but a general overview of operational limits for H35 hydrogen fueling [88].

SAE J2600 (October 2015)—"Compressed Hydrogen Surface Vehicle Fueling Connection Devices"—applies to the design and testing of compressed hydrogen surface vehicle fueling connectors, nozzles, and receptacles [96]. Connectors, nozzles, and receptacles must meet all SAE J2600 requirements and pass all SAE J2600 testing to be considered SAE J2600 compliant.

SAE J2799 (December 2019)—"Hydrogen Surface Vehicle to Station Communications Hardware and Software"—specifies the communications hardware and software requirements for fueling hydrogen surface vehicles, such as fuel cell vehicles, but may also be used, where appropriate, with heavy-duty vehicles (e.g., buses) and industrial trucks (e.g., forklifts) with compressed hydrogen storage [97]. This standard contains a description of the communications hardware and communications protocol that may be used to refuel hydrogen surface vehicles. The intent of this standard is to enable harmonized development and implementation of the hydrogen fueling interfaces, and it is expected to be used in conjunction with all versions of J2601 and nozzles and receptacles conforming with SAE J2600.

In addition to the SAE standards, the first interim report from a contract between CARB and the University of California, Irvine (Agreement No. 20MSC006) to assess MD/HD vehicle fueling and charging standardization identifies that to further facilitate the deployment of hydrogen fuel cell heavy-duty vehicles, the international community has been actively working on high-flow (70-MPa, H70), heavy-duty vehicle refueling standards within the International Organization for Standardization [85]. The two primary standards under development for the high-flow, heavy-duty vehicle refueling are an update to ISO 17268 and ISO 19885, which is a new standard [99]. ISO 17268 defines the design, safety, and operational characteristics of hydrogen refueling connectors, which consist of a nozzle, receptacle and protective cap, and communication hardware [99]. The scope of ISO 19885 is still being defined but is planned to include three parts: (1) design and development process for fueling protocols, (2) definition of communications between the vehicles and dispenser control systems, and (3) high-flow hydrogen fueling protocols for heavy-duty road vehicles.

At the regional level, there are also several standards development activities, such as a new Japanese protocol under JPEC [100] and a European protocol—PRHYDE ("Protocol for Heavy-Duty Hydrogen Refueling"). It is expected that work under these initiatives will be considered for—and, where possible, integrated with—the ongoing standards development by the International Organization for Standardization.

4. ZEB Costs

4.1 ZEB Capital Costs

Although capital costs have been decreasing for both BEBs and FCEBs, there remains a cost premium for these relatively new technologies compared to conventionally fueled transit buses. The capital cost for BEBs and FCEBs continues to be a key challenge to the widespread implementation of ZEB fleets.

Figure 5 shows capital cost trends from data reported in the 2020 APTA *Public Transportation Vehicle Database* [101]. These data have been filtered to include only confirmed data for standard, low-floor-style transit buses between 35 and 45 feet in length. The data represent purchases of buses that are currently active, on order, and planned by transit agencies throughout the United States, as reported by the transit agencies. The chart includes both ZEB types—FCEB (hydrogen) and BEB (battery-electric)—as well as three conventional fuel types (CNG, diesel, and diesel hybrid). The size of each data point is scaled to indicate the number of buses in the reported purchase. Linear trend lines have been added to help indicate the general change in prices over time for each type (not to represent future projections—especially in the case of hydrogen, where only limited data were available); the trend lines (listed in order from top to bottom) are shown for hydrogen (blue), BEB (green), diesel hybrid (orange), CNG (grey), and diesel (brown). Although this data set does not include all ZEB purchases, and while the price trends for ZEBs have not been exactly linear as displayed in the chart, the figure clearly shows that ZEB capital costs have generally been decreasing, while conventionally fueled buses have been linearly increasing in price for decades, based on the APTA database.

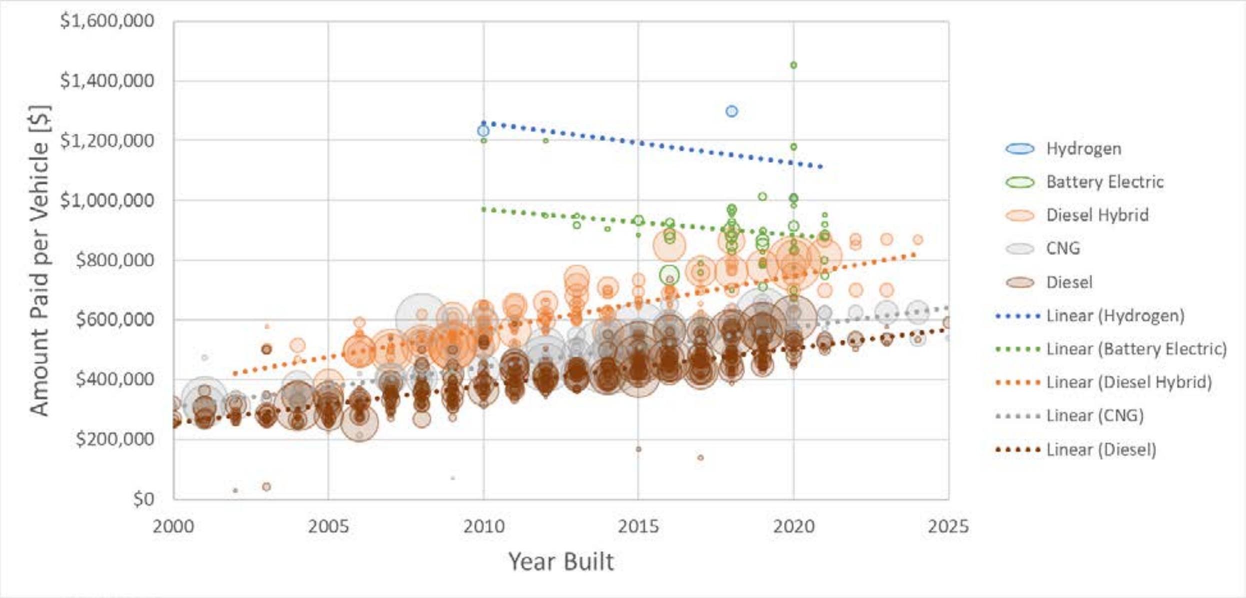


Figure 5. Standard transit bus capital cost trends.

Data from the 2020 APTA *Public Transportation Vehicle Database* [101]

The data points in Figure 5 are based on values voluntarily reported by transit agencies to the APTA database. Some ZEB purchases may not have been reported, and the capital costs of some ZEB purchases may not have been reported consistently between transit agencies with regard to grants being included or excluded in the reported values. Due to this potential data limitation, particularly for FCEBs, the project team also investigated other sources for reported ZEB costs. NREL's 2020 status report on transit FCEBs in the United States provides a detailed summary of the capital cost trend for FCEBs over the past two decades, as shown in Figure 6 [80]. Precommercial FCEB demonstrations in the early 2000s were reported to have cost between $2.4 and $3.5 million per bus, compared to approximately $300,000 per bus for diesel buses in the same time period (as shown in Figure 5). Initial commercial purchases of FCEBs from 2009 to 2014 cost $2.0 to $2.5 million per bus. Recent purchases of the latest model 40-foot FCEB reportedly cost between $1.1 and $1.3 million per bus for orders of 5–10 buses, while diesel buses are approximately $500,000 [80,102].

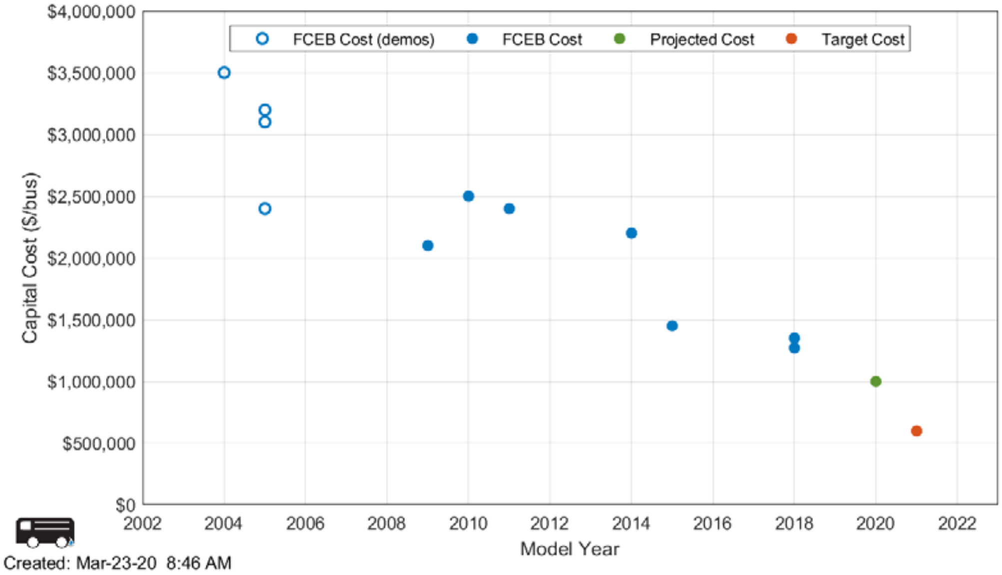


Figure 6. Reported capital costs for FCEBs [80]

Evaluations of early BEB deployments have reported bus capital costs between $800,000 and approximately $1.0 million per bus for orders of 2–14 buses. These include model year 2014–2017 standard BEBs from multiple manufacturers. Comparable baseline buses for these BEB evaluations cost between $410,000–$500,000 per bus for diesel and between $540,000–$690,000 per bus for CNG, covering a similar range of model years [103].

Capital cost estimates for standard 40-foot buses that were optionally included in ZEB rollout plans indicate that transit agencies are expecting to pay between $720,000–$1,200,000 per bus for future BEB purchases and between $850,000–$1,300,000 per bus for future FCEB purchases. For BEBs, the cost could also be affected by its range design, even for the same transit agency and bus model. For example, for HVIP participants, the prices ranged from $780,672 to $915,672 for Proterra model year 2020 35-foot Catalyst XR, E2, whereas Proterra's 40-foot Catalyst XR, E2, E2 max (also model year 2020) featured with a 660-kWh battery is shown for a price tag of $1,174,747 in HVIP. TriMet will purchase 24 long-range BEBs from Gillig with an estimated cost of $26.7 million, suggesting an average price of $1,112,500 per bus [104]. Most BEB cost estimates are less than $1,000,000 per bus, and most FCEB cost estimates are greater than $1,000,000 per bus. These cost estimates for standard 40-foot buses provided in the rollout plans were derived using a variety of different assessment methods, ranging from actual OEM quotes for specific bus orders (or previous orders) to best estimates based on an agency's internal research on ZEBs, and they do not necessarily reflect the same purchasing time frame or bus configurations. In addition, these costs represent a variety of different options, such as different battery capacities for the BEBs, which can have a significant influence on the BEB capital cost. However, the majority of the cost estimates reported in the rollout plans do correspond well to the near-term capital cost trends derived from the APTA database.

It is anticipated that as more ZEBs are ordered by transit agencies and the size of each order grows, the ZEB manufacturing sector will benefit from greater economies of scale, which will contribute further to the reduction in capital cost. Some OEMs have reported that the complexity of a particular configuration is currently more indicative of the per-bus price than the size of the bus order. Some configurations or specific order requirements are more challenging to design, engineer, and build, which increases the cost. For example, one agency's order for 40 BEBs will not necessarily be less expensive per bus than another agency's order for 10 BEBs from the same OEM. However, OEMs do expect that increased orders of ZEBs in the coming years and broad growth throughout the ZEB industry will provide downward pressure on all ZEB prices.

According to OEMs, the primary drivers of higher capital costs for ZEBs are propulsion-related components. This includes lithium-based batteries for BEBs and fuel cell stacks and balance-of-plant components for FCEBs, as well as common electric drivetrain components like electric motors and DC/DC converters. Figure 7 shows the results of a meta-analysis comparing numerous methods for projecting lithium-based battery pack prices ($/kWh) published in the academic literature [105]. The authors of the report combined numerous time-specific projections studied in the extensive analysis and applied a regression curve to indicate an aggregate expectation of the cost per kilowatt-hour for lithium batteries through 2050. Also included in the figure for reference to the projections are historical prices from 2010 through 2020. The past 10 years have seen steep reductions in the unit costs of lithium-based batteries, and although the cost reductions are expected to slow down, they are expected to continue and approach $100/kWh in the next 10–15 years, if not sooner. Notably, the reference prices in the chart have been below the aggregate projection line in recent years (2016–2020). While this trend is encouraging, it is important to note that these projections are for the commodity price of lithium-based batteries and do not necessarily reflect the actual battery costs for ZEB manufacturers in the United States. Some sources claim lithium-based battery prices are already nearing $100/kWh in some global markets, but there are many uncertainties in these price projections and there may be differences in battery costs between light-duty and heavy-duty vehicle markets. In addition, transit buses are subject to Buy America requirements, which may also impact the real cost of assembled battery packs (and other powertrain components) for ZEBs in the United States [106].

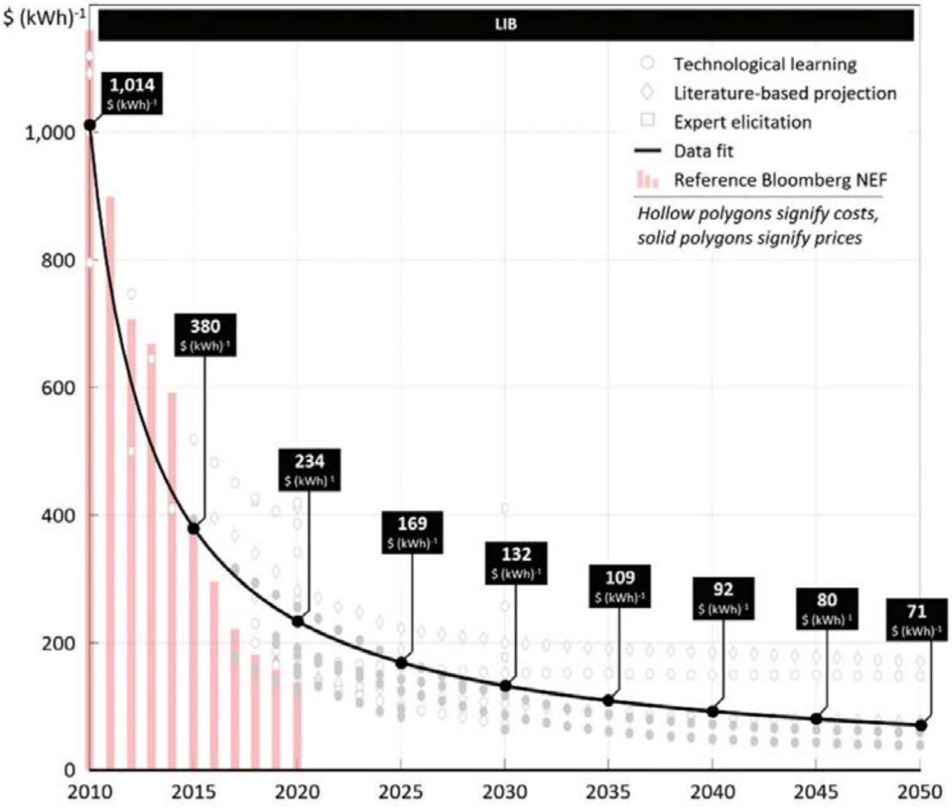


Figure 7. Historical and aggregate projected cost per kilowatt-hour for lithium-based battery packs.

Chart from a meta-analysis of battery cost forecasting methods, courtesy of The Royal Society of Chemistry [105]

4.2 ZEB Infrastructure Costs

One of the essential components of deploying ZEBs is the need for new infrastructure to supply the energy required to operate the bus fleet. Depending on the technology and the level of total power/system upgrades needed, the upfront costs associated with new ZEB infrastructure can be a significant investment for transit agencies. In addition to the purchase and installation of the BEB chargers/dispensers, providing sufficient electrical energy from the grid to recharge BEBs can require extensive upgrades to transit agencies' existing electrical infrastructure, which can be costly. Transit agencies planning to deploy FCEBs must construct a hydrogen fueling station on their property with on-site generation of hydrogen or have plans for the fuel to be delivered and stored on-site for dispensing into buses. A hydrogen station can be expensive and difficult to fund for a small fleet of FCEBs, yet it is generally considered easier and more cost-effective to scale up hydrogen infrastructure to fuel a large fleet of FCEBs than charging infrastructure for BEBs. For both types of infrastructure, there are learning curves and additional costs associated with the operation and maintenance of the fueling/charging stations.

4.2.1 Electric Charging Infrastructure Costs

The electrical infrastructure needed to charge a fleet of BEBs, as well as the associated costs to purchase and install the equipment, can vary widely between sites based on the specific circumstances for each transit agency. Some important factors affecting the costs include the number of buses to be charged, the number and type of chargers to install, the layout of the bus yard or facility, and the size and condition of the existing electrical infrastructure. The amount of energy needed by the fleet and the desired charging rates will dictate the necessary charging infrastructure for a BEB fleet. Faster charging rates require high-power equipment that is typically more expensive and may require more extensive construction work, as well as upgrades to the existing electrical service at the facility.

At minimum, BEB fleets require EVSE/dispensers to connect the site's electrical service to the vehicles for charging. EVSE costs generally scale with the power level and can range between a few thousand dollars per charger up to tens or hundreds of thousands of dollars per charger. Installations of plug-in chargers with associated upgrades to electric service equipment at bus depots have been reported to cost between $50,000–$60,000 per charger for 60–80-kW nominal power levels and between $80,000–$100,000 for 80–125-kW power levels; these examples indicate capital costs of approximately $1,000/kW for plug-in EVSE, as shown by the dashed reference line in Figure 8 [1,69,107]. The installation of plug-in EVSE can cost an additional $5,000–$90,000 per charger, the installation costs being highly dependent on the amount of construction necessary at the installation site and the number of chargers being installed.

Overhead chargers in the 300–500-kW range have been reported to cost between $100,000–$600,000 to purchase, and typically another $200,000–$400,000 for installation, depending on the equipment and site conditions. These include pantograph-style systems as well as other proprietary charger designs. Again, these documented costs are highly variable depending on the unique circumstances at each transit agency location as well as the size, type, and the number of chargers being installed. The total installed costs per charger are expected to decrease as EVSE deployments increase. For a large transit agency, the cost could go beyond EVSE if a new substation is needed.

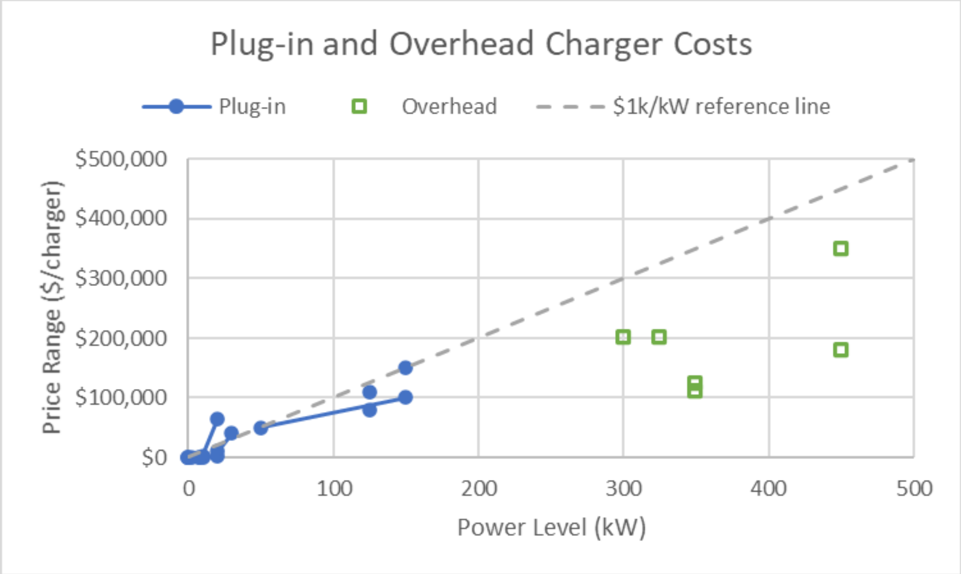


Figure 8. Capital cost estimates for plug-in and overhead chargers.

Data from EV charging guidebook, rollout plans, and Transit Cooperative Research Program report [1,69,107]

Several transit agencies who submitted ZEB rollout plans have conducted assessments of the costs to purchase and install charging infrastructure to power their fleet of BEBs. The detailed cost information provided in the ZEB rollout plans was collected and analyzed on a per-bus basis for plug-in chargers and overhead pantograph chargers, as shown in Figure 9. The four examples of plug-in charging (serving between 5–200 buses at each site with bus-to-charger ratios between 1.5–2.0) all selected chargers with power levels of 125 kW or 150 kW, and total infrastructure costs are all estimated to be less than $100,000 per bus. For the overhead pantograph examples, most agencies selected 125-kW or 150-kW chargers, and the estimated infrastructure costs range from $200,000–$600,000 per bus. One agency opted for 325-kW chargers in its plan, and the total infrastructure cost is estimated to be $300,000–$350,000 per bus.

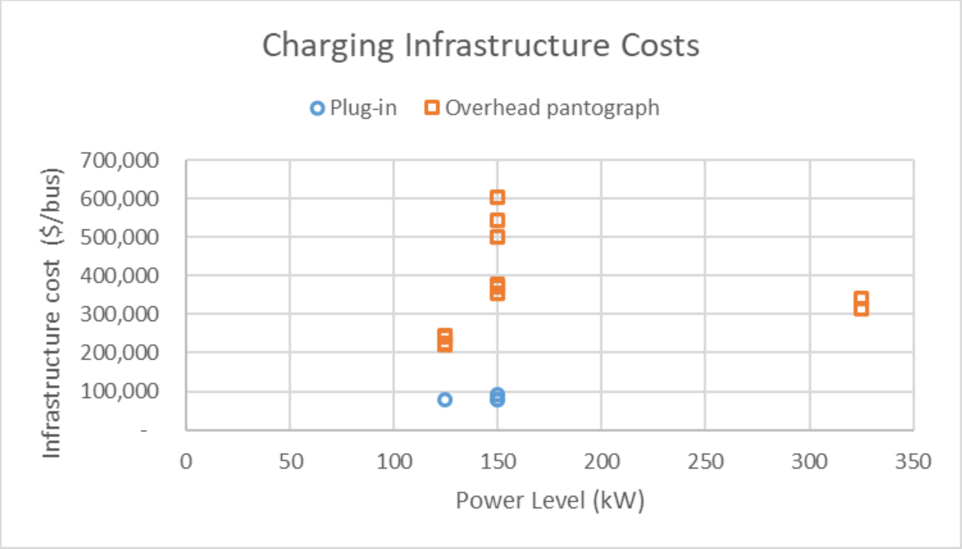


Figure 9. Infrastructure cost estimates (per bus) for plug-in and overhead pantograph chargers.

Infrastructure cost information extracted from ZEB rollout plans by CARB [1]

In many cases, delivering the amount of energy needed for a fleet of BEBs requires more extensive upgrades to the electrical service at a site, such as transformer and/or substation upgrades. Fortunately for transit agencies in California, several of the major investor-owned utilities in the state—in response to California Assembly Bill No. 841 [108]—have established "make-ready" infrastructure programs to assist transit agencies with planning and funding for charging infrastructure [70–72]. These incentive programs are designed to partially cover the costs of upgrades to the utility-owned assets, and some also offer rebates on the customer-owned assets, such as EVSE. The programs will provide support to eligible transit agencies through each stage of the process—design/engineering, permitting, construction, installation, and commissioning of equipment. Transit agencies must apply for assistance through these programs, which are discussed in more detail in Section 5. In addition, Senate Bill 350 was signed into law in 2015 comprising many grid and electrical utility-related elements that benefit the deployment of battery-electric vehicles, namely transportation electrification [7]. The implementation of transportation electrification started in 2017/2018 when the three major investor-owned utilities proposed or were approved by the California Public Utilities Commission to invest in medium- and heavy-duty infrastructure projects. The transportation electrification programs were intended to offset a substantial portion of the costs of making electrical service upgrades and installing charging infrastructure over a 5-year period.

Installing chargers to deploy a small number of BEBs is usually a straightforward process with minimal costs. Expanding from a small pilot fleet to a large fleet of BEBs, however, requires careful planning to scale up the infrastructure in a way that minimizes costs, project timelines, and operational disruptions. Large infrastructure projects requiring utility upgrades can take several months or more than a year to complete, including the necessary permitting. Transit agencies with experience operating BEBs emphasize it is especially important to communicate with the electric utility as early as possible to coordinate on the infrastructure timing and best approach to meet the needs of the electric fleet.

4.2.2 Hydrogen Fueling Infrastructure Costs

Hydrogen fueling stations can either be purchased by the transit agency or leased from the hydrogen supplier. Installations in California have typically been purchased with maintenance contracts in place for the station upkeep. These contracts can either be provided at a monthly cost or rolled into the station upkeep. Some options increase station costs but are implemented to meet performance or regulatory requirements. For example, precooling was added to the OCTA hydrogen station, and it added a small price increase over comparable stations installed at other locations at the same time but enabled faster fueling. On-site hydrogen production by electrolysis or steam methane reforming also adds cost to the station but is implemented to meet carbon neutrality goals or regulations. Table 6 shows a summary of the most recent hydrogen stations built in California, as well as a reference station located in Ohio.

Table 6. Hydrogen Fueling Station Capabilities and Costs

Transit Agency	# Dis-pensers	Pre-cooling	Electrolysis	Liquid Storage	Max Fills/Day	Year Built	Station Cost	Maintenance Cost
AC Transit Oakland [102]	2	–	65 kg/day	9,000 gallons	13	2014	$6.3 million	$15,500/month
AC Transit Emeryville [102]	–	–	–	9,000 gallons	13	2011	$5.1 million	–
AC Transit Emeryville [102]	2	–	–	15,000 gallons	65	2020 upgrade	$4.424 million	$11,800/month
OCTA [81]	2	10°C	–	18,000 gallons	50	2019	$4.7 million	–
SunLine [109]	2	–	900 kg/day	–	32	2019	$8.3 million	$0 for 3 years
SARTA [79]	1	–	–	9,000 gallons	20	2017	$2.9 million	$10,000/month
Foothill Transit [110]	–	–	–	5,000 kg	–	2022–2023	$6.6 million	–

4.2.3 Facility Modification Costs

In addition to the costs for purchasing and installing charging or fueling equipment, other facilities may require upgrades or modifications to accommodate ZEBs. Maintenance bays that service gaseous fuel vehicles require gas detection and ventilation. If a maintenance facility is already equipped for CNG vehicle maintenance, the upgrade for fuel cell vehicles is minimal [79]. Additional sensors—and, in some cases, more ventilation—will be needed. Converting a maintenance facility from diesel to hydrogen requires a considerably higher cost. Transit agencies deploying BEBs will have to ensure their maintenance shops have the tools and protective equipment to safely work on high-voltage electrical systems. Many transit agencies that have operated diesel- or gasoline-hybrid buses will already be equipped to maintain BEBs.

4.3 Operation & Maintenance Costs

Next to capital costs for ZEBs and required charging/fueling infrastructure, costs for operating and maintaining ZEBs are the most important cost considerations for ZEB deployment. The primary operational cost to consider for ZEBs is the cost of energy/fuel to operate the bus fleet—i.e., electricity for BEBs and hydrogen fuel for FCEBs. Assuming buses are replaced at a one-to-one ratio with minimal or no changes to route schedules, other operational costs for ZEBs (such as labor costs for drivers) will be the same as operating a conventional bus fleet. In some cases, transit agencies could have additional labor costs associated with charging or fueling the buses, depending on the infrastructure and the charging/fueling procedures established. In addition, during the early stages of ZEB deployment, transit agencies may need to rely on extended warranties from OEMs until more comprehensive training programs are available for their maintenance staff and they gain sufficient experience with the new technologies. Both of these steps will require additional costs in the near term.

4.3.1 Electricity Costs

The cost of electricity is generally a combination of subscription or service fees ($/month), energy consumption charges ($/kWh), and electric demand charges ($/kW). The subscription/service fees are fixed monthly costs required for maintaining electrical service from the utility. Consumption charges are the costs paid for the electrical energy delivered and often have variable rates such as a tiered structure or time-of-use cost structure. Time-of-use rates normally vary by time of day, day of week, and seasonally to reflect temporal differences in the cost to produce and deliver electrical energy. Demand charges are costs associated with the power level of electrical demand (or peak power) required for charging, as it is also more expensive for the utility to deliver more energy in a short time frame.

The costs for charging BEBs will ultimately be determined by the load profile of the fleet and the electricity rate structure. Electric utilities develop various rate structures for the different types of customers in their jurisdiction. Transit agencies operating BEBs are subject to the electric rate structures developed by their electric utility, and while they may be able to select from a number of defined rate structures, they usually do not have a choice to shop for a different energy provider (as may be the case for traditional transportation fuels).

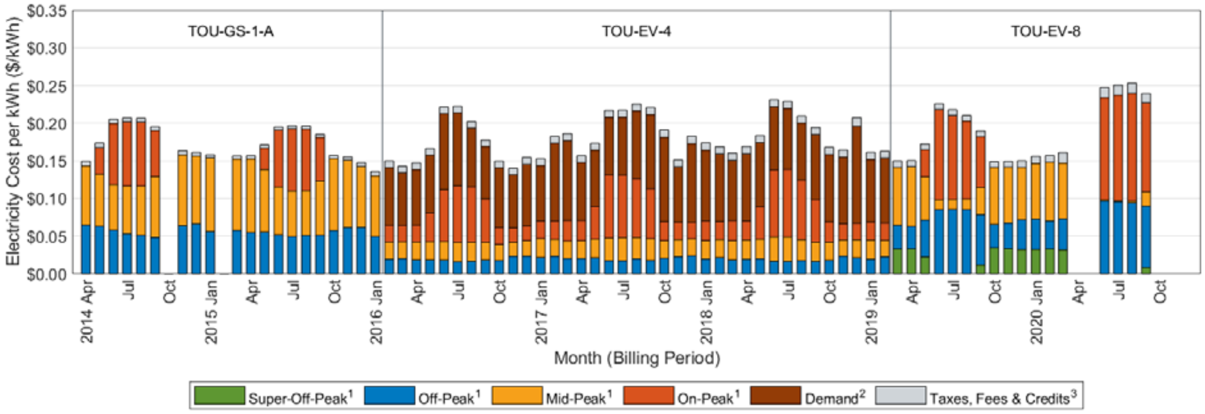
Many utilities are offering commercial EV-specific rate structures, which usually require separate meter(s) for the charger(s) to help facilitate the introduction of electric vehicles in various classes. Some have also instituted a temporary waiver of electricity demand charges to reduce the cost of charging electric vehicles and further encourage BEB adoption.

On an energy-equivalent basis, electricity costs tend to be higher than conventional transportation fuels. However, due to the energy efficiency benefit of BEBs, the electricity costs for BEBs are more similar to the fuel costs for conventional buses on a cost-per-mile basis [77,113–115]. Low electricity rates have the potential to offer fuel cost savings for BEBs over conventional buses, yet transit agencies operating BEBs often end up paying more than anticipated (i.e., the actual total costs paid per kilowatt-hour of energy delivered can be higher than the advertised price for electricity in dollars per kilowatt-hour). This is, in part, due to the complicated and variable nature of the electricity pricing structures and the inherent difficulty in predicting actual costs. Transit agencies, therefore, cite the cost of electricity and uncertainties of future pricing as major challenges to operating a fleet of BEBs cost-effectively.

The Low Carbon Fuel Standard (LCFS) implemented in California is a market-based mechanism helping to reduce the effective cost of low-carbon fuels, including electricity, by allowing transit agencies to earn credits for the use of those fuels. With credits earned through LCFS, lower effective costs for electricity have the great potential to offer fuel cost savings for BEBs relative to those of conventional buses. The LCFS program is discussed in more detail in Section 5.

Figure 10 shows an example of real-world electricity costs for charging BEBs. These monthly costs include seasonally varying time-of-use consumption charges (e.g., on-peak, off-peak) and demand charges for three different rate structures during the years of operation for this bus fleet. Depending on the rate structure, time of day, and total power level used for charging, a BEB fleet can have a significant impact on the overall monthly electricity costs and must be considered carefully when planning for BEB deployments.

It is important to note that Foothill Transit utilized on-route charging in this study and was able to control its summertime electricity cost no higher than $0.23/kWh before the pandemic, regardless of its electricity rate. This electricity cost is even lower than some depot charging costs [115]. This real-world example demonstrates that electricity costs can be managed with careful planning.



1. Time of use charge categories include respective costs for delivery and generation
2. Demand charges introduced in February 2016 with change to TOU-EV-4 rate structure and eliminated in March 2019 with change to TOU-EV-8 rate structure
3. Taxes, Fees & Credits category includes all remaining utility bill items (costs & credits)

Figure 10. Example of electricity costs for charging BEBs [77]

In most cases, the least expensive approach to charging BEBs is using lower-power and longer-duration overnight charging at a bus depot. This approach takes advantage of the lower-cost "off-peak" electricity and minimizes demand charges. Senate Bill 1000 [8] requires the California Public Utilities Commission to explore more targeted rate design strategies for commercial EV customers and to deploy charging stations where there is existing excess grid capacity. The California Public Utilities Commission has encouraged electric utilities to develop rate structures that "reduce the cost of using off-peak electricity as a transportation fuel to well below the cost of conventional fuels" [116]. Overnight charging, however, is not always the most practical or desirable for a transit operator. Agencies are choosing the BEB charging options that best meet the needs of their transit operation and any constraints at their depot/facility, and in some cases that includes midday charging and/or higher-power chargers, which can result in higher electricity costs. Implementing on-site energy storage may help some transit agencies decrease midday peak charging costs, but these options also come at a cost for purchasing and installing the energy storage systems.

It has been demonstrated that software controls for EVSE can be a critical tool for helping transit agencies minimize the costs of charging their BEB fleet. Depending on the specific hardware being used, charge management software has the capability to schedule charging around variable utility rates, prioritize charging based on bus schedules, control the number of buses charging simultaneously, and limit the overall peak demand of the chargers. These features can help transit agencies minimize charging costs and improve the reliability and operational efficiency of the BEB fleet.

4.3.2 Hydrogen Fuel Costs

The cost of hydrogen is highly variable in this emerging market. Several factors that influence hydrogen price include the method of production, proximity to production, delivery method, and storage type. Currently, the lowest-price hydrogen is produced using the steam methane reforming process that creates carbon dioxide from fossil fuels in the process. Introducing more renewable or low-carbon-intensity fuel pathways into the market could further reduce GHG emissions.

DOE launched the Hydrogen Shot program in June 2021 with the aim to reduce the production cost of renewable hydrogen from \$5/kg to \$1/kg by 2030. This target is ambitious but is intended to make the production of renewable hydrogen cost-competitive with conventional hydrogen production methods that are based on fossil fuels and produce significant amounts of GHG.

Average hydrogen fuel prices paid by transit agencies currently operating FCEBs are listed in Table 7. SunLine has the most renewable hydrogen mix and pays the most on average. OCTA and AC Transit have similar hydrogen cost per kilogram. AC Transit has a negotiated set price, whereas OCTA has a variable rate from the supplier. Located in Ohio, SARTA has the lowest cost per kilogram reported by FCEB operators, based on local supply and demand.

Table 7. Hydrogen Cost per Kilogram for Current Transit Agencies With FCEB Fleets [80,113]

Transit Agency	$/kg
AC Transit	7.93
OCTA	8.10
SunLine	10.10
SARTA	5.27

As with electricity, the use of hydrogen as a transportation fuel in FCEBs can earn credits through California's LCFS market, lowering the effective cost for hydrogen and potentially enabling fuel cost savings for FCEBs over conventional buses.

4.3.3 Vehicle Maintenance Costs

Zero-emission transit buses, particularly BEBs, are widely advertised to be less expensive and easier to maintain than their conventional counterparts. It is true that they have fewer mechanical parts (suggesting fewer parts to repair or replace) and do not require the same fluid and filter replacements (i.e., "consumables"). They also promise greatly reduced brake pad wear due to the design of regenerative braking. However, ZEBs contain advanced technologies that are still relatively new and expensive, and the real-world durability and costs required to maintain them are very important considerations for transit agencies planning to transition their fleets to ZEBs.

NREL performed a meta-analysis of maintenance costs to combine data from detailed ZEB evaluations conducted by NREL over the past 10 years, following a standard protocol for maintenance data collection and analysis. These BEB and FCEB fleet evaluations have all been previously reported individually, in separate reports found on NREL's website [103]. Combined, these evaluations create one of the richest data sets on ZEB maintenance costs that are directly comparable. A total of 158 standard transit buses are included—45 BEBs, 55 CNG buses, 25 diesel buses, and 33 FCEBs. The ZEB fleets (BEBs and FCEBs) represent buses with model years 2014 and newer, and the conventional fleets (CNG and diesel) include buses with model years 2011 and newer. A full list of the vehicles included in the analysis is provided in Appendix A.4. The analysis of maintenance costs excludes warranty- and accident-related repairs and is based on a fixed labor rate of $50 per hour for consistency between evaluations. Note that the fixed labor rate is not intended to reflect an average rate for any agency or for the industry, but is a reference point that was held constant to allow direct comparison of the data sets.

For each propulsion type, the monthly mileage and maintenance costs of all the buses were combined—based on the approximate age of each bus—into a cumulative average maintenance cost per mile. Although the buses accumulate mileage at slightly different rates, which are determined by their scheduled operation, this approach accounts for the impact of the age of the bus on the maintenance costs. The combined cumulative total cost trends for the four propulsion types investigated are shown in Figure 11.

Based on data available from the fleets evaluated, the combined FCEB trend line shows a higher initial maintenance cost per mile that quickly decreases during the first year of operation. This is likely attributed to increased learning curves for these transit agencies deploying the new technology (e.g., additional labor hours to train staff and to diagnose and repair unexpected issues). It could also indicate different warranty policies and levels of involvement from the vehicle manufacturers to support maintenance, as this varied between the ZEB deployments. For all bus types, the cumulative maintenance costs increase as the buses age. Although the bus evaluations analyzed here cover different lengths of time in service, the combined cumulative maintenance costs for each bus type are very similar—all in the range of $0.40–$0.46 per mile. In fact, applying a statistical test to compare the data sets representing each bus type reveals that there is greater variability in the per-mile cumulative maintenance costs within each data set (i.e., bus-to-bus variability) than between the data sets (e.g., BEB vs. FCEB or BEB vs. CNG). Thus, the differences in maintenance costs between bus types in this data set are not statistically significant (to a 95% confidence level). Another inherent challenge in determining maintenance costs for rapidly developing ZEB technologies is that data collected on ZEBs for 3–6 years of operation to inform an analysis of the long-term costs soon represent outdated generations of the technology, and OEMs have already improved upon those bus models/designs.

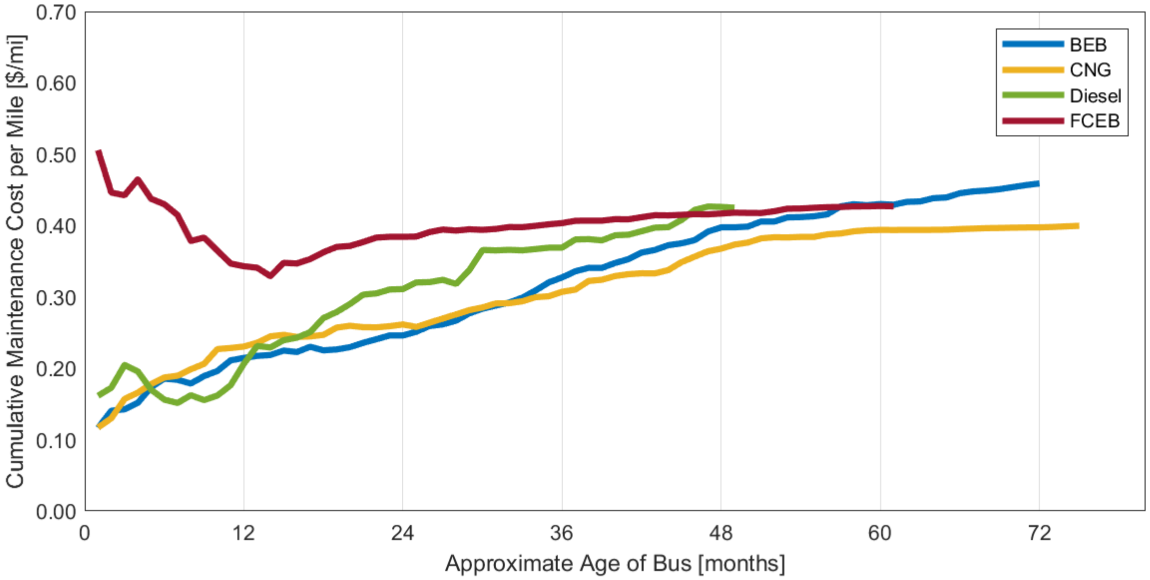


Figure 11. Combined cumulative maintenance cost per mile for BEBs, FCEBs, and CNG and diesel buses

These evaluations do not include planned midlife overhauls to the propulsion systems (i.e., refurbishment or replacement of engines, fuel cell stacks, or batteries) but may include repairs and replacements of those components, as needed, for any individual buses. The cost trends include scheduled and unscheduled maintenance on all vehicle systems (propulsion and non-propulsion). For the fleets analyzed, the fraction of propulsion-related maintenance costs, compared to total maintenance costs, varied from 11%–39% for BEBs, 23%–45% for CNG buses, 28%–32% for diesel buses, and 26%–49% for FCEBs.

In some cases, the propulsion systems for the zero-emission buses were less expensive to maintain, but the real-world maintenance costs from this limited data set were still highly dependent on the specific circumstances of these early deployments, such as route/service requirements, bus type and technology generation, maintenance and training practices, and level of support from the OEM. Maintenance costs are expected to decrease as transit agencies gain familiarity with maintaining and repairing ZEBs, and as replacement parts for propulsion systems become less expensive and more readily available from OEMs and other suppliers. It is important that all relevant technical information on these new technologies is transferred to transit agency staff and maintenance contractors and that robust training programs are established to prepare the transit workforce for properly maintaining zero-emission buses.

5. Incentive Funding Programs

ZEB financial incentive programs available to California transit agencies are made available through federal sources, especially the U.S. Department of Transportation and DOE; statewide funding sources in California such as CARB, California Energy Commission (CEC), California Department of Transportation (Caltrans), and California State Transportation Agency; and regional funding sources, such as those operated by air quality management districts (AQMDs) and air pollution control districts. Particularly important programs for ZEB deployments include the federal Low or No Emission Vehicle (Low-No) program and California's HVIP.

These types of transportation infrastructure investments help position California as the leader in the deployment of zero-emission technologies. Such incentive programs typically require a qualified transit agency to submit an application with procurement details and other agency information; the application is then reviewed with any questions posed. Once program funds are approved, they are typically awarded upon proof of actual bus purchase. In addition to vehicle capital cost support programs, other incentive programs target refueling infrastructure (especially electricity and hydrogen), operations and maintenance, and program planning grants.

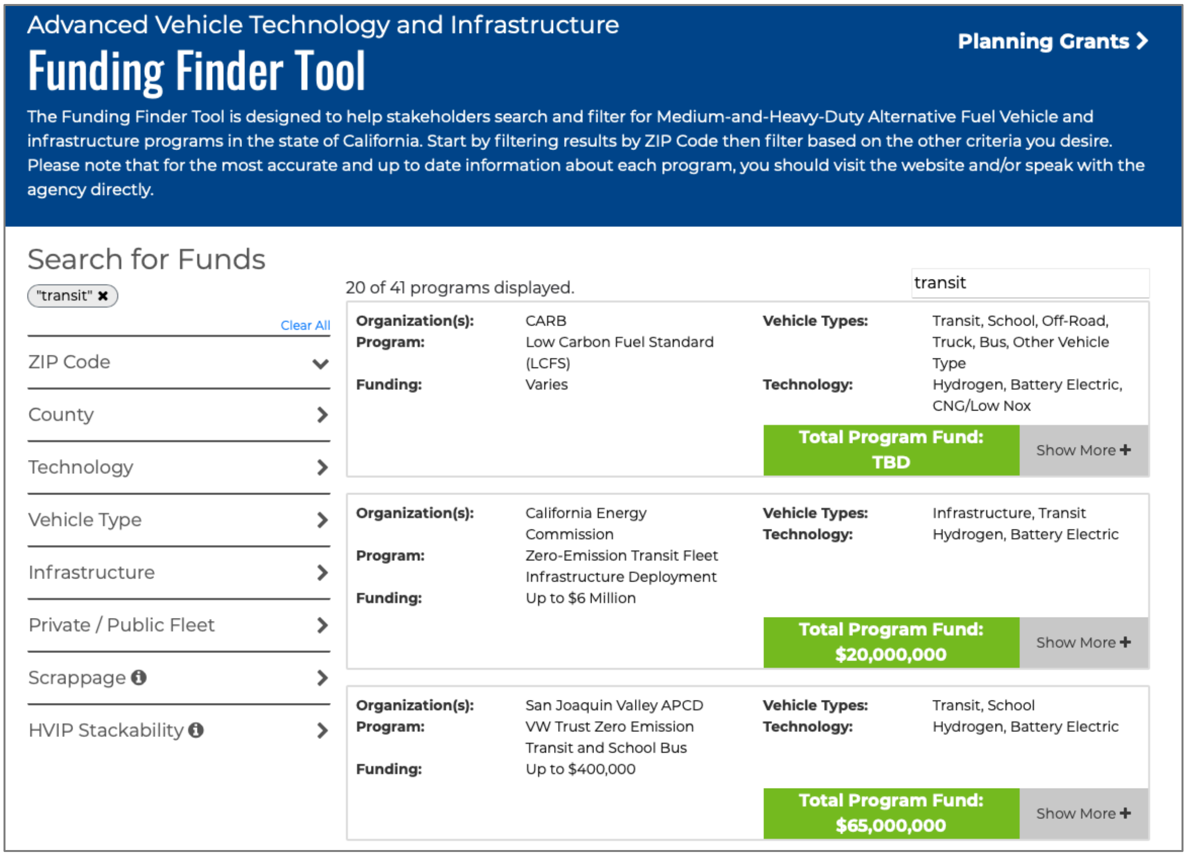
In recent years, considerable progress has been made to establish these incentive programs for ZEB purchases, as well as to make them more accessible to transit agencies through web-based program information and application sites and additional informational resources. The major ZEB incentive programs and other informational resources available for California transit agencies are summarized in this section.

5.1 Advanced Vehicle Technology and Infrastructure Funding Finder Tool

The Advanced Vehicle Technology and Infrastructure Funding Finder Tool was developed as a collaboration among various agencies, with the work led by CALSTART. It helps stakeholders search and filter for medium- and heavy-duty alternative fuel vehicle and infrastructure programs in California. The tool is a web-based resource for identifying the funding opportunities:

> Advanced Vehicle Technology and Infrastructure Funding Finder Tool:
> https://fundingfindertool.org/?keyword=transit

This resource currently lists 48 incentive programs, with the ability to search and sort them in various ways. Figure 12 shows the homepage for the funding finder tool, as well as the primary search categories.



Advanced Vehicle Technology and Infrastructure

Funding Finder Tool

The Funding Finder Tool is designed to help stakeholders search and filter for Medium-and-Heavy-Duty Alternative Fuel Vehicle and infrastructure programs in the state of California. Start by filtering results by ZIP Code then filter based on the other criteria you desire. Please note that for the most accurate and up to date information about each program, you should visit the website and/or speak with the agency directly.

Search for Funds

"transit"

20 of 41 programs displayed.

transit

Organization(s): CARB
Program: Low Carbon Fuel Standard (LCFS)
Funding: Varies
Vehicle Types: Transit, School, Off-Road, Truck, Bus, Other Vehicle Type
Technology: Hydrogen, Battery Electric, CNG/Low Nox
Total Program Fund: TBD

Organization(s): California Energy Commission
Program: Zero-Emission Transit Fleet Infrastructure Deployment
Funding: Up to $6 Million
Vehicle Types: Infrastructure, Transit
Technology: Hydrogen, Battery Electric
Total Program Fund: $20,000,000

Organization(s): San Joaquin Valley APCD
Program: VW Trust Zero Emission Transit and School Bus
Funding: Up to $400,000
Vehicle Types: Transit, School
Technology: Hydrogen, Battery Electric
Total Program Fund: $65,000,000

Figure 12. Advanced Vehicle Technology and Infrastructure Funding Finder Tool

The tool can be used to find funding programs that are available in specific ZIP codes. Other criteria that can be applied to narrow the scope of the search include requirements for vehicle scrappage; "stackability" of, for example, HVIP grants with other programs; and other eligibility requirements.

5.2 U.S. Federal ZEB Incentive Programs

At the federal level, incentive programs for ZEBs are primarily available through the U.S. Department of Transportation, specifically FTA. Programs are also available through DOE, especially for infrastructure funding. More information about the U.S. Department of Transportation and FTA incentive programs is discussed later in this section.

The Fixing America's Surface Transportation (FAST) Act of 2015 supported many transit funding programs from 2015–2020. The act provided over $300 billion for surface transportation, including public bus transit support opportunities through various program areas including the Accelerating Innovative Mobility, Better Utilizing Investments to Leverage Development (BUILD), Transportation Grants Program (formerly TIGER), Capital Investment Grants, and Grants for Buses and Bus Facilities programs.

On November 15, 2021, a major transportation infrastructure support package (H.R. 3684) known as the Infrastructure Investment and Jobs Act was officially signed into law. The extensive legislation—over $1 trillion in total over 5 years—includes a historically high level of funding for public transit at up to $108 billion. Key provisions of the legislation that are relevant for public transit buses include Section 30018 "Grants for Buses and Bus Facilities," Section 11130 "Public Transportation," and Section 30008 "Bus Testing Facilities" [117].

Section 30018 updates provisions of U.S. Code Title 49, Section 5339. This section provides for an overall increase in funding for buses and bus facilities up to about $2.2 billion per year. Minimum funding for each state in formula funds increased from $1.75 million to $4 million per state, and from $0.5 million to $1 million per U.S. territory. The breakdown in authorized funding for formula, competitive, and Low-No programs (discussed further below) are shown in Table 8.

Table 8. Funding Authorization for Grants for Buses and Bus Facilities in H.R. 3684 [118]

Fiscal Year	2022 (millions)	2023 (millions)	2024 (millions)	2025 (millions)	2026 (millions)
Formula Funds	$604	$617	$633	$646	$662
Competitive Grants	$376	$384	$394	$402	$412
Low-No Grants (competitive)	$1,122	$1,123	$1,125	$1,127	$1,128

Section 11130, funding for public transportation, updates provisions of U.S. Code Title 23, Section 142. The language in the section includes that the "Secretary may approve payment for carrying out a capital project for the construction of a bus rapid transit corridor or dedicated bus lanes, including the construction or installation of: traffic signaling and prioritization systems, redesigned intersections that are necessary for the establishment of a bus rapid transit corridor, on-street stations, fare collection systems, information and wayfinding systems, and depots." Specific funding levels for this section are not identified in the enabling legislation.

Finally, Section 30008 on bus testing facilities includes an update to U.S. Code Title 49, Section 5318 with the language: "A facility operated and maintained under this section may use funds made available under this section for the acquisition of equipment and capital projects related to testing new bus models." Further details and funding levels are not specified in this section.

5.2.1 U.S. Department of Transportation Programs

The U.S. Department of Transportation has additional established grant programs specifically for transit agencies; again, these are largely administered by FTA. These include the Low-No program, which had its most recent solicitation close on May 31, 2022. Historical funding for the program has ranged from $55 million in FY 2016, increasing to around $84 million in FY 2018, and then to nearly $130 million in FY 2020. In April 2021, a total of $182 million in funding was announced for 49 projects. As shown in Table 8 and in Figure 13, authorized funding for this program has now increased dramatically for FY 2022–2026 at about $1.1 billion per year under the Infrastructure Investment and Jobs Act (H.R. 3684). This represents a major shift in program priorities toward funding the lowest-emission bus technologies.

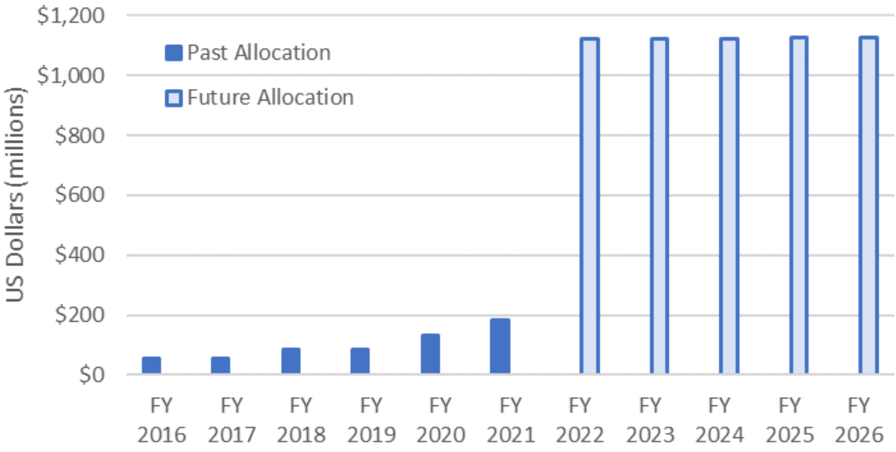


Figure 13. FTA Low-No program, past and future funding allocations [118,119]

The Low-No program provides funding for purchase or lease of zero- and low-emission transit buses, along with supporting infrastructure. Eligible projects include (1) purchasing or leasing low- or no-emission buses; (2) acquiring low- or no-emission buses with a leased power source; (3) constructing or leasing support facilities and related equipment, including intelligent technology and software; and (4) constructing, rehabilitating, or improving new public transportation facilities for low- or no-emission buses.

Program website: https://www.transit.dot.gov/lowno

The Low-No program is competitively awarded, where funds can be spent in the award year and for 3 additional years. A new program requirement is that any application for funding must now include a Zero-Emission Transition Plan. The cost of developing these plans cannot be covered with Low-No program funds but can be eligible for funding under planning grants and other formula funds [120].

Zero-Emission Transition Plan website: https://www.transit.dot.gov/funding/grants/zero-emission-fleet-transition-plan

The recent 2021 awardees under the Low-No program in California include the City of Anaheim, the City of Fresno, and the Golden Empire Transit Districts, each receiving approximately $2–$3 million. The City of Anaheim project is to support the implementation of BEBs to replace diesel buses, and the Fresno and Golden Empire district awards are to support the implementation of FCEBs in Fresno and a hydrogen station in Bakersfield.

There is also a Low and No-Emission Component Assessment Program (LoNo-CAP) at the U.S. Department of Transportation that funds institutions of higher education to work with component manufacturers and transit agencies to test new component technologies. Eligible activities include testing and assessing voluntarily submitted low- and no-emission components for transit buses, publishing the results of these component assessments, and preparing an annual report to Congress summarizing the assessment results. Although funding of $3 million per year was authorized in FY 2016, the last awards were made in FY 2017 to Auburn University and The Ohio State University [121]. With no recent awards, the future of this program remains unclear.

Program website: https://www.transit.dot.gov/research-innovation/lonocap

There is a Zero Emission Research Opportunity (ZERO) program at FTA that is designed to promote enhanced project management for fuel cell buses. The program was initially funded at $2.75 million in 2016, with the potential for additional funding. It was not funded for FY 2017–2020, but the program may be continued in the future. The program is described as follows:

> "In implementing ZERO, FTA will use a cooperative research model similar to FTA's successful National Fuel Cell Bus Program. Under this model, research and demonstration projects are defined and conducted by pre-selected non-profit consortia that, under FTA direction, assemble and manage project teams. Teams, comprised of transit agencies, vendors, suppliers, and others, will introduce an enhanced level of research management, program continuity, and flexibility to federally funded transit research. Through ZERO, FTA seeks to create a research environment that results in greater industry involvement and more innovative and successful projects."

Eligible activities and projects under this program include research, innovation and development, demonstration, deployment, and evaluation. Projects are intended to build on successful research, innovation, and development to facilitate the deployment of low- or zero-emission vehicles and associated advanced technology.

Program website: https://www.transit.dot.gov/funding/grants/grant-programs/zero-emission-research-opportunity-zero

5.3 California ZEB Incentive Programs

The California governor's annual budget proposal reflects the state's commitment to invest in zero-emission vehicles and advance climate change goals. There has been a significant increase of dedicated funds in FY 2021 and FY 2022 to support deployment of zero-emission vehicles. The latest FY 2022–2023 budget plan builds on momentum gained in 2021 from the Zero-Emission Vehicle Package that provides funds to put 1,000 zero-emission drayage trucks, 1,000 zero-emission school buses, and 1,000 zero-emission transit buses, as well as the necessary infrastructure, on California roads while prioritizing projects that benefit disadvantaged communities [122].

The FY 2022–2023 budget includes:

- $6.1 billion in new zero-emission transportation investments over 4 years, added to $3.1 billion in the previous year and including funds for transit and related infrastructure.
- $14.8 billion for regional transit, rail, and ports projects.
- $7.7 billion from the state general fund for the Transit and Intercity Rail Capital Program (TIRCP).
- Additional increases in road and transit formula funds of up to $2.2 billion per year from the federal Infrastructure Investment and Jobs Act.

There are several California state agency incentive programs that are available to transit agencies for potential procurements of ZEBs and associated infrastructure. These are primarily offered by

CARB and CEC. Additional agencies such as Caltrans and the California State Transportation Agency provide funding to help modernize the state's transit systems. Caltrans administers funds from the Low Carbon Transit Operations Program (LCTOP), and the California State Transportation Agency administers TIRCP funds. Collectively, these funds can support the state's transportation improvement programs.

5.3.1 CARB HVIP Program

One of the most important incentive programs for California transit bus agencies is CARB's HVIP. HVIP provides point-of-sale price reduction vouchers to approved applicants, which makes zero-emission transit buses more affordable. This long-standing program funded the first transit agency fuel cell bus at SunLine Transit in 2009 and has funded many other transit bus and other heavy-duty vehicle clean fuel and electrification programs. Many transit agencies interviewed for this report applied for and received HVIP vouchers. For example, Foothill Transit received HVIP vouchers to help reduce capital costs of $8.91 million to purchase 33 FCEBs in 2021. A total of 172 ZEBs have received HVIP vouchers. As of June 8, 2022, a list of new transit buses currently available in the HVIP Vehicle Catalog includes battery-electric and hydrogen fuel cell buses and vehicle incentives that range from $85,000 to $240,000 per eligible vehicle [123]. According to the HVIP impact map, as of June 8, 2022, a total of 604 vouchers totaling approximately $90 million have been awarded to public transit agencies for zero-emission BEBs and zero-emission FCEBs [124].

Program website: https://californiahvip.org/

New HVIP policies were approved by CARB on November 19, 2021 [125]. Significant changes to the program were made for FY 2022 including a $70-million carve-out set aside for transit buses. Additional provisions include an increase in voucher bonuses from 10% to 15% for vehicles domiciled in disadvantaged communities, for smaller fleets with 10 or fewer buses. HVIP opened on March 30, 2022, for voucher applications with $70 million in funding set aside for zero-emission transition bus incentives [126]. As of June 8, 2022, $53 million remains available to transit agencies in the category set aside for public transit buses [127].

Funding program website: https://californiahvip.org/funding/

5.3.2 California Energy Commission Programs

CEC awards grant funds especially for infrastructure projects to support clean-fuel, heavy-duty vehicle deployments, complementing funds to help support procurements for the vehicles themselves that typically come from Caltrans, CARB, and local air districts. CEC has awarded hundreds of millions of dollars in recent years for battery-electric vehicle infrastructure and hydrogen fueling infrastructure in support of light-duty and heavier-duty vehicle applications of zero-emission vehicle deployments.

CEC has recently released details of its multiyear funding plan for the Clean Transportation Program for FY 2021–2023. The focus of the program is on zero-emission vehicles and infrastructure and includes a total of nearly $1.4 billion across a series of programs for light-, medium-, and heavy-duty vehicles and infrastructure; zero- and near-zero-emission fuel production; ZEV manufacturing; and workforce development programs. The program leverages $238 million in direct funding along with $1.13 billion in general funds that are to be administered through the Clean Transportation Program. A total of $690 million is targeted at medium- and heavy-duty vehicles and infrastructure that are based on battery and hydrogen fuel cell technologies [128].

> Program website: https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program

CEC has also announced the “Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles” (EnergIIZE Commercial Vehicles) program. The program is currently being designed with CALSTART as the contractor that will administer the funding, targeted at supporting the development of recharging and refueling infrastructure for medium- and heavy-duty zero-emission vehicles, including transit buses. Over multiple years, the program will provide $50 million in infrastructure projects related to zero-emission vehicles, starting with an initial allocation of $17 million. The program is particularly targeted at projects in and around low-income communities that bear the heaviest burden of pollution from conventional commercial vehicles [129].

> Program website: https://www.energy.ca.gov/proceedings/energy-commission-proceedings/energy-infrastructure-incentives-zero-emission-commercial

There also are CEC infrastructure blueprint grants, ranging from $3–$6 million per year in total funding. These grants are targeted to “identify actions and milestones needed for implementation of medium- and heavy-duty (MD/HD) zero-emission vehicles (ZEVs) and the related electric charging and/or hydrogen refueling infrastructure.” The last awards were made in early 2021, with 28 awards for a total of $5.6 million. A relatively small number of these awards were specifically for transit agency ZEB projects, with the majority targeted at truck/freight and school bus projects.

> Program website: https://www.energy.ca.gov/solicitations/2020-07/gfo-20-601-blueprints-medium-and-heavy-duty-zero-emission-vehicle

5.3.3 California State Transportation Agency and Caltrans Programs

Caltrans operates the LCTOP, one of several funding programs that are part of the Transit, Affordable Housing, and Sustainable Communities Program established by the California Legislature in 2014 by Senate Bill 862. The LCTOP is designed to reduce GHG emissions and improve mobility, with a priority focus on disadvantaged communities. Caltrans is responsible for ensuring that LCTOP meets statutory requirements in terms of project eligibility, GHG reduction, disadvantaged community benefits, and other requirements of the law [130].

Eligible transit agencies must quantify GHG reductions in their projects and prioritize disadvantaged and low-income communities. Past LCTOP recipients received funding to replace diesel electric buses with ZEBs, as well as to construct a hydrogen fueling station. In addition, the program funds new or expanded bus or rail services, intermodal transit facilities, and implementation of facility and operational support (such as free or reduced fares).

A total of over $146 million was awarded in 2019–2020 to 166 programs across 12 Caltrans districts. Many of these were relatively small awards for operation support, but examples of the larger awards include $2.9 million to Orange County Transportation Authority to match other grant funds to purchase 10 BEBs and associated charging infrastructure; North County Transit District will receive about $2.2 million to purchase six BEBs and eight FCEBs; Omnitrans will receive $3.2 million to purchase five ZEBs; San Francisco Municipal Transportation Agency will receive $3.3 million to purchase three long-range BEBs; Santa Clara Valley Transportation Authority will receive $2.4 million to support purchase of 15–20 BEBs; and San Diego Metropolitan Transit System will receive $6 million to purchase 14 ZEBs in the future to replace aging CNG buses. In the largest award, Los Angeles County Metropolitan Transportation Authority will receive $39 million for a major BEB charging facility, including new stationary and portable charging equipment. Because this is a formula program, it can be difficult for transit agencies to use these funds to build a hydrogen fueling station due to the allocation amounts, unless they can combine funds from multiple programs.

Requests for LCTOP funding for FY 2021–2022 were accepted through March 25, 2022. Caltrans and CARB plan to submit their list of approved projects to the State Controller's Office in mid-June 2022, with funding to be released on June 30, 2022 [130].

> Program website: https://dot.ca.gov/programs/rail-and-mass-transportation/low-carbon-transit-operations-program-lctop

The Transit and Intercity Rail Capital Program (TIRCP) was developed to "provide grants from the Greenhouse Gas Reduction Fund to fund transformative capital improvements that will modernize California's intercity, commuter, and urban rail systems, and bus and ferry transit systems, to significantly reduce emissions of greenhouse gases, vehicle miles traveled, and congestion." TIRCP funding comes from Senate Bill 1 and a continuous (through 2030) appropriation of 10% from the quarterly cap-and-trade auction proceeds deposited in the Greenhouse Gas Reduction Fund. The California State Transportation Agency administers TIRCP funds.

TIRCP funds capital projects, including feeder buses to intercity rail services, as well as vanpool services that are eligible to report as public transit to FTA. Also included are ferry and rail transit system projects. There have been three prior cycles of TIRCP funding, in which the California State Transportation Agency awarded $5.3 billion in funding to 56 projects around the state. The 2018 funding cycle funded almost 300 ZEBs, and the 2020 funding cycle supported 37 ZEBs [131,132].

Recent additions to the 2021 TIRCP guidelines support transit agencies that need to retire their aging fleet. Cycle 5 funding guidelines included a new category to help transit agencies recover capital costs in their transition to ZEVs and associated infrastructure costs for fueling and charging. The Clean Fleet and Facilities Network Improvement category was added in 2021 to provide additional support and funding to transit agencies deploying ZEVs [133].

Funding for the 2022 TIRCP cycle will be awarded to applicants in June 2022, and awards will include 2022 projects as well as previously awarded and active Cycle 3 and 4 projects that were not fully allocated by the end of FY 2021–2022 for various reasons.

> Program website: https://calsta.ca.gov/subject-areas/transit-intercity-rail-capital-prog

Many agencies interviewed for this report indicated that they plan to continue to take advantage of funding incentives for future bus procurements through the LCTOP and TIRCP funding programs.

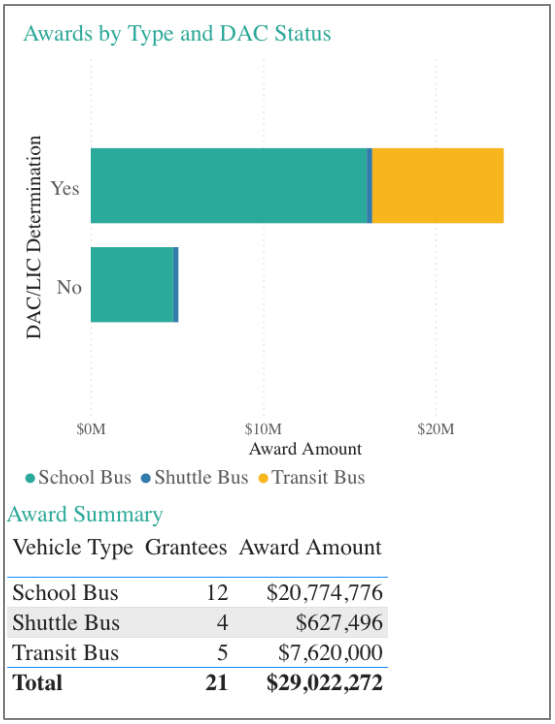
5.3.4. Volkswagen Environmental Mitigation Trust

The Volkswagen Environmental Mitigation Trust was established from a legal settlement in response to Volkswagen’s use of illegal emissions testing defeat devices in certain Volkswagen diesel vehicles. A total fund of $2.9 billion was established for the mitigation trust, of which $423 million was designated for California specifically.

The California mitigation trust program is divided into three program areas: (1) zero-emission transit, school, and shuttle buses; (2) zero-emission trucks and combustion freight and marine; and (3) zero-emission freight, marine, and infrastructure. The zero-emission bus program has $130 million to help replace older buses with new battery or fuel cell electric buses [134].

Awards through the mitigation trust have totaled about $29 million through mid-2021 (Figure 14). The transit bus awards have been directed at communities with disadvantaged or low-income community status, as shown in Figure 14.

Program information: https://ww2.arb.ca.gov/vwmitigationtrust



Award Summary

Vehicle Type	Grantees	Award Amount
School Bus	12	$20,774,776
Shuttle Bus	4	$627,496
Transit Bus	5	$7,620,000
Total	**21**	**$29,022,272**

Figure 14. Volkswagen Environmental Mitigation Trust expenditures by type and DAC status [135]

5.4 California State Regulations and Support Programs

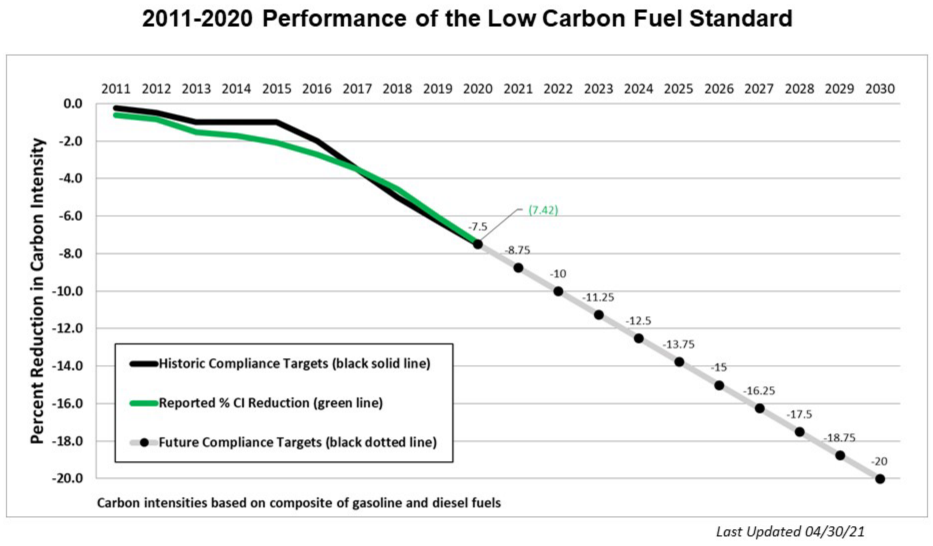
5.4.1 Low Carbon Fuel Standard Regulation

In addition to direct support for ZEBs and infrastructure from the incentive programs described in this report, California also has a Low Carbon Fuel Standard (LCFS) program that is a regulation for stimulating investments and implementation of low-carbon fuels for vehicles. The LCFS regulation was designed to reduce GHG emissions and provide to California's transportation sector an increasing range of low-carbon and renewable alternative fuels such as hydrogen and electricity. This regulation provides strong support for implementation of clean fuels based on recent credit prices, providing a market-based policy designed to reduce the carbon intensity of transportation fuels in the state.

The California LCFS was first adopted in 2009 as part of the state's overarching Global Warming Solutions Act (AB 32) with the goal of achieving a 10% reduction in carbon intensity from 2010 values by 2020. The LCFS was then amended several times, partly in response to litigation about the treatment of fuels being imported from out of state. The last amendment in 2018 included additional methods of receiving credits and with a 20% carbon intensity reduction level from the 2010 baseline. This update also promoted further zero-emission vehicle adoption and carbon capture and sequestration techniques. The 2018 amendment also provided support for the deployment of zero-emission infrastructure. The LCFS provides credits for installing ZEV infrastructure based on the capacity of the hydrogen station or EV fast charging site [136].

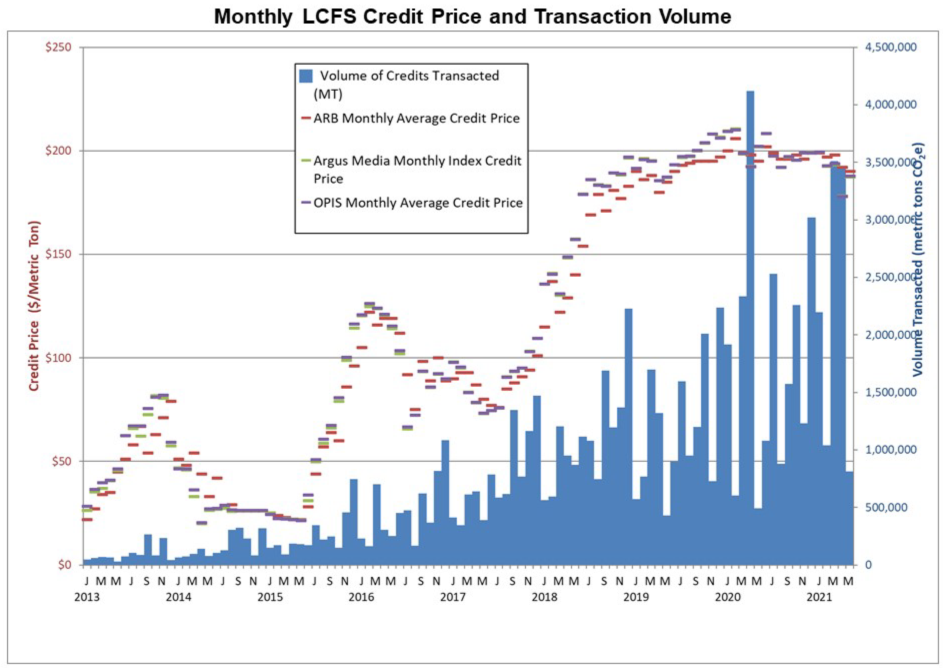
LCFS establishes a market mechanism to incentivize the production of low-carbon fuels and renewable alternative fuels. LCFS credit prices were fairly constant from 2019 through 2021, trading in the band of about $180–$200 per credit (see Figures 15 and 16). The impact on overall fuel prices can be significant when low-carbon-intensity fuels such as electricity and hydrogen are adopted by transit agencies. For example, at a credit price of $196 per credit and a replacement fuel with a carbon intensity score of 30 (versus about 90 for conventional alternatives), the credit value is estimated at $1.44 per gallon equivalent [137]. This equates to about $0.26/kWh based on a California grid mix for BEB charging, covering most or all of the total electricity cost, and about $1.44 per kilogram of hydrogen produced with an (example) fuel production pathway and carbon intensity score of 30.

However, in 2022, credit prices have declined to a low of about $80 per credit in June 2022 but then rebounded to about $100 per credit in July. These fluctuating prices complicate the value of the LCFS program for transit agencies as they plan to adopt lower-carbon-intensity—but in some cases, higher-cost—renewable fuels relative to the conventional alternatives. The value of credits is further eroded by brokerage fees that typically must be paid to capture the credits.



This figure shows the percent reduction in the carbon intensity (CI) of California's transportation fuel pool. The LCFS target is to achieve a 20% reduction by 2030 by setting a declining annual target, or compliance standard. The compliance standard was frozen at 1% reduction from 2013-2015 due to legal challenges, contributing to a build-up of banked credits as regulated parties bringing new alternative fuels to market continued to over-comply with the standard. The program will continue post 2030 at a to be determined stringency.

Figure 15. 2011–2020 performance of the Low Carbon Fuel Standard [137]



This chart tracks credit prices and transaction volumes over time. Monthly average credit prices reported by Argus Media and OPIS [used with permission] are shown along with CARB monthly average price.

Figure 16. Monthly LCFS credit price and transaction volume [137]

5.4.2 Group Bus Procurement

Group bus procurement has been utilized to reduce cost and improve efficiency. This becomes more important for ZEBs as more specifications are expected to be identified for each ZEB procurement. California's Department of General Services has secured a statewide contract for ZEB procurements that covers multiple manufacturers, fuel types, and models [12]. This contract also meets FTA's bus procurement criteria. Besides California, similar zero-emission bus statewide contracts have been released or are underway by other states such as Washington state's Department of Enterprise Service, Georgia's Department of Administrative Services, and Virginia's Department of General Services [138]. In addition, transit agencies have also been putting out joint procurement solicitations for transit buses to relieve the procurement burden for many of the participating agencies. For example, in February 2021, Morongo Basin Transit Authority, on behalf of the California Association for Coordinated Transportation member agencies, issued a request for proposal (RFP-20-01) of a joint procurement for the manufacture and delivery of accessible transit/paratransit vehicles, which also included BEBs [13].

5.5 California Regional ZEB Incentive Programs

At the regional level, ZEB incentive programs are primarily provided at the AQMD level, although these programs are variable and typically focused more on light-duty vehicles and heavy-duty vehicles for trucks/ports than public transit agency buses. Also at a regional level, the major electric utilities in California are offering incentives for installing BEB charging infrastructure. These programs are listed in the following sections.

5.5.1 Air Quality Management District Programs

California includes 35 regional AQMD and air pollution control district (APCD) areas, including the South Coast AQMD, Bay Area AQMD, Sacramento Metro AQMD, and San Joaquin Valley APCD. These AQMD/APCD programs typically focus on stationary sources of pollution such as oil refineries, large food-processing centers, cement manufacturing, and other industrial sources, with a particular focus on particulate matter emissions and precursors to ozone production such as nitrogen oxides and volatile organic compounds. They historically have provided some funds for vehicle retrofit technologies such as particulate matter filters, especially for trucks, but have also been supportive of clean transit programs through various coordinated efforts with local transit agencies.

Links to the major air district programs addressing clean transportation and additional details are provided below:

- Bay Area AQMD – MD and HD ZEV and Infrastructure Program
    - http://www.baaqmd.gov/hdzev
        - "Up to $5 million is available for fiscal year ending (FYE) 2016."
        - "The FYE 2016 cycle closed on June 22, 2016."
        - The program allows subscription to receive information about future developments and solicitations.
- Bay Area AQMD – Carl Moyer Program
    - https://www.baaqmd.gov/?sc_itemid=7A9A5ACC-1CD1-41E9-B429-7BFDAE17FEF3
        - For 2022 application cycle, "more than $40 million is available for projects to upgrade or replace on-road vehicles, school buses, off-road and agricultural equipment, marine equipment, and locomotives."
        - Funding provided on first-come, first-served basis and can go toward vehicle replacement, engine replacement, power system conversion, or battery charging and hydrogen fueling infrastructure.

- Bay Area AQMD – Community Health Protection Grant Program
    - https://www.baaqmd.gov/community-health/community-health-protection-program/grant-program.
- Sacramento Metropolitan AQMD
    - http://www.airquality.org/Businesses/Incentive-Programs
    - Provided up to $18 million in most recent solicitation that closed in May 2021 for ZEBs and zero-emission trucks.
- San Joaquin Valley Air Pollution Control District – Volkswagen Trust Zero-Emission Transit and School Bus
    - http://vwbusmoney.valleyair.org/
    - See Section 5.3.4: Volkswagen Environmental Mitigation Trust.
- South Coast AQMD – Clean Technology programs
    - http://www.aqmd.gov/home/programs
    - Vehicle and Engine Upgrades programs available: http://www.aqmd.gov/home/programs/business/business-detail?title=vehicle-engine-upgrades.
- South Coast AQMD – Carl Moyer Program
    - http://www.aqmd.gov/home/programs/business/business-detail?title=heavy-duty-engines&parent=vehicle-engine-upgrades
    - Vehicle and Engine Upgrade Programs (e.g., Carl Moyer, Clean School Buses): http://www.aqmd.gov/home/programs/business/business-detail?title=vehicle-engine-upgrades.

5.6 Electric Utility Programs

Programs sponsored by major electric utilities in California include “make-ready” programs to develop electrical charging infrastructure, as well as vehicle rebate programs, charger installation rebate programs, and interim rate designs for electricity charging costs. Historically, the utility rate structures for medium and large commercial and industrial facilities have included “demand charges” that require payments for peak energy usage per month, as well as “energy charges” for actual kilowatt-hours of electricity delivered. To help transit agencies adjust to increased use of electricity for bus charging, some utilities have eliminated demand charges on a temporary basis for these EV rate structures. However, there are plans to reintroduce these utility demand charges in the coming years, and transit agencies should carefully review and understand these changes for financial planning purposes around fuel shifting from diesel and CNG to electricity and hydrogen.

The major California utility programs are provided by Southern California Edison (SCE), Pacific Gas and Electric Company (PG&E), San Diego Gas and Electric Company (SDG&E), and Sacramento Municipal Utility District (SMUD). These are summarized below:

- SCE – Charge Ready Transport Program
    - https://crt.sce.com/overview
    - “SCE’s Charge Ready Transport (CRT) Program offers low- to no-cost electrical system upgrades to support the installation of electric vehicle (EV) charging equipment for qualifying vehicles.”

    - SCE will help with planning and installation, as well as "install a separate meter dedicated to the EV charging infrastructure and waive customer demand charges through 2024 with our commercial EV rates."
    - In return, the customer must convert vehicles to electric and keep chargers active for 10 years, as well as provide charging data for 5 years.
- PG&E – EV Fleet program
    - https://www.pge.com/en_US/large-business/solar-and-vehicles/clean-vehicles/ev-fleet-program/ev-fleet-program.page
    - Incentives for medium- and heavy-duty vehicle electrification.
    - Provides incentives and rebates for vehicles and chargers.
    - Also helps with planning, installation, and maintenance of relevant infrastructure.
    - Requires 10-year commitment and sharing of data with PG&E.
- SDG&E – Power Your Drive for Fleets program
    - https://www.sdge.com/business/electric-vehicles/power-your-drive-for-fleets
    - Similar to other utility programs, assists with installation of electrification infrastructure.
    - No costs to property owner for utility-owned charging infrastructure, but note that any support structural infrastructure and some site work is typically not covered.
    - Rebates are available for different tiers of chargers.
    - Can also be combined with local and state programs to help with funding of electric vehicles: https://www.sdge.com/sites/default/files/documents/SDGE.PYDFF%20-%20Vehicle%20Funding%20Summary%20-%20Feb%202021.pdf.
- Sacramento Municipal Utility District (SMUD) – Commercial EV Fleet program
    - https://www.smud.org/en/Going-Green/Electric-Vehicles/Business
    - Program helps businesses with commercial vehicles, including light-duty cars, trucks, or semi-tractors, and organizations (like school districts) with purchase of electric vehicles, with fixed rate incentives for different vehicle classes.

5.7 Transit Agency Experience and Use of Incentive Programs

Many of the transit agencies interviewed highlighted the critical importance of incentive programs to provide capital cost assistance for new buses and infrastructure, as well as additional support programs. Some agencies indicated an interest and need for additional information about the full range of available funding programs, but others said they have enough information and are knowledgeable of the programs relevant for their agency. They stressed a desire for the funding to flow as effectively as possible and with the least amount of administrative difficulty. This includes improving the application processes and timelines to make it easier for transit agencies to combine funding awards from multiple federal, state, and regional incentive programs.

Many of the agencies interviewed have taken advantage of the HVIP and/or Low-No programs and are planning to do so with their next procurements. Other programs were used to a lesser extent among the agencies interviewed; those include the Carl Moyer Program, the LCTOP, California Energy Commission projects supporting infrastructure, regional programs provided by South Coast AQMD and Bay Area AQMD, the Volkswagen Electrify America program, and utility "make-ready"-type programs such as those administered by SCE.

These funding programs can significantly offset the upfront cost of ZEBs at this early stage, and the LCFS program will provide continued monetary returns for operating ZEBs without a sunset date. Despite recent announcements of increased funding levels for commercial electrification programs at the federal, state, and regional levels, transit agencies planning for ZEB transition still cite funding assistance as one of their most significant needs to comply with upcoming ICT ZEB purchase requirements. Additional funds are needed to purchase vehicles, install charging/fueling infrastructure, and train their workforce for operating and maintaining the ZEBs.

6. ZEB Economic Modeling

NREL developed the Vehicle and Infrastructure Cash-Flow Evaluation (VICE) model to evaluate the relative impact of a range of economic inputs on the purchase and operation of ZEBs and charging/fueling infrastructure in comparison to conventional buses. The VICE model is a discounted cashflow model with outputs including relative net present value (NPV), discounted payback period, and return on investment over the life of a bus fleet. For this comprehensive review, the VICE model was used to evaluate "typical" ZEB economics with a focus on relative sensitivities to key economic parameters using California-based inputs. The VICE model is not used to determine costs for a specific transit agency or make predictions about cost trends in the ZEB industry—the model results are scenario-based, and different transit agencies will have different outputs based on the transit agency's own information. Rather, it is used to provide insights into the comparative costs between the purchase and operation of advanced technology buses compared to conventional buses over a range of input assumptions, and to highlight the primary factors affecting the economics of the bus purchases. More details on the background of the VICE model can be found in *Financial Analysis of Battery Electric Transit Buses* [139].

VICE model inputs include the major cost components for the purchase and operation of new buses and related infrastructure, for both conventional buses and ZEBs, as the model compares the economics of the two options. VICE model outputs include NPV, discounted payback period, and simple payback period for a range of economic inputs calibrated to California transit markets. CNG was used as the comparison since it is the most common fuel for transit buses in California. Transit service and fares were assumed to remain the same regardless of fuel type. This section develops baseline investments in BEBs and FCEBs with fleet parameters that were estimated for California. We assess the economics of the baseline investments, then evaluate the sensitivity of key input parameters by adjusting them from minimum to maximum estimated realistic values and determining the impact on the model outputs. Findings from the VICE model are useful as an indicator of the relative economic impacts of cost parameters for entities developing incentive programs for ZEBs and for fleets considering ZEB investments. It is recommended that in addition to reading this report, fleets model their exact financial investment by downloading the VICE model from the Alternative Fuels Data Center [140].

6.1 Battery-Electric Buses Compared to CNG Buses

The first investment to be analyzed is the purchase of BEBs and chargers instead of CNG buses. The input parameters for this investment and the source or rationale for these parameters are outlined in Table 9. The CNG inputs represent forgone CNG buses—the buses that would have been procured if they hadn't been replaced by BEBs. California-specific values and sources were used whenever possible, and nationwide values were used otherwise.

Table 9. BEB and CNG Bus Input Assumptions for the Baseline Scenario

	Parameter	Value	Unit	Source
General	Number of electric buses obtained	25	vehicles	Rollout plans for ZEBs [1]
	Average life of bus	12	years	APTA procurement guidelines [141]
	Discount rate or required rate of return	3.6	%	5-year annual returns on Standard & Poor's municipal bond index [142]
	Average annual miles traveled	44,061	miles per bus	APTA 2020 fact book [143], in agreement with CARB [24]
	Residual (end-of-life) value of bus	2	% of price	Laver et al. [144], updated with fleet input from AC Transit, RTC, and San Joaquin Regional Transit District
CNG Bus	Purchase price of new 40-ft CNG bus	598,680	$/bus	APTA 2020 vehicle database, 2019–2021 weighted average [101]
	Fuel economy of CNG buses	4.03	mpdge [a]	Meta-analysis of NREL bus fleet evaluations
	CNG fuel price	1.30	$/DGE [b]	Average price of six California depots, adjusted to 2022 dollars [24]
	CNG price increase	−0.5	%/year	U.S. Reference case 2020–2050, Annual Energy Outlook [145]
	CNG vehicle maintenance	0.85	$/mile	CARB [24]
Electric Bus	Purchase price of 40-ft battery-electric bus	861,886	$/bus	APTA 2020 vehicle database, 2019–2021 weighted average [101]
	Grant amount	5.8	million $	Average 2016–2020 Low-No grant [119] plus HVIP grant of $150,000/vehicle
	Electric bus efficiency	2.18	kWh/mile	Altoona testing results, unweighted average from seven 40-foot BEBs [67]
	Battery life	12	years	From cycle-based calculations, preliminary field reports [146], and manufacturer warranties
	BEB vehicle maintenance costs	0.43	$/mile	Meta-analysis of NREL fleet evaluations
	Price of electricity	0.1311	$/kWh	Applicable PG&E and SCE EV rates (servicing 78% of California customers) [147–149]
	Electricity price increase	−0.20	%/year	Reference case, Commercial Electricity Price 2020–2050 Annual Energy Outlook [145]
	Utility monthly subscription/flat fee	2,023	$/month	Applicable PG&E and SCE EV fees (servicing 78% of California customers) [147–149]

	Parameter	Value	Unit	Source
Charger	Number of chargers	25	chargers	One depot charger per vehicle
	Charger price	50,000	$/charger	Depot chargers, per Hanlin et al. [107]
	Installation cost	17,050	$/charger	Facility-level upgrades, per Hanlin et al. [107]
	Peak charger draw	70	kW	Chargers for overnight charging
	Charger efficiency	91	%	Eudy and Jeffers [114,146]

[a] Miles per diesel gallon equivalent.
[b] Diesel gallon equivalent.

Most baseline parameters are explained sufficiently by Table 9, but some need elaboration. The grant amount includes Low-No and HVIP funding because, as described in Section 5, these are the most important, applicable, and broadly available of all funding sources in California. The Low-No funding is $2 million—the average size of 2016–2020 grants regardless of fleet size because these grants are not directly tied to the number of buses. In addition to the Low-No funding, HVIP grants were applied, which are assumed to be tied to the number of buses ($150,000/bus, including a $12,000 incentive for operating in a disadvantaged community). Since Low-No grants are awarded on a more limited, competitive basis and may be challenging to combine with HVIP, we modeled a scenario that includes only the HVIP grant of $150,000 per BEB. Depot chargers were assumed for the baseline scenario because they are much more common than on-route chargers, and it is assumed that there is one for each BEB in the fleet. Pantograph chargers will be explored in the following sensitivity analysis. CNG bus maintenance costs were taken from CARB since they were California-specific numbers [3]. However, bus maintenance costs for BEBs are based on NREL's meta-analysis described in Section 4.3.3 because CARB did not have actual data for these inputs, but derived estimates based on a literature review.

The electricity rates are derived from the commercial EV rates offered by PG&E and SCE, since these two utilities split 78% of California's population.[1] As shown in Figure 17, these rates include both an energy charge ($/kWh) and a monthly subscription fee ($/month) that are tied to peak demand. Both rates were averaged between the two utilities, with the energy charge of $0.13/kWh across the demand ranges explored and the equation for the monthly subscription fee as follows:

$$\text{Subscription fee} = 1.0462 \times (\text{peak demand}) + 181.9 \qquad \text{Equation (1)}$$

It should be noted that the PG&E rate for low peak demand is BEV-1, then transfers to BEV-2-S (with secondary voltage because no investment in a transformer is assumed) at peak demand of 50 kW or more. For SCE, TOU-EV-8 is used below 500 kW peak demand and TOU-EV-9 is assumed for all fleets with 500 kW or greater peak demand.

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[1] Based on estimates from PG&E [150]and SCE [151].

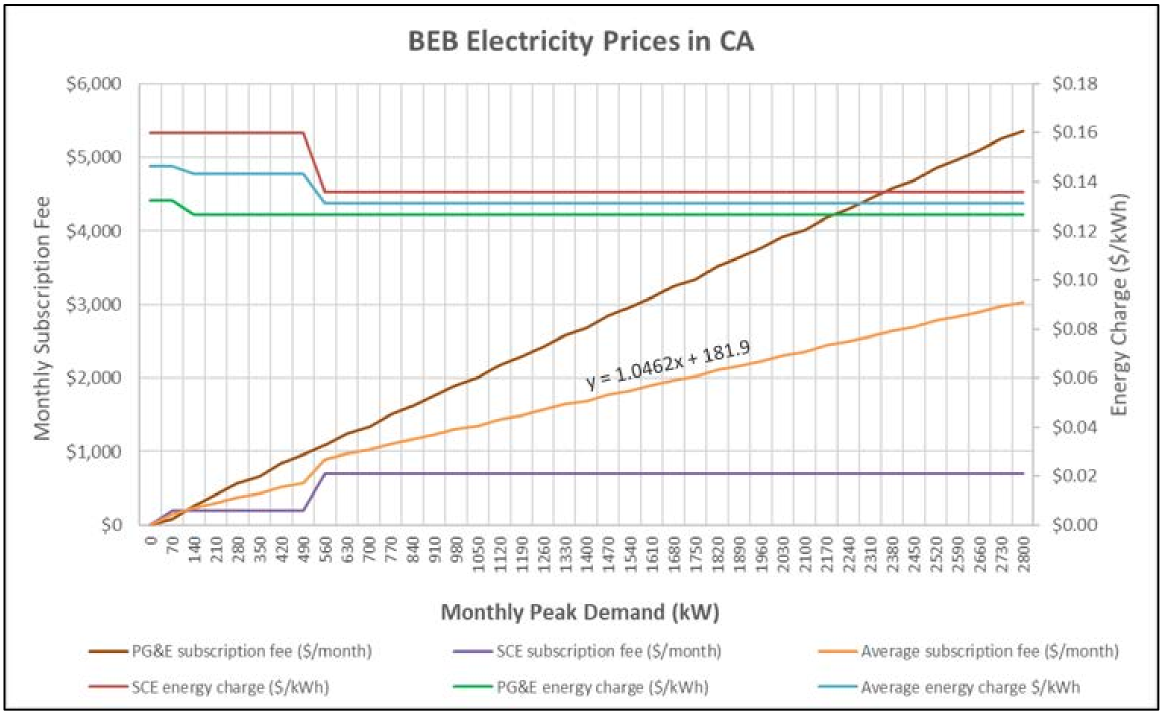

Figure 17. Combination of the applicable EV electricity rates from PG&E and SCE [147–149]

6.1.1 VICE Results for Battery-Electric Buses Baseline Scenario

The baseline scenario for purchasing 25 standard 40-foot BEBs instead of CNG buses resulted in an NPV of almost $2.0 million, with a discounted payback of 6.2 years and simple payback of 5.5 years, as shown in Figure 18. The difference between the discounted and simple paybacks is that the discounted payback assumes that money decreases in value every year to compensate for the amount that could have been made in an alternative investment. For the economic inputs outlined in Table 9, Figure 18 shows that the substantial investment for the purchase of 25 buses costing over $2.3 million in year 1 is more than made up for by reduced operating costs throughout the 12-year life of the buses. At the end of 12 years, the 25 buses are retired and the NPV of the project is a positive $2.0 million.

Removing the Low-No grant (HVIP-only scenario) reduced the 12-year lifetime NPV of the baseline scenario from $2 million to −$55,000 for the 25-BEB fleet. This scenario is near cost parity given all the other input assumptions, with a simple payback period of approximately 10 years and a discounted payback period slightly longer than the targeted 12-year expected life of the bus. This scenario can result in a positive NPV if the required rate of return is decreased from 3.6% down to 3.4% or the annual miles traveled is increased from 44,061 to 44,591 miles.

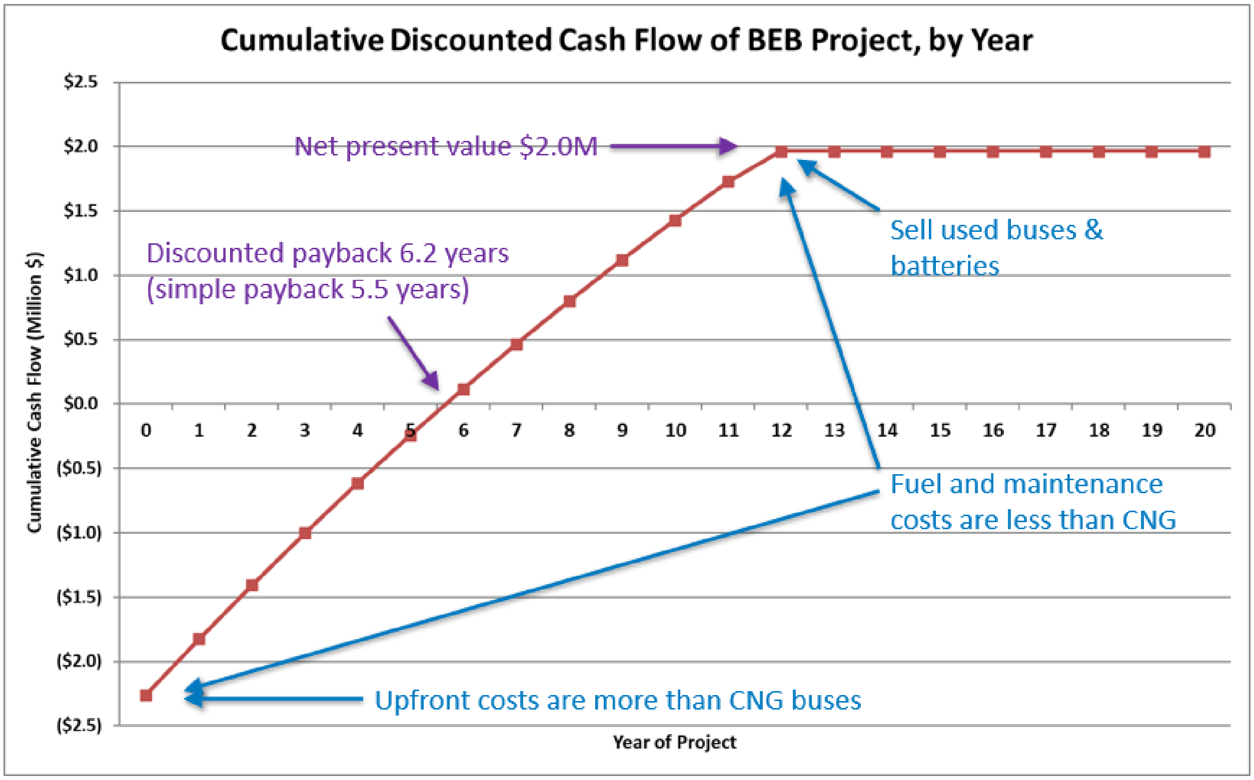

Figure 18. Payback schedule of BEB baseline investment

6.1.2 Sensitivity Analyses for BEB Investment Parameters

Because no fleet exactly matches the baseline fleet modeled here, we need to analyze deviations from this baseline to determine what fleet characteristics make a BEB procurement more likely to be profitable. This will help determine which fleets are likely to have a profitable BEB investment, and it can steer fleets to make procurement or operational changes that increase their likelihood of a profitable investment.

In order to analyze the impact of these parameters on investment economics, we first had to determine the realistic maximum and minimum values for model input parameters. These values, along with their sources or justification, are displayed in Table 10. Values that were more consistent, with little deviation from their baseline values, were omitted because their variations are unlikely to have a large impact on overall project economics.

Table 10. Maximum and Minimum Values for CNG to BEB Sensitivity Analyses

Note: Parameters in this table were placed in order of highest sensitivity to lowest. Many parameters were not included because their range was too narrow.

Parameter	Minimum	Maximum	Unit	Source
BEB purchase price	$787,375	$975,162	$/bus	California ZEB rollout plans, 25th and 75th percentile
CNG fuel price	$0.94	$4.41	$/DGE	Alternative Fuel Price Report, July 21 [140]. West Coast CNG. LA Airport (max.) and City of Sacramento (min.)
CNG maintenance costs	$0.22	$1.02	$/mile	Meta-analysis of NREL fleet evaluations and CARB 2018 +20%
CNG bus purchase price	$491,622	$658,887	$/bus	2020 APTA vehicle database [101]
BEB maintenance costs	$0.25	$0.57	$/mile	Meta-analysis of NREL fleet evaluations
Grant amount	$4,187,451	$7,480,170	$ total	10th percentile Low-No grant plus $138,000/bus HVIP to 90th percentile Low-No [119] plus $150,000/bus HVIP
EVSE price [a]	$2,000	$100,000	$/EVSE	California ZEB rollout plans and California Public Utilities Commission PRP report for depot chargers
Annual VMT [b]	33,046	55,076	miles/year	±25% from APTA 2020 average [101]
Discount rate	0.0%	10.0%	%/year	0% for entities without alternative investments; 10% for long-term U.S. stock market annual return
Number of BEBs [a]	10	40	BEBs	California ZEB rollout plans [1]
BEB efficiency	1.82	2.83	kWh/mi	Meta-analysis of NREL fleet evaluations
Monthly electricity fee	$701	$3,345	$/month	Max. is PGE BEV2S, min. is SCE TOU-EV-9, both at 25 buses.

[a] Larger fleets that use pantograph chargers are addressed separately in the text that follows.
[b] Vehicle miles traveled.

Each input paramter in Table 10 was modeled independently of the others, with the exception of the number of BEBs, which impacts the electricity rates. The resulting change in NPV that these input values produced is displayed in Table 11. For the range of values shown in Table 10, the CNG fuel price was the most influential parameter, resulting in an NPV change between $1 million and $10 million (simple payback of 1.9 years up to 7.5 years). The CNG fuel price is influential because the input values cover a large range. There are many factors affecting the large range of CNG prices, including the fuel contract length, size of the contract, and refueling equipment being amortized. The CNG bus maintenance cost is likewise very influential due to its wide range of inputs, stemming from variations in local labor rates, bus manufacturer and age, local driving conditions, and more. The BEB purchase price and CNG bus purchase price are quite influential despite their smaller range of inputs because they are large upfront costs, and their impact does not get dampened by discounting from future years.

Table 11. Sensitivity of Key BEB Investment Parameters

Parameter	Low NPV	High NPV	NPV Change
CNG fuel price	$1,030,891	$10,047,354	$9,016,463
CNG maintenance costs	($4,820,364)	$3,797,643	$8,618,007
BEB purchase price	($828,533)	$3,804,721	$4,633,254
CNG bus purchase price	($675,117)	$3,451,799	$4,126,916
BEB maintenance costs	$458,165	$3,905,368	$3,447,203
Grant amount	$382,181	$3,674,900	$3,292,719
Charger price	$716,317	$3,166,317	$2,450,000
Annual VMT	$817,355	$3,115,279	$2,297,924
Discount rate	$754,409	$2,999,083	$2,244,674
BEB efficiency	$980,424	$2,512,349	$1,531,925
Monthly electricity fee	$1,809,970	$2,120,258	$310,288
Number of BEBs	$1,945,963	$1,986,671	$40,708

As outlined above, the baseline case focuses on BEBs and equipment indicated in California ZEB rollout plans and is therefore focused on fleet sizes between 10 and 40 buses with plug-in depot chargers. However, as we look further into the future, it is possible that much larger BEB purchases could be made, which may require more costly charging equipment such as pantograph or induction chargers that can charge numerous buses. These chargers may become more competitive as they drop in price (currently $200,000–$600,000 each with installation costs) and as fleets devise strategies to charge more buses by a single charger. Essentially, these could become more prevalent if the *per-bus* cost of charging equipment becomes less for pantographs than it is for plug-in chargers. However, the current rollout plans indicate that the per-bus cost of pantographs (including installation costs) is an average of $470,000/bus, while the average plug-in charger is $76,000/bus. One way for these chargers to come closer to cost parity with plug-in chargers would be to increase the number of buses that utilize each pantograph charger. Once more data on this emerging technology are available, further research is needed as to the feasibility of how many buses can realistically share a pantograph, the costs included in utilizing a pantograph in such a fashion, and the ratio of pantographs to depot chargers that fleets trend toward.

6.2 Fuel Cell Electric Buses Compared to CNG Buses

A similar analysis was done for the investment in 40-foot standard FCEBs as opposed to CNG buses. The baseline investment scenario utilizes the input parameters shown in Table 12. These input parameters assume that the hydrogen refueling station is operated by a third party rather than the transit authority. In other words, the hydrogen fueling station cost is not paid for by the transit agency. Those costs are accounted for in the price of hydrogen. Another notable difference for the fuel cell scenario is that it was assumed hydrogen costs would drop by 10% per year to reach a projected value of $3.00/kg by 2030, per the DOE technical target.

Table 12. FCEB and CNG Bus Input Assumptions for the Baseline Scenario

	Parameter	Value	Unit	Source
General	Number of FCEBs obtained	25	vehicles	Rollout plans for ZEBs [1]
	Average life of bus	12	years	APTA procurement guidelines [141]
	Discount rate or required rate of return	3.6	%	5-year annual returns on Standard & Poor's municipal bond index [142]
	Average annual miles traveled	44,061	miles/year	APTA 2020 fact book [143], in agreement with CARB [24]
	Residual (end-of-life) value of bus	2	% of price	Laver et al. [144], updated with fleet input from AC Transit, RTC, and San Joaquin Regional Transit District
CNG Bus	Purchase price of new 40-ft CNG bus	598,680	$	APTA 2020 vehicle database, 2019–2021 weighted average [101]
	Fuel economy of CNG buses	4.03	mpdge	Meta-analysis of NREL bus fleet evaluations
	CNG fuel price	1.30	$/DGE	Average price of six California depots, adjusted to 2022 dollars [24]
	CNG price increase	−0.5%	%/year	U.S. Reference case 2020–2050 Annual Energy Outlook [145]
	CNG vehicle maintenance	0.85	$/mile	CARB [24]
FCEB	Purchase price of new 40-ft FCEB	1,136,279	$	APTA 2020 vehicle database, 2018–2021 weighted average [101]
	Grant amount	9.1	$ million	Average 2016–2020 Low-No grant [119] plus HVIP grant of $270,000/vehicle
	Fuel economy of FCEBs	8.1	mile/kg	FCEB 2020 status report, Eudy and Post [80]
	Hydrogen fuel price	7.79	$/kg	AC Transit, 2021 *Zero-Emission Transit Bus Technology Analysis* [102]
	Hydrogen price decrease	10	%/year	Annual reduction in order to reach $3.00/kg by 2030, per DOE technical target [152]
	Hydrogen vehicle maintenance	0.43	$/mile	Meta-analysis of NREL fleet evaluations

6.2.1 VICE Results for Fuel Cell Electric Buses Baseline Scenario

Based on the inputs outlined in Table 12, the baseline scenario for purchasing 25 FCEBs instead of CNG buses resulted in an NPV of negative $2.4 million, as shown in Figure 19. The upfront cost of 25 FCEBs, even after receiving the $9.1-million grant, is $4.5 million greater than the investment in 25 CNG buses would have been. For the next 2 years, the NPV continues to drop because operating costs (fuel and maintenance) are greater than those of CNG buses. Starting in year 4, the price of hydrogen has reduced enough so that the investment starts to pay back, but this progress is ended by the end of the bus life in year 12.

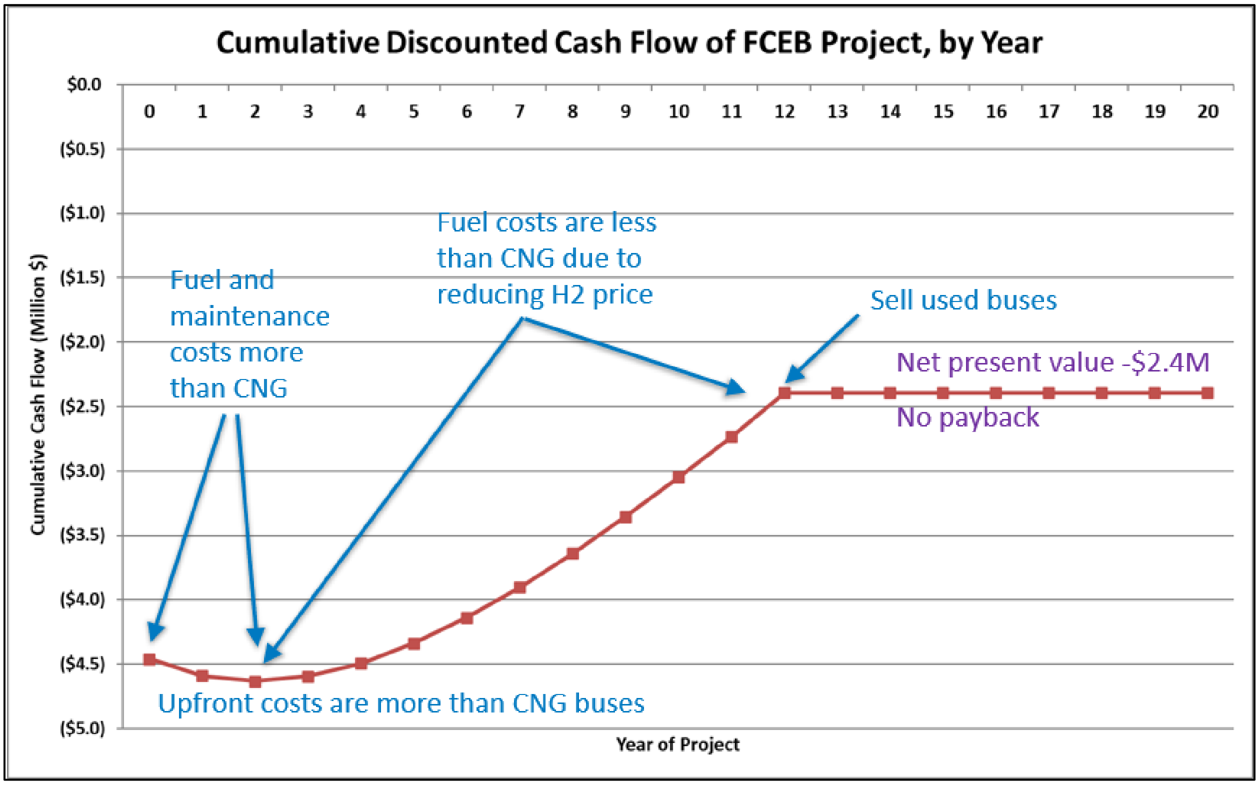

Figure 19. Payback schedule of FCEB baseline investment

In addition to results from the grant shown above, a scenario without Low-No funding was also assessed. Removing Low-No funding reduced the NPV of the baseline scenario from −$2.4 million to −$4.7 million for the 25-FCEB fleet. This removal did not remove the inverse economies of scale mentioned above, since each bus still costs more over its lifetime than a CNG bus.

6.2.2 Sensitivity Analyses for FCEB Investment Parameters

A sensitivity analysis similar to the one performed on the BEB investment was also conducted for the FCEB investment. Minimum and maximum values were determined for each input parameter, as shown in Table 13. Only two of the individually modeled inputs resulted in a positive NPV for the investment: the high value for CNG price of $4.41/DGE and a fleet size of 10. The reason that a smaller fleet size is better for the project economics modeled here is because the Low-No portion of the grant funding is not tied to the number of buses, so smaller fleet sizes can have comparatively larger per-bus grants. Table 13 also shows the “break-even value” or the value each parameter would need to achieve an NPV of zero, which is the point at which the required rate of return (return on investment), which is the same as the discount factor, is achieved. This breakeven input is color-coded according to how it compares to the specified minimum-maximum range of input values. Green indicates that it is within the range, yellow indicates <20% outside the range, and red indicates >20% outside the range. The large font size correlates to green cells, medium font size to yellow, and small font size to red.

Table 13. Minimum, Maximum, and Breakeven Inputs for FCEB Investment Projects

Note: Parameters in this table were placed in order of highest sensitivity to lowest (meaning the largest impact on NPV when comparing between min. and max. inputs). Many parameters were not included because their range was too narrow. Green cells (large font) indicate that the breakeven value, as calculated by the VICE model, was within the min.-max. range. Yellow cells (medium font) indicate the breakeven values were less than 20% outside the range. Red cells (small font) indicate breakeven values that were more than 20% outside the range.

Parameter	Minimum	Maximum	Breakeven Input	Unit	Source of Min/Max
CNG fuel price	$0.94	$4.41	≥4.41	$/DGE	Alternative Fuel Price Report; July 21 [140]. West Coast CNG. LA Airport (max.) and City of Sacramento (min.).
CNG maintenance costs	$0.22	$1.02	≥1.07	$/mile	CARB 2018 +20%
FCEB purchase price	$1,011,000	$1,297,838	≤1,039,326	$/bus	2020 APTA database [101]
Number of FCEBs	10	40	≤12	FCEBs	California ZEB rollout plans [1]
CNG bus purchase price	$491,622	$658,887	≥695,633	$/bus	2020 APTA database [101]
H_2 price reduction	5%	15%	≥21%	%/year	±5% from DOE technical target [152]
Grant amount	$7.9 million	$10.6 million	≥11.5	$ million total	Smallest FC Low-No grant [119] plus $258,000/bus HVIP to largest Low-No plus $270,000/bus HVIP
FCEB maintenance costs	$0.26	$0.49	≤0.21	$/mile	Meta-analysis of NREL fleet evaluations
H_2 price	$7.79	$10.10	≤4.75	$/kg	AC Transit, 2021 *Zero-Emission Transit Bus Technology Analysis* [102]
Discount rate	0.0%	10.0%	≤-4.5%	%/year	0% for entities without alternative investments; 10% for long-term U.S. stock market annual return
FCEB efficiency	6.94	8.65	≤7.53	kg/mi	FCEB 2020 status report, Eudy and Post [80]
Annual VMT	33,046	55,076	≥103,576	miles/year	±25% from APTA 2020 Fact Book average [143]

Three of the four input parameters for which the investment economics are most sensitive (CNG fuel price, FCEB purchase price, and number of FCEBs purchased) also have breakeven values that are within their minimum-maximum ranges. These three parameters should therefore be focused on when determining the suitability of a fleet to profitably adopt FCEBs. If the LCFS credit of $1.44/kg from the example in Section 5 was applied to the baseline scenario, the NPV would increase by $1.1 million but the investment would still not break even. These three influential parameters have a compounding impact on project economics: If an investment is made in which each of those three have the most favorable input within their minimum-maximum range, the NPV is a positive $5.4 million with a payback period of less than 1 year. This example demonstrates that it is possible to have a profitable purchase and implementation of FCEBs relative to conventional buses depending on the project-specific costs and circumstances. Hydrogen price appears to be not very influential in Table 13 because the minimum-maximum price range applied here is relatively narrow—a finding that could be at odds with nationwide total cost of ownership assessments that use wider ranges and found hydrogen prices to be highly influential.

The grant amount for ZEB projects is of particular interest to policymakers in addition to fleet managers. Table 13 shows that for the baseline fleet to break even, a grant of nearly $11.5 million is needed for the purchase of 25 FCEBs. It is important to note that the grant input in VICE assumes that the Low-No portion is not tied to the number of buses. Therefore, the investment shows reverse economies of scale. This conflicts with likely economies of scale in retail fuel prices that could not be added to the model due to lack of supporting data. A grant of $12.4 million for a purchase of 25 FCEBs would comprise $6.75 million of HVIP funding (at $270,000 per bus) and the remaining $5.65 million from Low-No grants or any of the other funding sources covered in Section 5 of this report. To date, the largest Low-No grant has been $3.85 million, so the likelihood of covering the remaining $1.8 million ($72,000 per bus) from other sources needs to be assessed. The inverse economies of scale tied to the Low-No portion of the grant are the reason that a hypothetical fleet of 200 FCEBs would have an NPV of negative $36 million. More research is needed once such large FCEB fleets have been in operation for long enough to accrue reliable data. This research needs to investigate likely economies of scale such as fuel prices, FCEB purchase prices, and FCEB maintenance costs that will improve the economics of large FCEB fleets.

7. ZEB Performance

Assessing ZEB performance is critical to planning for and achieving successful ZEB implementation. Most transit agencies begin their fleet transition with a small number of ZEBs in a pilot or demonstration program to begin learning about the technology and how it fits within their existing service/operations.

A few transit agencies have even begun to operate ZEBs with multiple different propulsion systems and/or different manufacturers to compare the ZEB performance directly in their specific service. The results of these head-to-head evaluations are intended to help the transit agencies choose the best fit to electrify their fleets moving forward [102,153–156]. These evaluations are also helping bus OEMs receive feedback directly from transit agencies and identify important areas for improvement needed to meet the zero-emission needs of the transit industry.

NREL and other research and consulting organizations have performed detailed evaluations of early ZEB deployments throughout the United States and Canada to provide valuable cost and performance results to all stakeholders in the ZEB industry [103]. Some of the metrics commonly evaluated include bus use and availability, energy efficiency (i.e., equivalent fuel economy), driving range between charging/fueling events, bus reliability, and maintainability/serviceability.

Zero-emission technologies for standard transit buses are in the early stages of commercialization but have been progressing quickly in recent years. Technology readiness level (TRL) is sometimes used to measure the maturity of a technology. The latest TRL review on BEBs and FCEBs was noted in CARB's *Proposed Fiscal Year 2021-22 Funding Plan for Clean Transportation Incentives*, in which it identifies both BEBs and FCEBs at a TRL of 9 for transit buses when compared to other on-road vocational applications [20]. A TRL of 9 indicates that the technology is in its final form (deployment marketing), and support is available for commercial products.

7.1 Bus Availability

Bus availability is a measure of the percentage of time a bus is ready for revenue service compared to the time it is planned for service. The time a bus is unavailable represents the downtime needed for scheduled and unscheduled maintenance (excluding accident-related repairs). Fleet availability of 85%–90% is a generally accepted target for transit fleets due to FTA's maximum 20% spare ratio limit for urban transit agencies, although actual availability rates can vary for each transit agency. Figure 20 shows the average fleet availability results from numerous evaluations of BEB and FCEB deployments [102,103,153–156]. The evaluations cover ZEB fleets of various size, age, make/model, service requirements, and length of data analysis. The BEB fleets include model years 2014–2019, and the FCEB fleets include model years 2010–2019, which cover some early-generation BEBs and FCEBs. In most cases, the average availability of the ZEB fleets fell below 85%. Monthly fleet availability for some evaluations varied by as much as 30% above and below the average. For others, the monthly values were as close as ±5% from the overall average. This highlights the high level of variability between different fleets and changes from month to month. These availability numbers suggest that early deployments of ZEBs had more frequent and/or longer-duration downtime for repairs than what transit agencies expect for their fleets. Some of the additional downtimes could be attributed to troubleshooting issues with the new technology buses and training maintenance staff to make repairs on the ZEBs during these evaluations. Availability is expected to improve as ZEB technologies continue to mature and operators gain more experience with the technologies; however, in-use operational data take time to collect and analyze, so there are fewer published results from the latest-generation ZEBs. Recent results from Antelope Valley Transit Agency do indicate that their BEB fleet has been able to achieve monthly availability above 90% consistently throughout a 1-year monitoring period between June 2020 and May 2021, as shown in Figure 21 [157].

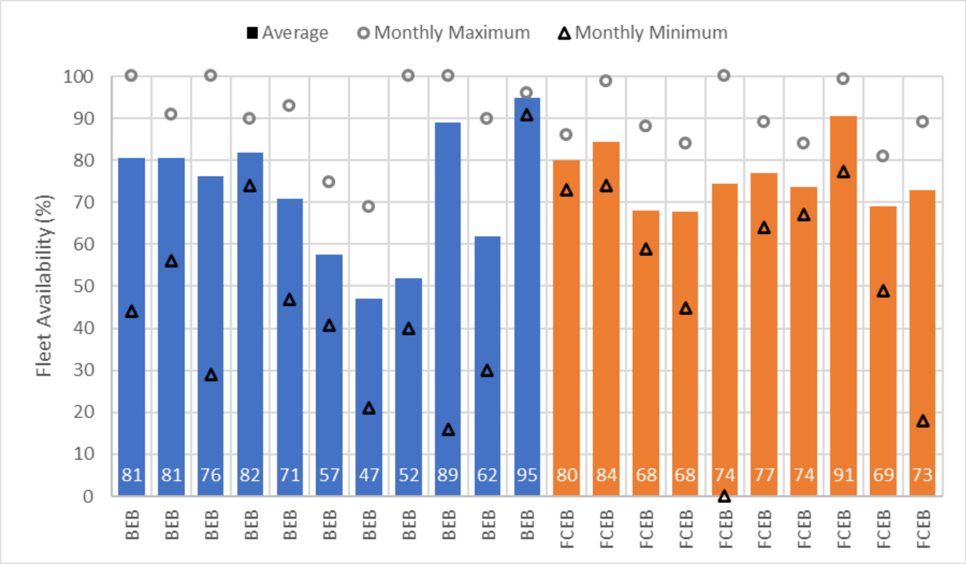

Figure 20. Reported availability for BEB and FCEB fleets.

Data from published ZEB evaluations from NREL and others [102,103,153–156]

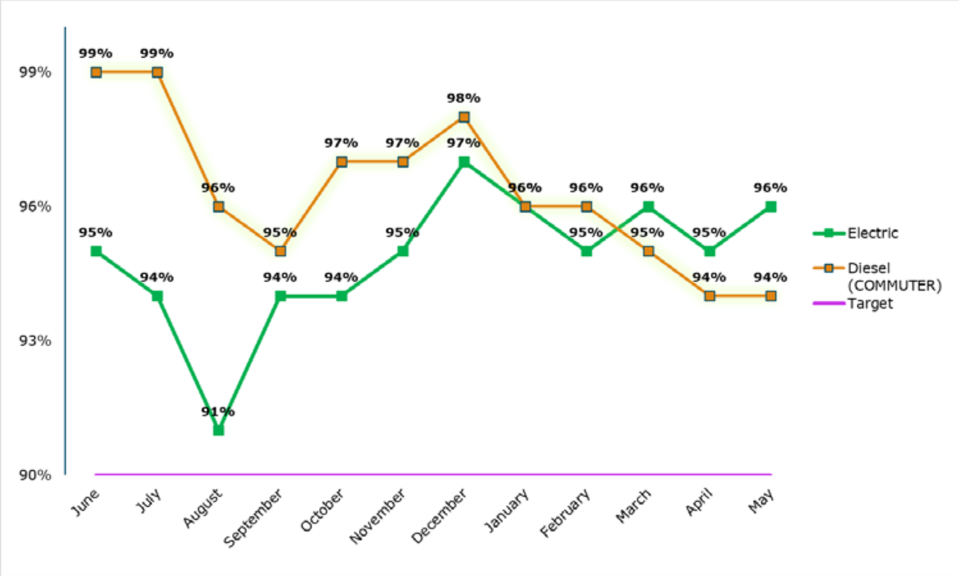

Figure 21. Monthly BEB fleet availability during from June 2020 to May 2021 at Antelope Valley Transit Authority [157]

7.2 Energy Efficiency

One of the largest advantages of electrified powertrains, particularly in transit service, is the significant improvement in energy efficiency over conventional combustion technologies. It is well documented that BEBs can achieve 3–5 times as many miles per unit of energy as their conventional counterparts. This is primarily due to the efficiency of the electric motors compared to internal combustion engines and the application of regenerative braking, whereby some of the kinetic energy of a moving bus can be converted back to stored energy in the batteries when the bus is slowed down. It is also well documented, however, that BEB energy efficiency is more sensitive to several external factors, such as weather conditions (temperature, humidity, precipitation), driving conditions (traffic, road grade, speed, stop frequency), vehicle weight (passenger loading), and operator behavior (acceleration/deceleration rates) [103,158,159].

Ambient temperature tends to be the most notable factor affecting BEB driving efficiency, with reports of up to 30% reduction in efficiency for an approximately 30°F drop in ambient temperature, due primarily to cabin heating loads (estimates are closer to 24% reduction when accounting for additional variables that affect efficiency, such as bus size and weight). Likewise, for cabin cooling, an ambient temperature increase of approximately 20°F can cause more than 6% reduction in overall efficiency [158,159]. The energy efficiency of BEBs operating in cold environments can also be reduced by snow, as the slippery conditions can cause temporary reduction of regenerative braking. Cold weather and snowy conditions are generally not concerns for California transit agencies, which help make the state a favorable region for early ZEB adoption.

Lower energy efficiency results in reduced driving range, which can make route planning and dispatching for ZEBs more difficult. Lower energy efficiency also results in higher energy cost per mile of transit service. The average energy efficiency of BEBs demonstrated in real-world transit service ranges from approximately 13 mpdge to more than 20 mpdge, with an average (from multiple demonstrations) near 18 mpdge. Conventional buses are less sensitive to ambient weather and driving conditions; diesel and CNG transit buses achieve approximately 5 mpdge and 4 mpdge, respectively [103].

The newest-generation FCEBs have demonstrated significant improvement in energy efficiency in recent years. On a diesel-equivalent basis, FCEBs achieve approximately half the fuel economy of BEBs today but are still nearly double the equivalent fuel economy of conventional buses. Reported fuel economy for FCEB fleets range from 5.6 mpdge to 9.8 mpdge and an average of approximately 7.7 mpdge, with the latest-generation FCEBs accounting for the higher fuel efficiency [103].

7.3 Driving Range

7.3.1 BEB Driving Range

BEBs that utilize on-route charging (conductive or inductive) can generally operate continuously for as long as the block schedule dictates and are not limited in daily operating range. For depot-charged BEBs, however, the operating range is determined by the energy storage capacity of the onboard battery pack. Despite the ever-improving energy density and increasing size of battery packs available for BEBs today, even the "extended-range" BEBs have significant range limitations compared to the conventional buses they are replacing.

Battery pack sizes listed for standard BEBs range from 215 kWh up to 675 kWh, and corresponding driving ranges advertised by OEMs span from approximately 120 miles to 330 miles (Figure 22). These are "nominal" (or often, maximum) operating ranges, which are typically estimated for favorable or near-ideal conditions. Figure 23 shows average BEB driving ranges resulting from dynamometer tests conducted at Pennsylvania State University's Altoona Bus Research and Testing Center [67]. These tests use standard test cycles (Manhattan Driving Cycle, Orange County Bus Cycle, and HD-UDDS Cycle) to measure energy efficiency and driving range. The tests are intended to provide comparable range and efficiency results for buses "under specified operating conditions that are typical of transit bus operation… [but] the results of [the tests] will not represent actual energy usage." The factors affecting energy efficiency described above can reduce the actual driving range that BEBs achieve in real-world operation. In addition, the useable battery energy is less than the nominal size, as the top and bottom portions of the battery capacity (approximately 10% state of charge on each side) are reserved and prevented from charging/discharging to protect the health of the battery. As the battery slowly degrades over time, the battery capacity decreases and the useable energy is further reduced, leading to reduced driving ranges. Actual pack degradation depends on battery chemistry, duty cycles, and operating temperatures.

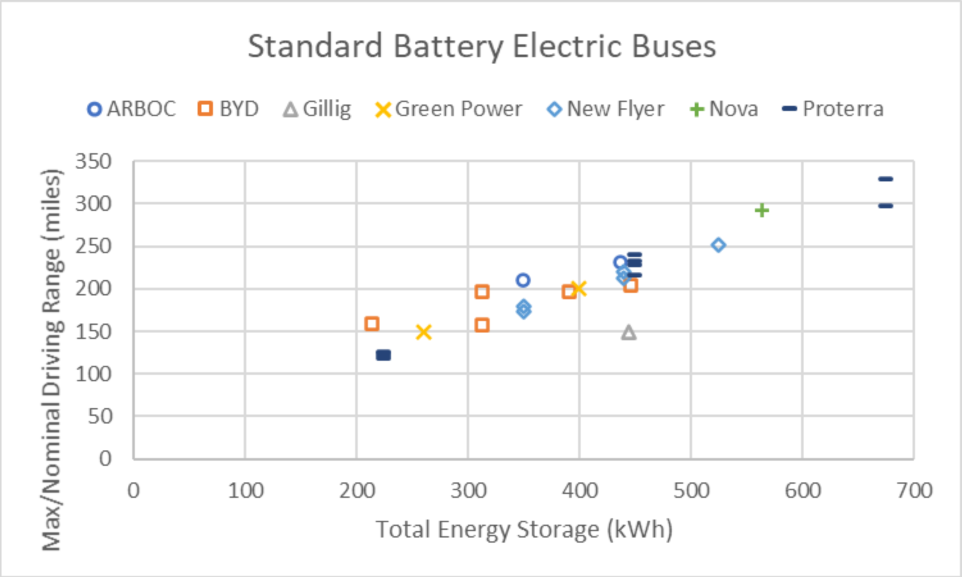

Figure 22. OEM-advertised nominal driving range and energy storage for standard BEBs.

Data from OEM websites and bus brochures (Appendix A.7)

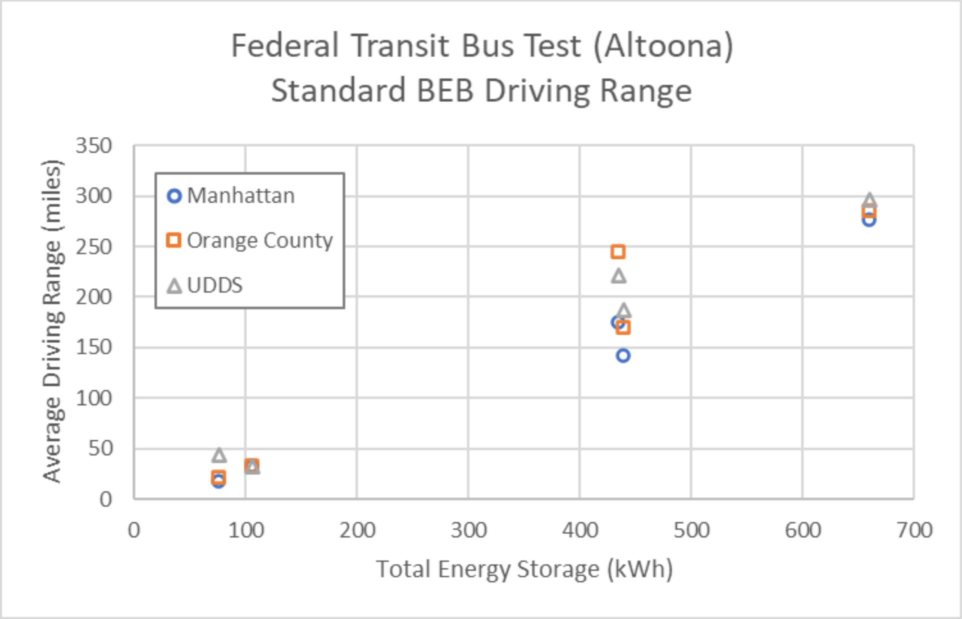

Figure 23. Altoona-tested average driving range and total energy for standard BEBs.

Data from Altoona reports of dynamometer testing using standard test cycles [67]

Transit agencies must plan route assignments based on the minimum reliable range of the bus; i.e., the range a bus can reliably achieve even under harsh conditions, which are usually in the hottest or coldest conditions for a given location. For many BEBs in operation today, the minimum reliable range is around 150 miles or less [160]. New BEB models with larger onboard energy storage are expected to achieve a daily driving range of greater than 200 miles in real-world operation. However, there are cost, vehicle weight, and space constraints to the size and number of battery packs for BEBs, so the driving range limitations cannot easily be solved by simply increasing the size of BEB energy storage.

BEBs are often first deployed by transit agencies on suitable routes/blocks that have shorter daily distances, less demanding duty cycles, or shorter service hours. Some route schedules—those supporting morning and afternoon service peaks, for instance—allow for midday charging, which can also enable BEB operation. Many existing routes/blocks within transit agencies' service territories are suitable for depot-charged BEBs, but transit agencies often cite range limitation as one of the most significant barriers to implementing BEBs. Having a sub-fleet of buses that can only be dispatched on a portion of an agency's routes/blocks reduces operational flexibility and can require larger fleet spare ratios. This limitation could hinder the scale-up to 100% BEB fleets.

CARB conducted a survey of California transit agencies in 2016 and analyzed the daily driving requirements for their existing routes [24,161]. Figure 24 shows the results from the 37 transit agencies who responded (of 150 to whom the survey was distributed). While only a small percentage of the aggregate buses have a daily VMT of less than 100 miles (skewed toward smaller transit agencies), more than 50% of buses in the survey have a daily VMT of less than 150 miles.

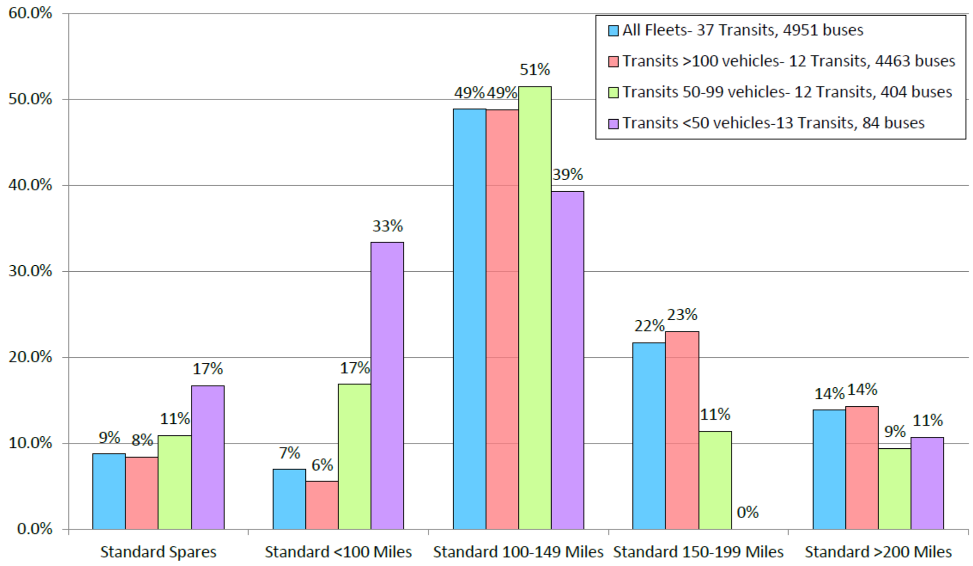

Figure 24. Daily VMT for standard (40-ft) buses.

Data from CARB 2016 survey of California transit agencies [161]

Figure 25 reveals the wide distribution of daily VMT from the transit agency view. Several agencies have buses that are all or nearly all operated for less than 150 miles per day. Two agencies reported having zero buses that operate for less than 150 miles per day. However, most agencies who responded to the survey (both small and large) are spread out along this spectrum, having between 11%–92% of their fleet falling below a daily VMT of 150 miles.

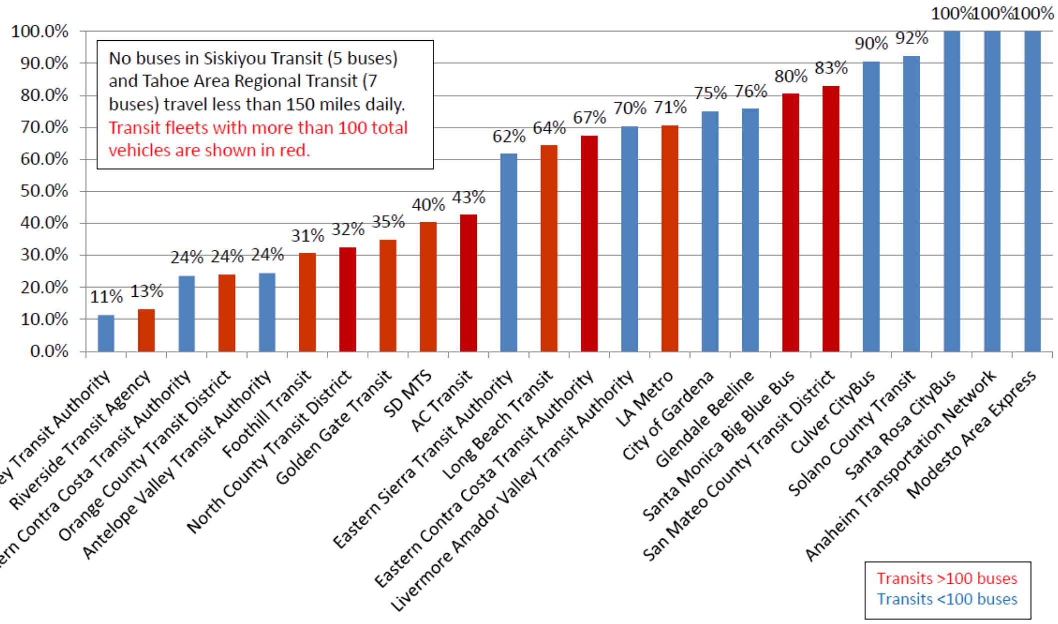
No buses in Siskiyou Transit (5 buses) and Tahoe Area Regional Transit (7 buses) travel less than 150 miles daily. Transit fleets with more than 100 total vehicles are shown in red.

Figure 25. Percent of standard (40-ft) bus fleet with daily VMT less than 150 miles per day.

Data from CARB 2016 survey of California transit agencies [161]

Many agencies are carefully evaluating range requirements as part of their planning process for developing ZEB rollout plans; for instance, Santa Monica's Big Blue Bus lists 200 miles as their required BEB range for all purchases after 2021 [162].

Researchers around the world are working on further improving the energy densities of current battery chemistries and exploring new batteries for electric vehicle applications. New generations of extended-range BEBs are expected to benefit from these advancements to offer a greater driving range, but it is unknown at this time whether the pace of improvement will be able to keep up with the need for transit agencies to transition their fleets to 100% BEBs with depot charging strategies. In cases where transit agencies operate routes/blocks longer than current BEB capabilities, transit agencies may choose to deploy FCEBs, use on-route charging to extend the driving range, or split the longest routes/blocks into smaller blocks in order to operate BEBs. Modifying the routes/blocks in this way would require transit agencies to purchase more BEBs than the conventional buses being replaced (i.e., not a 1:1 replacement ratio for the entire fleet at this time), which entails greater capital and operating expenses for the agency.

7.3.2 FCEB Driving Range

For FCEBs, the driving range is limited by the amount of hydrogen carried on board. Current-generation FCEBs have a range of approximately 300 miles and offer a longer driving range than BEBs. Some transit agencies are choosing to implement FCEBs because the driving range provides greater operational flexibility. They are typically considered to provide a one-to-one replacement ratio for conventional buses, as they can be dispatched on nearly all transit agencies' existing blocks without modifying the routes or schedules. Increasing the driving range of FCEBs, as with conventional buses, can be achieved by increasing the size or number of fuel tanks on the bus.

7.4 Durability/Reliability

7.4.1 ZEB Durability/Reliability

The reliability of transit buses is indicated by the frequency of road calls—when a bus must be unexpectedly removed from revenue service due to a malfunction or breakdown in service. The reliability is quantified by miles between road calls (MBRC), which is also known as mean distance between failures. MBRC can vary significantly between individual buses, fleets, and locations based on differences in vehicle operations and other factors. It is most useful to compare MBRC on a fleet-average basis and compare ZEB performance to a conventional fleet of similar age, type, and operation.

Detailed ZEB fleet evaluations that track MBRC data have been conducted and reported by NREL, transit agencies, and others [102,103,153–157]. Based on these reports, Table 14 and Figure 26 show that cumulative MBRC values calculated for BEB fleets range from 2,700 miles to 27,200 miles, with an average of approximately 13,000 miles. For FCEB fleets analyzed, MBRC varies from 2,300 miles to 11,400 miles, with an average of approximately 5,900 miles. Corresponding MBRC values from the baseline conventional buses in these evaluations are included in Table 14 for comparison.

Problems resulting in road calls are not always related to the propulsion system. They can originate in many other vehicle systems that are very similar (or potentially the same, depending on vehicle manufacturer) between buses of different powertrains, such as steering or suspension systems. Road calls can also originate from safety-related systems, because even a minor or easily resolved issue with a safety-related system requires the bus to be removed from service and inspected. Of particular interest to transit agencies looking to deploy ZEBs is whether the zero-emission propulsion systems are responsible for more road calls than their conventional buses.

From the evaluations that have reported separately on MBRC for the propulsion system only, which is a subset of the total MBRC, the propulsion-related MBRC values for BEBs range from 6,900 miles to 54,400 miles, with an average of approximately 21,200 miles. Propulsion-related MBRC for FCEBs range from 4,300 miles to 34,300 miles and average approximately 12,400 miles. These evaluations indicate that ZEBs have notably lower MBRC and propulsion-related MBRC for both ZEB types compared to the conventional counterparts.

Table 14. Cumulative Fleet MBRC and Propulsion-Related MBRC

	MBRC				Propulsion-Related MBRC			
	BEB	FCEB	CNG	Diesel	BEB	FCEB	CNG	Diesel
Minimum	2,771	2,338	7,936	6,669	6,927	4,384	31,494	13,479
Maximum	27,194	11,444	31,299	63,023	54,389	34,332	55,886	189,068
Average	**12,168**	**5,602**	**19,808**	**23,858**	**21,204**	**12,375**	**43,047**	**68,910**

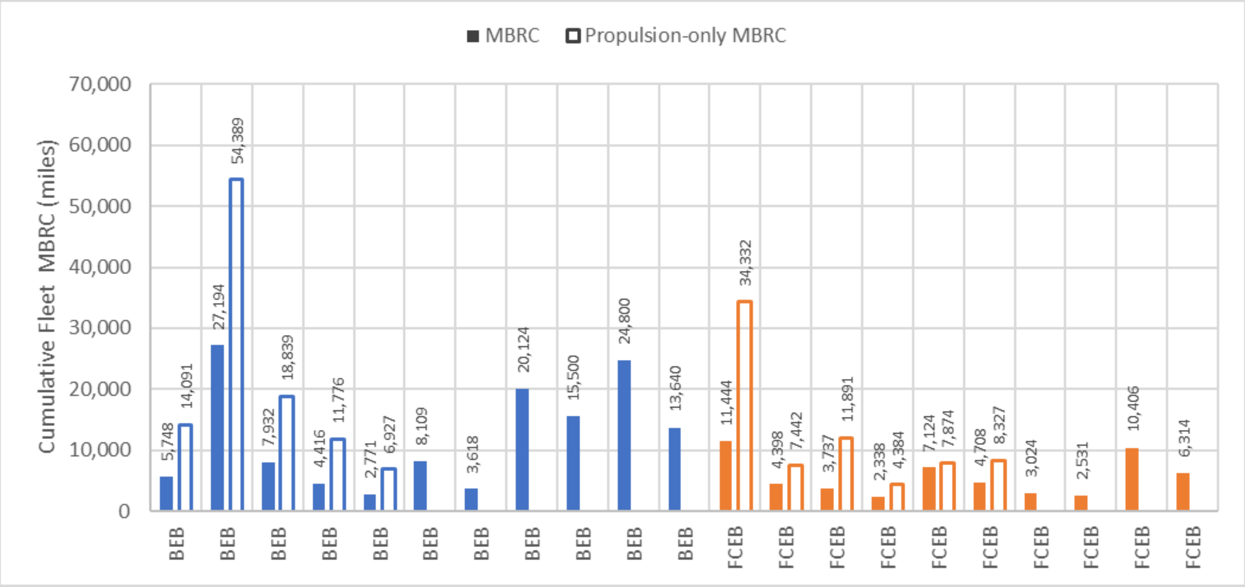

Figure 26. Cumulative MBRC for BEB and FCEB fleets

As ZEB technologies continue to mature and operators gain more experience with the technologies, ZEB MBRC are expected to achieve a similar level to conventional buses; however, in-use operational data take time to collect and analyze, so there are fewer published results from the latest-generation ZEBs. Recent results from the Antelope Valley Transit Authority indicate that their BEB fleet had average monthly MBRC of 18,520 miles (15,875–

20,821 miles) during the first 5 months of operation in 2021, indicating that these BEBs have achieved MBRC values similar to those of conventional CNG buses (see Table 14) [157].

7.4.2 Station Durability/Reliability

Hydrogen stations for light-duty vehicles are installed throughout California and have experienced issues with reliability [163]. In comparison, hydrogen stations deployed at transit agencies have had much higher reliability and have been reported to have 100% availability with very few failures, leading to >99% reliability [153]. The high reliability of hydrogen dispensers at transit agencies can be attributed to the station being sized according to a known usage, as well as trained staff performing the refueling.

8. Training Program for Employment in Manufacturing, Operating, and Maintaining ZEBs

An important topic for ZEB implementation is the workforce development and human operations and resources needed to support the physical transition to new generations of bus technology. Transit agencies employ various strategies for achieving their training goals, working closely with bus OEMs, BEB charger manufacturers, hydrogen fuel providers, hydrogen station developers, and established training programs for operators, mechanics, and maintenance workers. Many transit agencies also work proactively with fire safety officials on first responder training. These training programs and transit agency experiences with training operations are briefly summarized in this section.

8.1 U.S. Federal and Nongovernment National Training Programs

The FTA has established a Transit Workforce Center that provides workforce training support—including through its International Transportation Learning Center—which was recently allocated $5 million in FY 2021 funding. The mission of the center is "to help transit agencies recruit, hire, train, and retain a diverse workforce needed now and in the future." The program provides technical assistance; human resources and training, including outreach to underrepresented communities; and innovative "frontline" workforce development projects. The workforce development grants through the Transit Workforce Center have previously been awarded to both urban and rural transit bus operators, typically on an 80% (federal) and 20% (match) basis. Further details of recent efforts can be found through the program site.

> Program site: https://www.transit.dot.gov/research-innovation/workforce-development-initiative

Additionally, nationwide, there is an important program for training electricians to install EV charging infrastructure known as the Electric Vehicle Infrastructure Training Program (EVITP). This training program is offered at various locations such as industry training centers and community colleges. The program provides comprehensive training for the installation of EVSE in North America. Along with a technical installation course, the program offers a larger overview of the EV industry. Modules include automaker experience with EV charging, types and characteristics of EV batteries, utility interconnect procedures, possible role of electricity storage in conjunction with EVSE, first responder training and fire hazards, as well as many other aspects in addition to the actual installation of various types and power levels of EVSE.

> Program site: https://evitp.org/training/

DOE has also funded the Pacific Northwest National Laboratory to create a set of hydrogen fuel training materials known as H2Tools [164]. These include training around the safe transport, storage, and use of hydrogen as a vehicle fuel. More specific training around hydrogen production systems (e.g., electrolyzers and methane/biogas reformers) seem to be still under development. However, there are other large efforts related to hydrogen safety and best practices, including the Hydrogen Safety Council and the International Conference on Hydrogen Safety, organized biannually by the International Association for Hydrogen Safety [165].

8.2 Statewide and Regional Programs

A training program in California known as the Southern California Regional Transit Training Consortium has recently been expanded to a statewide effort called the California Transit Training Consortium. The program has included a wide range of training programs focusing on electrical systems; braking systems; engines; hybrid systems; heating, ventilating, and air-conditioning systems; and system diagnostics. Members include transit agencies, government agencies, and community colleges. Further details on this program are available at: http://www.scrttc.com/images/stories/PDFs/brochure-scrttc.pdf. A revised website reflecting details of the new California Transit Training Consortium program is anticipated around fall 2022.

The Center for Transportation and the Environment leads an effort called the Zero Emission Bus Resource Alliance (ZEBRA). The consortium was developed to facilitate information exchanges, training programs, shared research, and public education. Over 40 transit agencies are currently members, with bimonthly meetings for information exchanges, as well as a membership portal with a collection of resources. Annual membership fees range from $1,000 to $5,000 per agency based on the size of the agency. Further details can be found at: http://zebragrp.org/zebra-mission/.

State funding for workforce training has increased since the adoption of the ICT regulation in 2018. In 2021, CEC's Clean Transportation Program and CARB jointly allocated up to $6.8 million in grant funds for projects that will provide workforce training and development that support ZEVs, ZEV infrastructure, and ZEV-related commercial technologies in California [14]. Eight entities were awarded under this program, including SunLine Transit Agency, Kern Community College District, Fresno City College, Los Angeles Pierce College, and California State University Long Beach [1]. In addition, CARB has instructed CALSTART, who administers the HVIP program, to allocate $250,000 of the HVIP outreach funding to support SunLine's training program at its West Coast Center of Excellence in Zero-Emission Technology, described in the following section. Investment in this training program could benefit transit agencies and school districts immediately.

8.3 Industry-Based Training Programs

In addition to these government- and trade-union-sponsored programs, there also are significant industry-based training programs for transit bus operators and mechanics for new ZEB technologies. The following list describes additional training programs to support a transit ZEB workforce:

- MCI Academy
    - New Flyer, a subsidiary of NFI Group Inc., has launched its electrical technician training program. The program provides employees with knowledge and skills to continue leading and supporting zero-emission adoption across North America.
    - MCI Academy website: https://www.mciacademy.com/.
- New Flyer Vehicle Innovation Center
    - New Flyer also operates a more general training center called the Vehicle Innovation Center, emphasizing training for new workers on public transit buses and motor coaches.

  - Website: https://www.newflyer.com/company/vehicle-innovation-center/.
- New Flyer Anniston Workforce Development Program
  - This is one of several local programs developing under New Flyer's Community Benefits Framework, a national workforce development initiative announced by New Flyer and the Transportation Diversity Council in 2020.
  - The program includes "the execution of a workforce development program, including training and development, skill gap assessments, wage and benefit commitments, fulfillment of diversity and hiring objectives, and pre-apprenticeship and apprenticeship programs" [166].
  - It also includes development of an innovative 4-year electrical technician apprenticeship program, which was launched in 2021 [167].
- Proterra, Los Angeles County, Citrus College, and USM Local 675 – Electric Bus Manufacturing Technology Program
  - 9-week workforce training program for advanced electric bus manufacturing [168].
  - "Unique partnership [that] launches new electric bus manufacturing training program and union contract" [169].
  - Inaugural cohort of students completed the training program in January 2021 [170].
- San Bernardino Valley College, Heavy/Medium Duty Clean Vehicle Technology certificate program
  - "The curriculum prepares students for entry-level positions in Heavy-Duty Truck and electrical maintenance, field service, and networking, in the field of Hybrid/ Alternative fuel to include electrical power technology" [171].
  - The "certificate program [is designed] to develop a local workforce of technicians that can provide the service and maintenance support needed long after the initial BEVs have hit the roads" [172].
- SunLine's West Coast Center of Excellence in Zero-Emission Technology (CoEZET)
  - "CoEZET is a workforce training program focused on maintaining and operating zero-emission buses in public fleets. Public and private organizations, including transit agencies, colleges, private industry, and government agencies, are collaborating with SunLine to develop training and resources for zero-emission bus maintenance including all kinds of alternative and emerging energy technologies" [15].
- AC Transit has developed extensive internal training courses/curriculum for ZEBs
  - Per recent reports on the Zero-Emission Transit Bus Technology Analysis ("5x5" bus study), over 23,000 hours of training have been scheduled and conducted over 19 courses on ZEB technology, utilizing the learning management system on AC Transit's intranet site. AC Transit estimates that about 318 hours of training are required for a mechanic to become proficient in diagnosing and maintaining ZEB technologies [102,153,154].

8.4 Transit Bus Agency Training Plans and Experiences

The transit agencies interviewed for this review have a wide range of plans and experiences around operator and mechanic training. The larger transit agencies tended to have established more extensive internal training programs, while smaller agencies were more likely to rely on assistance from bus OEMs, charger manufacturers, and other established programs.

Bus operator training is often integrated with the initial bus purchase agreements. Transit agencies reported mixed experiences with training programs offered by OEMs, with some being relatively effective but others reporting some difficulties with unclear training manuals and difficulties in establishing their own internal mechanical and diagnostic programs.

Agencies also reported high variability in bus efficiency related to operators. Some reported that the efficiency of operators in driving the buses improved over time (converging closer to expectations), either as a function of training or experience, and largely related to the familiarity and proper use of ZEB braking systems. One agency reported that Proterra has a "train the trainer" program where the OEM's customer support staff first provide instruction to the lead trainers or designated operators at a transit agency, who then provide training to the rest of the individual operators. The focus is on acceleration and braking and how driving ZEBs is different than conventional buses in terms of achieving the highest fuel economy.

Operators of FCEBs are also trained on hydrogen safety issues, with some concerns about the flammability hazards of the fuel. They are trained to recognize and respond to warning signals and dashboard signs, along with any other indications (e.g., unusual noises) of a potential problem, and to react appropriately. These trainings are aided by support materials available through DOE's Hydrogen Tools web portal and the California Fuel Cell Partnership resources website [164,173].

As for mechanics and service technician training, once trained, mechanics are reported to be generally able to deal with the basic electric bus mechanical issues, but high-voltage electrical system maintenance requires special training. One agency employs a two-phase plan for mechanic training. In Phase I, mechanics must complete 8 hours of training on proper use of electricity/volt meters and other basic electrical training. In Phase II, mechanics receive an additional 24 hours of technical training. This particular agency also requires completion of modules for mechanics on ZEB familiarization, high-voltage system safety, charging infrastructure training, and arc flash electrical safety.

Another agency first requires 1 hour of basic safety training followed by a 5-week program for preventive maintenance. The program is conducted with pairs of mechanics, more and less experienced, so they can help train each other. The agency indicates that with proper training, many potential issues can be avoided, and that upfront investments in operator and mechanic time and training are likely to more than pay off in the longer term.

Transit agencies have also indicated the importance of establishing training program plans at the time of bus purchase, including specific courses. One recommends having extensive multimedia training to record training for future use. Others suggested including as many useful visual aids as possible, such as computer-aided design drawings, posters, and mock-ups of key mechanical systems.

Another issue that arose is the use of specialized diagnostic equipment needed for ZEBs. This is another needed area for training because these diagnostic systems (laptops and test stations) require specialized OEM software and operations that some agencies reported struggles with. In some cases, they would like to develop their own internal capabilities to speed diagnostics and repairs and reduce downtime but were unable to do so because of the specialized nature of these skills and systems. Thus, they are continuing to be reliant on the OEMs for these services, sometimes resulting in maintenance and service delays.

A few of the transit agencies also suggested the need to share best practices and other experiences among agencies, indicating that this has historically happened for previous new bus types and emerging technologies. APTA's Zero Emission Fleet Committee (open to all ZEB stakeholders) and the Zero Emission Bus Resource Alliance group (open to transit agencies only) are two existing avenues for this type of valuable peer-to-peer information exchange [174,175]. Within California, California Transit Association's ZEB Task Force Maintenance Committee also helps to provide this function. Some transit agencies feel that the state should clearly define required safety training for mechanics and operators, and to make sure that the buses arrive with clear plans for immediate safety training to put safety first.

Remaining needs for California transit agencies regarding training and workforce development:

- Training programs need to be improved and expanded to reach regional levels, and much more training is needed in general as the buses are procured and placed into service.
- Transit agencies are seeking partnerships with academic institutions for better organization and delivery of curricula.
- Certificate training programs are desired to establish specific training levels for individual staff on various topics, such as high-voltage electrical and high-pressure gas systems.
- There is need for greater state support, as in the latest Clean Transportation Program funding plan.

9. Job Creation in Manufacturing, Operating, and Maintaining ZEBs

California has become a leader in decarbonizing transit service while bolstering the economy with clean energy jobs. On a large scale, California's clean energy sector provided almost half a million jobs in 2020 [176]. The transition from the state's current bus fleets, primarily operated on fossil fuels, to ZEB technologies is expected to lead to an increased number of local jobs in multiple sectors, including manufacturing, construction, and services.

Installing ZEV infrastructure could provide skilled jobs and workforces, including those in traditional fossil energy communities. Trade unions, for example, anticipate job growth under the state's climate change policies and have created strategies to adapt their workforce to a zero-emission economy. Some have formed community-based agreements with electric bus manufacturers to provide training and apprenticeship programs that lead to well-paying clean energy jobs for community members [177].

California's ZEV industry provides a range of manufacturing and technology jobs that support the state's move toward zero-emission vehicles. Approximately 15 manufacturers produce ZEBs (e.g., shuttles, school buses, coaches), zero-emission trucks (e.g., box trucks, step vans), electric drivetrain systems, advanced battery integration systems, power conversion systems, energy management systems, and electric powertrains in California (Figure 27) [178].

In this section, we analyze the temporary and recurrent economic impacts of this transition locally and statewide to highlight the possible economic benefits of the ICT regulation.

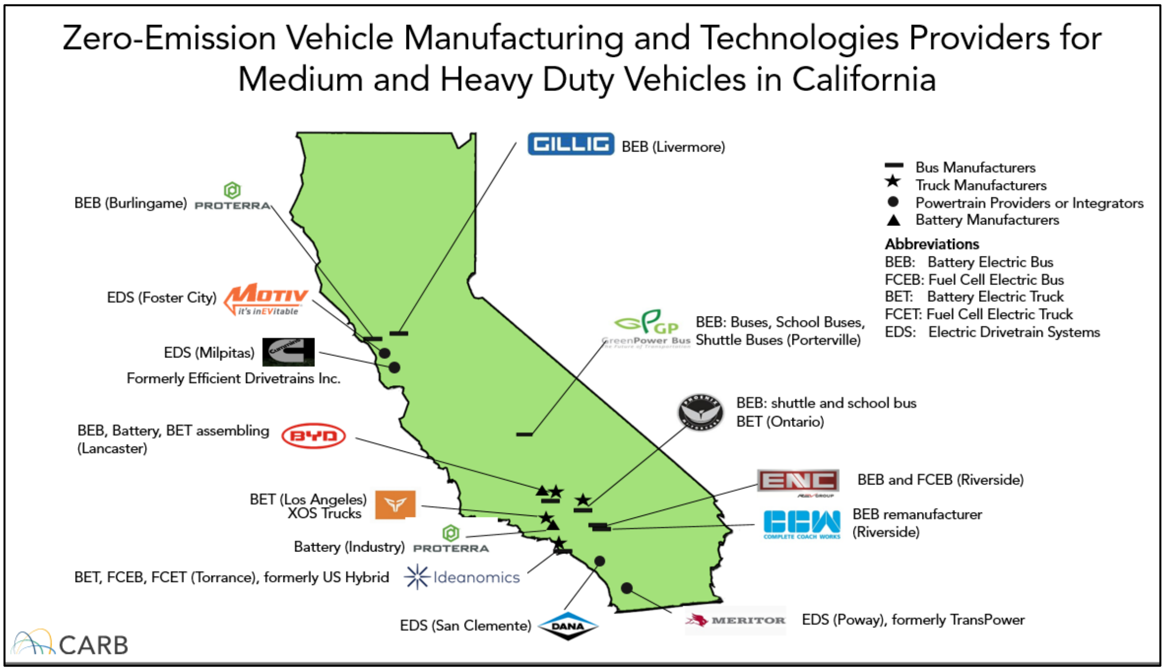

Figure 27. ZEV manufacturing and technology providers in California [178]

9.1 Methodology for Estimating Economic Impacts

The Economic Impact Analysis for Planning (IMPLAN) was applied to quantify the impacts on job, gross domestic product (GDP), income, and industrial output resulting from the investments in new ZEBs and infrastructure, as well as annual operation and maintenance of the ZEB fleets. IMPLAN is a platform for estimating the total impact of structural changes (new industries, sector growth, and demand shocks) in a given region in terms of local jobs, GDP, labor income, industrial output, and taxes. Underlying these analyses is a data set of social accounting matrices that include sectoral, demographic, and governmental data reflecting how the economy of the region operates in a given year. A social accounting matrix reflects economic flows between sectors, consumers, and institutions at the state, county, and ZIP-code levels. In essence, IMPLAN is an input-output model, one of the most commonly used and straightforward methods for estimating economywide impacts induced by a change in demand of a given sector (e.g., an increased demand for new ZEBs).

The demand-driven input-output model is composed of several equations reflecting each sector's production function and representing the structure of an economy as a network of sectors that sell to one another, to local households and governments, and to external markets (exports), as depicted in Figure 28. The outputs from IMPLAN modeling provide a quantitative estimate of the supply chain's responses and the total macro-level impacts from changes in demand for goods or services in a region. Using California-specific multipliers (derived from IMPLAN), we estimated the direct, indirect, and induced[2] effects on employment (temporary and permanent jobs), taxes, and GDP from the ICT regulation resulting from manufacturing, operating, and maintaining ZEBs, as well as from the buildout of the required infrastructure such as electric chargers and hydrogen fuel stations by the transit agencies.

From the total amount of investments in a year (direct effect), part of the goods and services are provided by companies outside California (non-local purchases) and do not generate local impacts. Those are excluded from the analysis based on IMPLAN's regional purchase coefficients that determine the percentage of local purchases for each good/service in the model (regional purchase coefficients vary by year due to the evolving regional economic structure). The amount of spending within California is then used to introduce a demand shock into the model to determine the total economic impact, including jobs created in the state due to these investments. Impacts can be classified as direct, indirect (from supply-chain linkages), or induced (resulting from the spending of wages/salaries by workers) by year.

For this analysis, we used California's 2019 social accounting matrix from IMPLAN (2021, the most recent year available), which reflects the economywide linkages (i.e., sectoral supply chains, population's spending patterns, and transfers between institutions) in that year [179]. Impacts from 2020–2040 were estimated using the 2019 matrix assuming constant prices.

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[2] "Direct effects" refer to those economic impacts generated by the purchase of commodities and services. To supply those commodities/services, however, commodities/services from the local economy are required as inputs to production, other commodities/services are required as inputs to these inputs, and so on. The economic impacts generated by these upstream supply-chain linkages are denoted "indirect effects." Finally, in every step of production in each supply chain, labor is required and remuneration paid. "Induced effects" account for the economic impacts resulting from the spending of such wages/salaries by workers, which create additional rounds of production in the local economy.

Occupational information, including types of occupations, average wages, and education, experience, and training requirements are based on IMPLAN's Occupational Dataset for 2019. The analysis focused on transit agencies that had provided rollout plans by October 2021, which comprise all large transit agencies and one small agency (Table 15). The analysis considered only standard ZEB purchases but all required infrastructure investments (for the entire fleet).

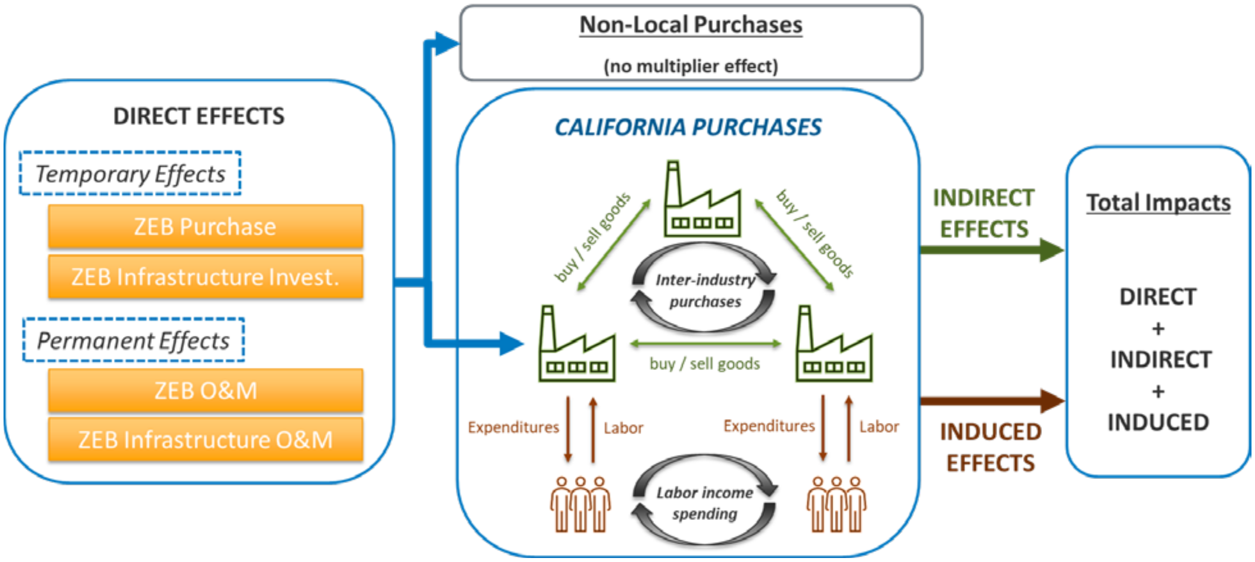

Figure 28. Job analysis IMPLAN workflow

We used the regional purchase coefficients provided by IMPLAN for 2019 to allocate local/non-local purchases and assumed that 85% of BEBs and 22% of FCEBs are manufactured in the state (following the current ZEB fleet distribution). For the temporary impacts (due to infrastructure construction and ZEB manufacturing), lower and upper bounds are shown, reflecting the assumption that all ZEB purchases are from companies outside or within California, respectively. All battery packs for BEBs are assumed to be produced in state. The original sectors in IMPLAN were expanded to account for BEB and FCEB manufacturing industries. Those were created by modifying the original heavy-duty vehicle manufacturing industry with additional data [180–183].

Bus purchases were allocated according to the schedule and type provided by the rollout plan of each transit agency. For those agencies that did not specify ZEB types, it was assumed that 75% are FCEB and 25% BEB, based on the expected future growth of FCEB market share relative to BEBs. Infrastructure investment cost breakdown was based on Foothill Transit's detailed investment plan for BEBs [184] and the heavy-duty refueling station analysis model from Argonne National Laboratory for FCEBs [1]. The annual operation and maintenance cost breakdown for the infrastructure was assumed to be 3% of equipment capital costs for BEBs, and the breakdown provided by Argonne National Laboratory was used for FCEBs [1]. See additional details in Appendix A.5.

Table 15. List of Transit Agencies Analyzed

Transit Agency	County	Acronym	Size
AC Transit	Alameda, Contra-Costa	ACT	Large
City of Santa Clarita	Los Angeles	CSC	Large
City of Santa Monica	Los Angeles	BBB	Large
Foothill Transit	Los Angeles	FHT	Large
Fresno Area Express	Fresno	FAX	Large
Golden Empire	Kern	GET	Large
Los Angeles County Metropolitan Transportation	Los Angeles	LAT	Large
Los Angeles Department of Transportation	Los Angeles	LDT	Large
Long Beach Transit	Los Angeles	LBT	Large
North County Transit	San Diego	NCT	Large
Orange County Transportation	Orange	OCT	Large
OMNITRANS	San Bernardino	OMT	Large
Riverside Transit	Riverside	RTA	Large
Sacramento Regional Transit	Sacramento	SRT	Large
San Diego Metropolitan Transit	San Diego	SDT	Large
San Joaquin Regional Transit	San Joaquin	SJT	Large
San Mateo County Transit	San Mateo	SMT	Large
Santa Clara Valley Transportation	Santa Clara	VTA	Large
San Francisco Municipal Transportation	San Francisco	SFT	Large
SunLine Transit	Riverside	SLT	Small

ZEB annual fuel requirements were based on the VICE model inputs assuming an average annual VMT of 44,061 miles/year/bus. BEB efficiency was assumed to be 2.18 kWh/mi with electricity prices of $0.1311/kWh plus $1.16/kW/month (1,750-kW peak demand). FCEB efficiency was assumed at 8.1 mi/kg with liquid hydrogen price of $7.79/kg. Both buses were assumed to have a replacement period of 12 years. Total annual ZEB purchases and cumulative ZEB fleet sizes for all transit agencies considered are shown in Figure 29.

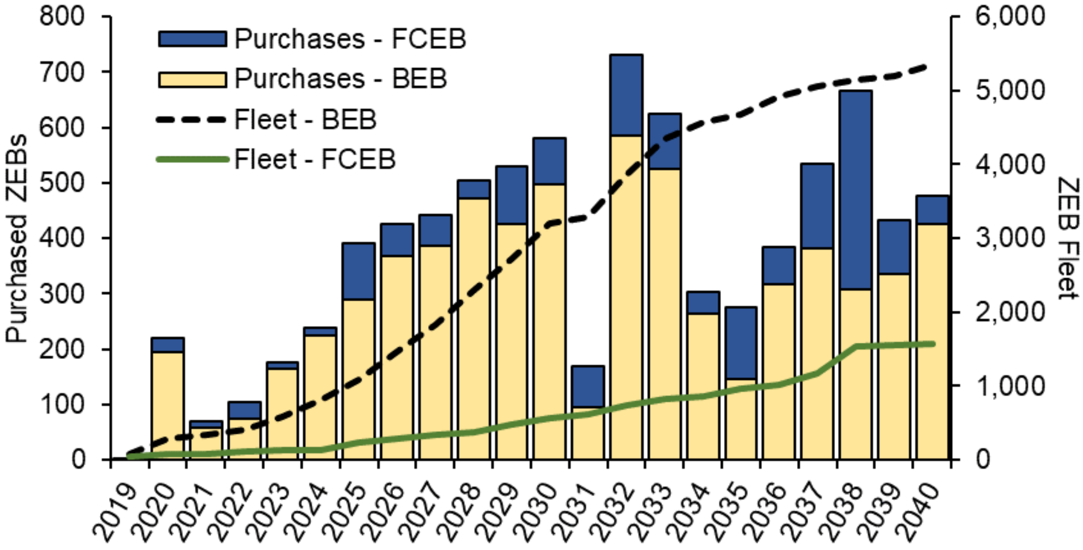

Figure 29. Standard ZEB purchases and total fleet per year

Analysis Limitations

It is important to note that estimates from any input-output analysis should be interpreted within the context of the assumptions employed in the modeling. It is also important to note the primary limitations of the method and analysis. The input-output model employed for this analysis is a static model (representing the economywide linkages and spending patterns in 2019, in particular). The model does not account for dynamic impacts or changes over time. As such, the following results do not account for changes in the economic structure (including electricity grid) over time. Thus, there are no economies of scale or technology changes in any industry (including changes in ZEB operation and maintenance expenses), nor for job losses due to the replacement of internal combustion engine buses. Hence, this is not a net job analysis. Moreover, price effects are not accounted for in this framework. In addition, we did not account for the construction impact of a methane gas reformer for hydrogen production by the City of Santa Clarita Transit District.

9.2 Temporary Economic Impacts

Purchases of new ZEBs and construction of the necessary infrastructure are estimated to add $2.1 billion to California's GDP (Figure 30), generate $240 million in state/county taxes, and generate $3.8 billion in additional industrial output over the 2019–2040 period. Most of these impacts are due to ZEB manufacturing, as construction impacts account for $505 million in GDP. Hence, the choice of bus manufacturer has a significant effect on the total impacts in California. Also, most of the impacts are concentrated in Los Angeles County, where two large ZEB suppliers are located: Proterra and BYD.

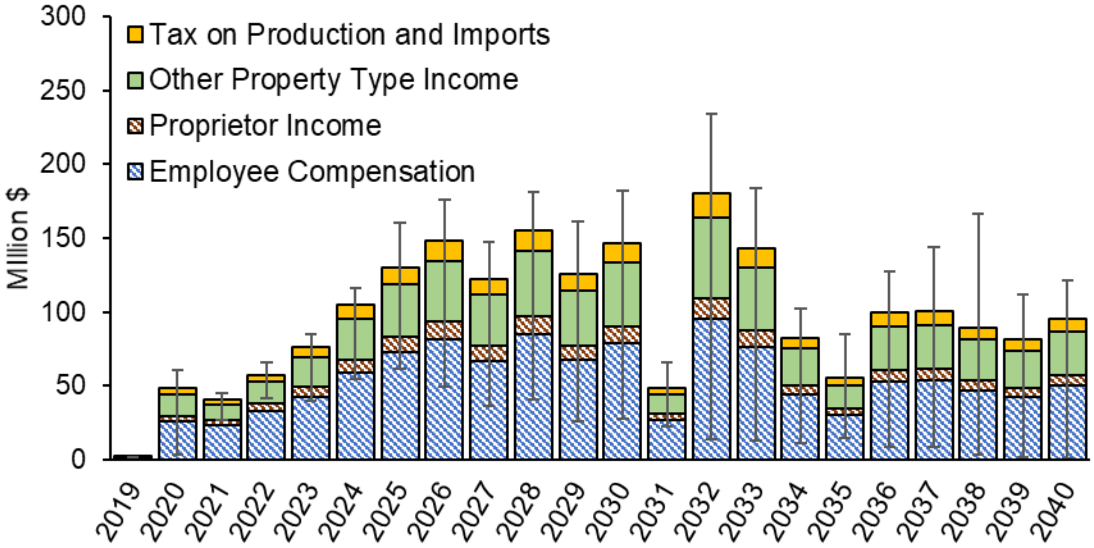

Figure 30. Additional GDP by year and type, temporary effects

On average, 611 jobs per year could be created in California due to ZEB investments between 2019–2040 (Figure 31), of which half are due to indirect/induced effects. As shown in Figure 31, more than one-third of jobs are low skilled (i.e., require a high school diploma or less), and this share is slightly higher for construction-induced jobs than ZEB manufacturing-induced jobs (Appendix A.8). The average profile of the jobs created is shown for 2032, the year with the most investments. Based on the model, almost a quarter of jobs required no previous experience (Figure 32), and average salaries range between $50,000/year and $60,000/year, with median wage distribution higher than those from California in 2019 (Figure 33). Around 29% of the jobs created would be in sales and administrative support occupations (41-0000 and 43-0000) and one quarter in manufacturing and transportation jobs (51-0000 and 53-0000) (Table 16).

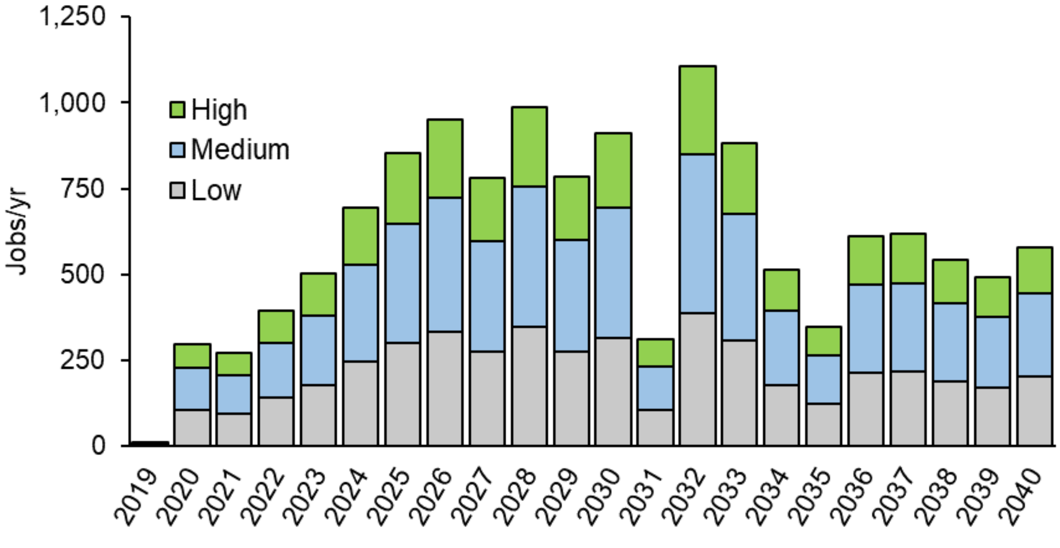

Figure 31. Total employment by skill level per year, temporary effects.

Note: low skill: high school diploma or less; medium skill: associate degree or less; high skill: bachelor's degree or more.

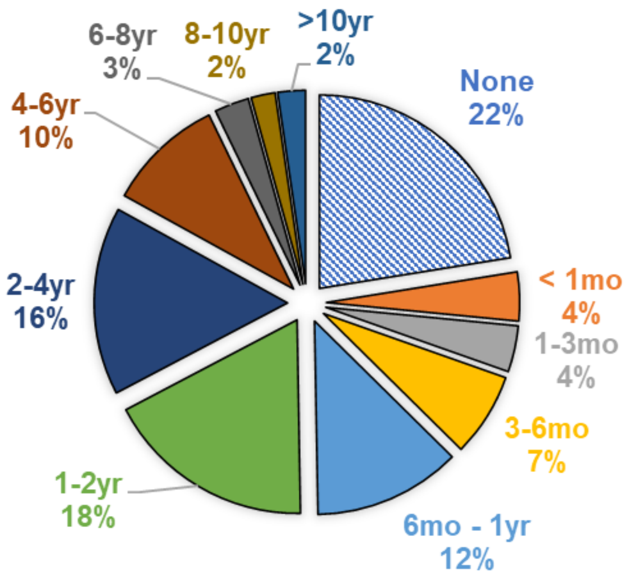

Figure 32. Distribution of required experience for jobs created in 2032

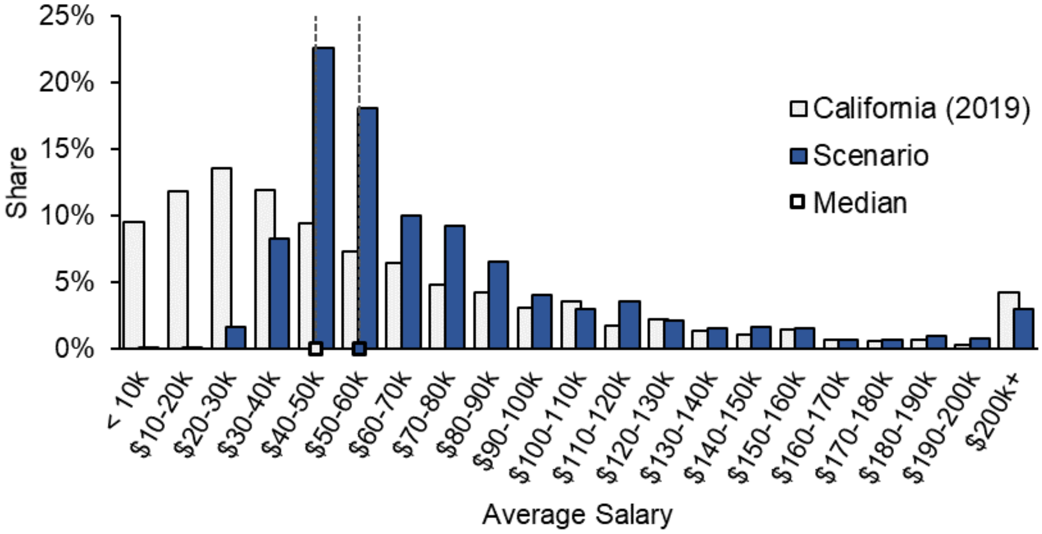

Figure 33. Average annual wage distribution for jobs created in 2032 (2019 dollars).

Source: California data based on the U.S. Census Bureau's American Community Survey: https://datausa.io/

Table 16. Share of Employment by Occupation, Jobs Created in 2032

SOC CODE [A]	OCCUPATION GROUP	SHARE
11-0000	Management Occupations	2%
13-0000	Business and Financial Operations Occupations	5%
15-0000	Computer and Mathematical Occupations	3%
17-0000	Architecture and Engineering Occupations	3%
19-0000	Life, Physical, and Social Science Occupations	0%
21-0000	Community and Social Service Occupations	1%
23-0000	Legal Occupations	1%
25-0000	Educational Instruction and Library Occupations	1%
27-0000	Arts, Design, Entertainment, Sports, and Media Occupations	1%
29-0000	Healthcare Practitioners and Technical Occupations	2%
31-0000	Healthcare Support Occupations	2%
33-0000	Protective Service Occupations	2%
35-0000	Food Preparation and Serving Related Occupations	6%
37-0000	Building and Grounds Cleaning and Maintenance Occupations	2%
39-0000	Personal Care and Service Occupations	1%
41-0000	Sales and Related Occupations	14%
43-0000	Office and Administrative Support Occupations	15%
45-0000	Farming, Fishing, and Forestry Occupations	0%
47-0000	Construction and Extraction Occupations	1%
49-0000	Installation, Maintenance, and Repair Occupations	7%
51-0000	Production Occupations	11%
53-0000	Transportation and Material Moving Occupations	15%
99-0000	Military	0%

[a] Standard Occupational Classification Code (http://www.bls.gov/soc/home.htm).

9.3 Permanent Economic Impacts

Operation and maintenance of both ZEBs and new infrastructure are estimated to add $144 million per year to California's GDP by 2040 (Figure 34). Moreover, we also estimated an additional $19 million in state/county taxes and $248 million in additional industrial output per year. These impacts are more spatially distributed across different counties, driven by the size of the transit agencies.

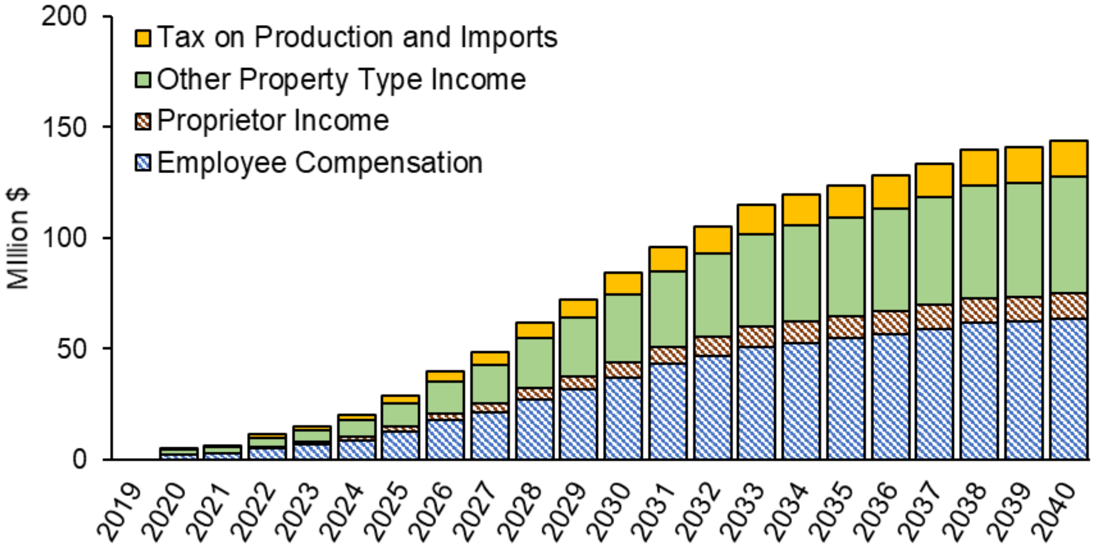

Figure 34. Additional GDP by year and type, permanent effects

By 2040, around 789 jobs/year are estimated to be sustained by the ICT regulation in California (Figure 35), of which 70% are due to indirect/induced effects. As shown in Figure 35, more than one-third of jobs per year are projected to be low skilled (i.e., require a high school diploma or less), almost a quarter of jobs required no previous experience (Figure 36), and average salaries are clustered in the $50,000–$60,000/year range, with median wage distribution higher than those from California in 2019 (Figure 37). From the model results, around 41% of the jobs sustained would be in service sectors (41-0000, 43-0000, and 35-0000) and 14% in manufacturing and transportation jobs (51-0000 and 53-0000) (Table 17).

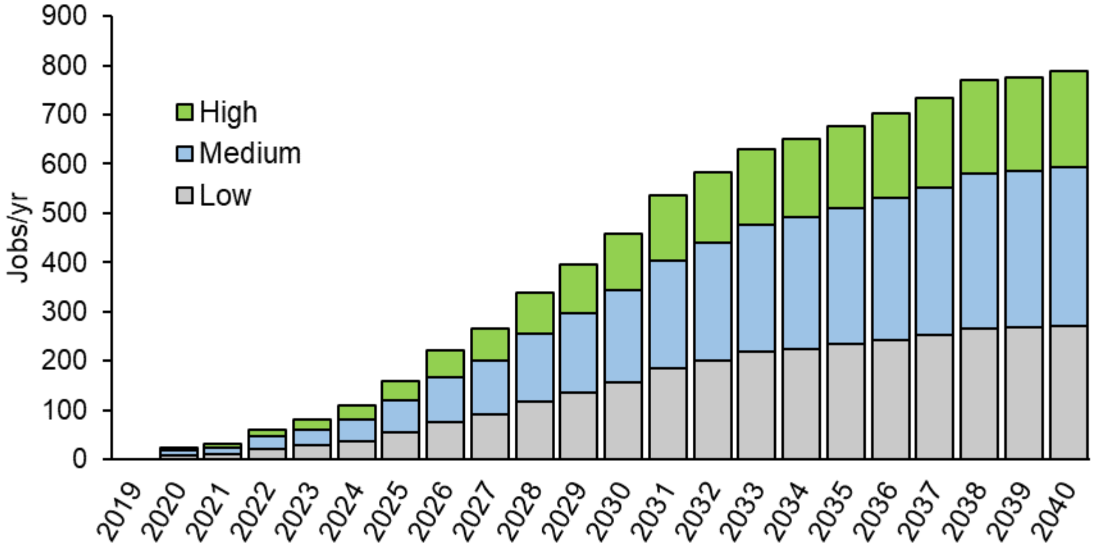

Figure 35. Total employment by skill level per year, permanent effects.

Note: low skill: high school diploma or less; medium skill: associate degree or less; high skill: bachelor's degree or more.

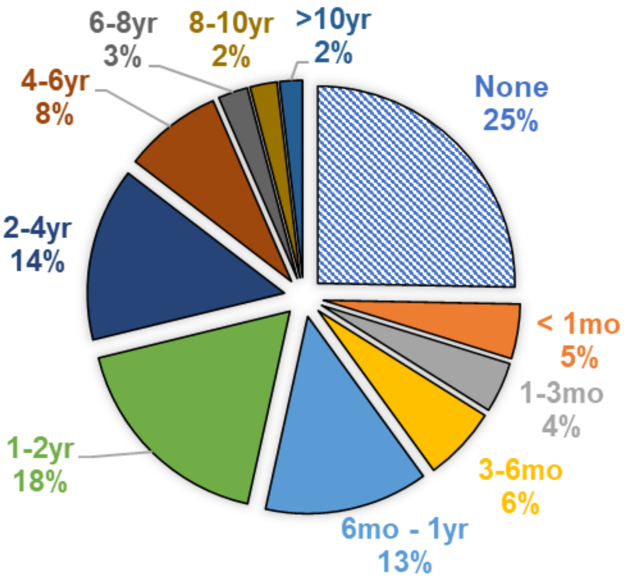

Figure 36. Distribution of required experience for jobs created in 2040

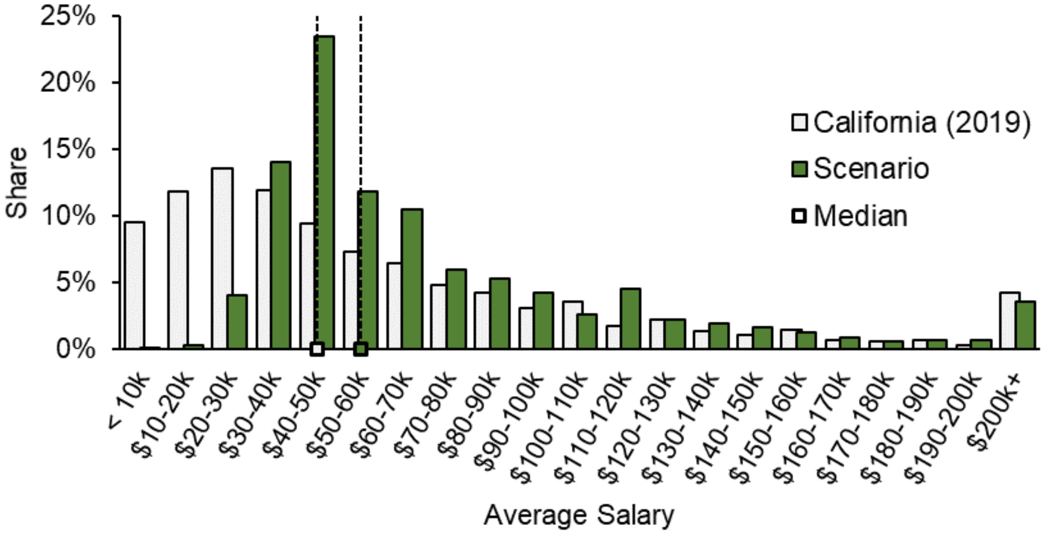

Figure 37. Average annual wage distribution for jobs created in 2040 (2019 dollars).

Source: California data based on U.S. Census Bureau's American Community Survey: https://datausa.io/

Table 17. Share of Employment by Occupation, Jobs Created in 2040

SOC CODE [A]	OCCUPATION GROUP	SHARE
11-0000	Management Occupations	2%
13-0000	Business and Financial Operations Occupations	5%
15-0000	Computer and Mathematical Occupations	2%
17-0000	Architecture and Engineering Occupations	1%
19-0000	Life, Physical, and Social Science Occupations	0%
21-0000	Community and Social Service Occupations	2%
23-0000	Legal Occupations	1%
25-0000	Educational Instruction and Library Occupations	2%
27-0000	Arts, Design, Entertainment, Sports, and Media Occupations	1%
29-0000	Healthcare Practitioners and Technical Occupations	5%
31-0000	Healthcare Support Occupations	5%
33-0000	Protective Service Occupations	1%
35-0000	Food Preparation and Serving Related Occupations	12%
37-0000	Building and Grounds Cleaning and Maintenance Occupations	3%
39-0000	Personal Care and Service Occupations	3%
41-0000	Sales and Related Occupations	16%
43-0000	Office and Administrative Support Occupations	13%
45-0000	Farming, Fishing, and Forestry Occupations	0%
47-0000	Construction and Extraction Occupations	1%
49-0000	Installation, Maintenance, and Repair Occupations	7%
51-0000	Production Occupations	4%
53-0000	Transportation and Material Moving Occupations	10%
99-0000	Military	0%

[a] Standard Occupational Classification Code (http://www.bls.gov/soc/home.htm).

10. Lessons Learned and Remaining Challenges

10.1 Early ZEB Demonstration Lessons Learned

Early adopters of ZEBs emphasize that the success of a ZEB deployment relies on careful planning and early engagement with all partners in the ZEB technology network—vehicle OEMs, infrastructure and technology providers, electric utilities or fuel providers, local officials, and other partners. Planning for ZEBs begins with identifying a good match between available ZEB technologies and specific routes/blocks within an agency's service territory. In some cases, favorable routes are easily identified by the transit agency, but in others, particularly when scaling up to a larger ZEB fleet, a thorough route analysis is necessary to identify and rank the candidate routes for ZEBs. Detailed analysis also helps clarify charging/fueling logistics and determine whether sufficient downtime exists in the current schedules to accommodate charging/fueling time or if schedule modifications are required.

Transit agencies should each develop a ZEB deployment plan or roadmap (e.g., rollout plan), as required by the ICT regulation, that can guide the transition of their specific fleet to ZEBs, including bus technology and infrastructure choices, funding opportunities, procurement steps, and construction timelines. The planning process will require each transit agency to carefully review their fleet inventory and bus replacement schedules, regulatory purchase requirements, route/block requirements and anticipated changes in service levels, available ZEB technology and required infrastructure, facility modifications and/or space constraints, total project costs, and available funding. In some cases, this may require transit agencies to hire a research or consulting entity to assist with this detailed planning process, which will carry additional costs. This planning process will help each transit agency establish a sustainable and achievable long-term plan for transitioning their bus fleet to ZEBs. Selecting the best technology mix and pathway at the beginning of the ZEB transition, based on each transit agency's unique circumstances, will be critical to ensure the most cost-effective scale-up and avoid stranded assets.

Early ZEB adopters have highlighted the importance of reviewing all available incentive funding programs (federal, state, and regional) for eligibility and being proactive in planning and applying for these funds to support the deployment of ZEBs and necessary infrastructure. Many of the funding programs are discretionary and competitively awarded, and some funding programs have different application requirements and timelines, which can make it challenging to pursue awards from multiple funding sources for the same project; however, securing these funds and strategically combining them whenever possible is required for most transit agencies to begin deploying ZEBs.

Evaluations of the initial ZEB demonstrations have tracked the improvement in BEB and FCEB technology performance and costs, helping to inform other transit agencies planning for ZEB deployments. The evaluations have also highlighted the importance of closely monitoring factors such as fuel costs and maintenance costs in order to operate ZEBs cost-effectively. Transit agencies are encouraged to work closely with their bus OEMs to establish initial training programs and maintenance protocols. They are also strongly encouraged to track their progress and share their ZEB experiences with the industry; many other transit agencies (as well as groups in other transportation sectors) have benefitted immensely from the lessons learned and challenges from transit early ZEB adopters.

Transit agencies purchasing BEBs are shifting away from short-range BEBs that require on-route charging (which quickly and frequently recharges a small battery pack) to extended-range BEBs with larger battery packs that utilize plug-in charging. The list of BEB models available today reflects this trend. This is due to a number of factors, including improvements in battery energy density and costs, improvements in DC fast charging technology for plug-in buses, and the cost and complexity associated with siting and installing on-route chargers. It is also a reflection of the preferences of transit agencies and the need for operational flexibility in dispatching their bus fleets. Transit agencies often prefer extended-range BEBs that can be fully charged at the depot and dispatched on a wider variety of routes (potentially increasing to all of the agency's routes), similar to a conventional fleet, rather than being restricted to those routes that align with on-route charging equipment. Utilizing more extended-range BEBs also allows bus routes and schedules to be updated more easily to meet the changing needs of each community. However, there are significant cost, vehicle weight, and space constraints to increasing the onboard energy storage of BEBs, so there is a trade-off between increased driving range, vehicle cost, and passenger capacity.

10.2 Remaining Challenges Related to ZEB Deployment

Despite all the recent advancements in ZEB technologies and the growth of the industry, many challenges remain for transit agencies planning for transition to 100% ZEB fleets. The significant challenges revolve around costs. First and foremost, ZEBs remain more expensive to purchase than the conventional buses being replaced. The high costs are largely driven by propulsion-system components, such as batteries, fuel cells, and electric motors. The component-level costs and overall capital costs are slowly decreasing throughout the ZEB industry, but transit agencies remain heavily reliant on grant funding to purchase new technology buses.

Importantly, transitioning to ZEBs requires new charging or fueling infrastructure that transit agencies are not used to planning for, purchasing, installing, or operating. New infrastructure adds considerable cost and complexity, especially for scaling up a large fleet to ZEBs. In addition, new ZEBs and charging/fueling infrastructure often require additional modifications or upgrades to bus yards (potentially interrupting operations), maintenance facilities, and/or the existing utility grid. The costs associated with these modifications will be unique to each transit agency, but they can be significant investments. For most transit agencies, the necessary infrastructure and facility improvements to support ZEBs are very costly without external grant funding.

The most significant operating cost for ZEBs is the energy cost, which can be variable and difficult to predict for both electricity and hydrogen. Some California utilities have rolled back electricity demand charges on a temporary basis, but they are expected to be reinstated gradually in the future. It is often estimated that ZEB energy costs will be lower than conventional fuel costs on a per-mile basis, and therefore offer savings throughout the life of the bus, but this is not a given in all cases. Careful planning and close monitoring and control of the factors affecting energy costs (e.g., charging time of day and maximum power demand for charging BEBs) are important to ensure that the costs are minimized. Once the electric rate structures are well understood and charging is well managed for BEBs, the energy costs have potential to be more predictable and consistent than for traditional fossil fuels, which fluctuate with the market.

Similarly, the cost of scheduled and unscheduled maintenance can have a significant impact on the total cost of ownership, potentially making the difference between whether a ZEB fleet is more or less expensive than the conventional counterpart. Maintenance support provided by OEMs until transit agency staff are trained and familiar with the technology has been effective at minimizing ZEB maintenance costs for initial deployments, but there is a need for more streamlined support and training for diagnostic/troubleshooting tools (such as for battery systems). Technology advancements and expanded workforce training are important to reduce the maintenance costs. Technology advancements will improve bus reliability and decrease parts costs, and expanded workforce training will help streamline diagnostics and repairs.

Another concern related to the maintenance of ZEBs is vehicle durability/longevity. Transit agencies voiced concern that despite standard test procedures to assess the durability of transit buses, the current generation of ZEBs and associated charging/fueling infrastructure may not last the expected 12 years or more in transit service. ZEB technologies are evolving quickly, and some of the commercial products available for purchase may not have had time to prove their real-world durability to the satisfaction of transit agencies. There is also some concern that replacement parts for ZEBs and charging/fueling stations could become obsolete before the 12-year target lifetime—especially with vehicles and equipment that have already been purchased or will be purchased in the near term. This concern has important implications for the financial aspects of transit agencies' ZEB transition plans. Continued tracking and independent evaluation of key industry metrics is critical to making informed policy decisions.

Daily operating range is still a barrier to scaling up ZEB fleets for many transit agencies, especially as purchase requirements reach full replacement levels. For BEBs, onboard energy storage capacity has increased with recent bus generations, but the larger battery packs contribute to other challenges related to bus capital costs, vehicle weight limits, and passenger capacities. In addition, the sensitivity of operating range to hot and cold environments makes planning and operating BEBs more challenging. BEBs in some cold climates outside of California are currently utilizing diesel fuel-fired heaters to minimize this impact and reduce the operational risk of deploying BEBs. If the current available BEBs cannot meet the daily operating range of all routes/blocks, transit agencies may need to modify their routes or deploy FCEBs. With continued ZEB technology improvements, these vehicles will be capable of meeting transit services as one-to-one replacements.

The ZEB industry still has remaining challenges related to interoperability of recharging and refueling equipment. The harmonization of charging standards and fueling protocols have improved, but more needs to be done to ensure equipment purchased by transit agencies at different times and/or from different OEMs will be compatible with charging and fueling infrastructure that require large upfront investments. Standardization of charging systems will benefit the industry by allowing multiple vehicle types to utilize the same infrastructure. It also reduces capital costs through volume production. Infrastructure suppliers must work with bus OEMs, transit agencies, and providers of third-party telematics devices and operational platforms to ensure seamless integration in the long term.

Finally, not least of the challenges is the development of a workforce trained to operate and maintain ZEBs. Several training programs and centers are currently being created by transit agencies, bus OEMs, educational institutions, and other stakeholders in the ZEB industry. However, there are emerging gaps in developing the skilled workforce needed to maintain, repair, and operate these vehicles; for the most part, transit agencies would prefer to control these operations internally rather than relying on external service contracts. Future workforce development efforts should address the following remaining needs for California transit agencies:

- Training programs need to be improved and expanded to reach regional levels.
- More training is needed as more ZEBs are procured and placed into service.
- Transit agencies are seeking partnerships with academic institutions for better organization and delivery of curricula.
- Certificate training programs are desired to establish specific training levels for individual staff on various topics, such as high-voltage electrical and high-pressure gas systems.
- There are needs for greater state support.

11. Conclusion

11.1 Innovative Clean Transit Program Assessment

CARB’s ICT regulation is the first regulation in the United States that requires a vocational heavy-duty vehicle application to completely transition to zero-emission technologies over time. ZEBs serve as a foundation for transitioning the entire heavy-duty vehicle sector. The deployment of ZEBs can demonstrate the technology viability for the entire medium- and heavy-duty vehicle sector and support California to achieve its air quality, public health, and climate protection goals. As transit agencies deploy ZEBs in their daily operations and help advance the technologies, it is important to ensure they can continue providing their critical services to Californians, especially to transit-dependent riders.

CARB directed staff (Resolution 18-60) to conduct a comprehensive review of program readiness—with multiple metrics included such as costs, performance, and reliability of ZEBs and corresponding infrastructure—prior to initiating any purchase requirement. The NREL/UCB team was awarded the contract by CARB to conduct the comprehensive review, which was divided into two phases to adequately address the purpose laid out in Resolution 18-60. Phase I focuses on the “standard-length” (approximately 40-foot), low-floor-type transit buses. Phase II of the comprehensive review will provide an update to the standard 40-foot bus (from Phase I) and cover a variety of transit vehicle types, including articulated buses, over-the-road coaches, “cutaway” shuttle buses, and double-decker buses. This report represents the findings from Phase I of the review. The results for Phase II are planned to be delivered in 2024.

The objective of Phase I is to determine whether the currently available ZEB technologies in standard buses can be used by large transit agencies to meet the ZEB purchase requirement in 2023, while ensuring transit service or fares are not adversely impacted by the transition. The review also aims to identify the remaining needs necessary for the full transition of the California transit bus fleets, and determine what additional programs, resources, or support are needed by transit agencies. This review is intended to inform and improve policies to advance heavy-duty, zero-emission technologies and inform funding strategies related to zero-emission buses and infrastructure.

The overall approach for the comprehensive review includes the following elements:

- Conduct literature reviews for the latest information on ZEBs, including results of pilot and demonstration projects, incentive funding programs, and available ZEB models and infrastructure.
- Interview ZEB stakeholders—transit agencies, OEMs and technology providers, utilities, and fuel providers.
- Combine analyzed data from NREL’s detailed fleet evaluations and other published ZEB studies.
- Utilize modeling tools to compare economics of ZEBs to conventional bus purchases and to estimate the economic impact of the ZEB transition in California.

11.1.1 ZEB Deployment Momentum and Success

Over a decade of successful partnership and collaboration between transit agencies, OEMs, infrastructure entities, and utility providers has allowed zero-emission technologies to improve and become more widespread. The California transit industry was already a leader in the ZEB transition prior to the ICT regulation, but the regulation has accelerated plans to electrify transit and ensures the state continues on its path to achieve 100% zero-emission transit fleets. Compared to when the ICT regulation was first adopted in 2018, there has been more than a twofold increase in ZEBs. According to the CALSTART 2021 report, California has the most ZEBs in the country, with 1,244 BEBs and 127 FCEBs in service or on order at all public and private institutions, including but not limited to transit agencies [36]. This accounts for nearly 40% of ZEBs in the United States (75% of all FCEBs) and places California far ahead of other states. CALSTART data also show that from the 229 transit agencies operating in the United States and Canada and those that have deployed or purchased ZEBs, 57 (25%) are located in California [35]. CARB's Innovative Clean Transit Reporting Tool is also being used to track ZEB deployments for the ICT regulation. Public transit agencies in California have reported that 336 ZEBs (46 FCEBs vs. 290 BEBs) were in service and another 318 ZEBs (30 FCEBs vs. 288 BEBs) were on order, for a total of 654 purchased ZEBs as of December 31, 2020 [29]. Many California transit agencies, regardless of size, have already deployed ZEBs at least on a small scale and are preparing for large-scale deployments based on experience gained from their initial deployments. As reported in the rollout plans, transit agencies plan to acquire approximately 8,000 standard ZEBs in the next 2 decades. FCEB purchases account for approximately 1,200 of the buses, BEBs account for 5,250 of the buses, and the zero-emission technology for the remaining 1,550 buses remain to be determined.

11.1.2 Program Readiness for the 2023 ZEB Purchase Requirement

Evaluations of early pilot deployments have demonstrated the successful operation of ZEBs, indicating that ZEBs are indeed capable of meeting most transit service requirements. The latest TRL review on BEBs and FCEBs was noted in CARB's *Proposed Fiscal Year 2021-22 Funding Plan for Clean Transportation Incentives*, in which it identifies both BEBs and FCEBs at a TRL of 9 for transit buses when compared to other on-road vocational applications [20]. A TRL of 9 indicates that the technology is in its final form (deployment marketing) and support is available for commercial products. Some early-generation technology buses, in comparison to conventional internal combustion engine buses, need improvements in areas that include bus availability, reliability, and driving range (for BEBs). It is important to note that the technologies are continuously improving and BEBs can meet a fair number of transit service requirements, especially when different charging methods are combined.

Despite the pandemic's impact that generated both near-term challenges and long-term uncertainties, transit agencies maintain their efforts in meeting the 2040 goal of transitioning to 100% ZEB fleets. Large transit agencies together have accrued 107 bonus credits by the end of 2020 and received about 450 HVIP vouchers by the end of April 2022. More vouchers are anticipated to be applied for by the large transit agencies in 2022.

Based on the information collected and evaluated under this report, it appears that the California transit industry is well positioned to proceed with the 2023 requirement of 25% of new bus purchases being ZEBs for large transit agencies. This is supported by large transit agencies' ZEB rollout plans; momentum developed from over a decade of ZEB demonstrations and deployments; continued product development and refinement led by the transit industry; a supportive environment for ZEBs as described previously; and successful partnership and collaboration of California transit agencies, vehicle manufacturers, charging and fuel equipment suppliers, utility providers, and others.

11.2 Toward a Complete Fleet Transition

With the readiness for the 2023 ZEB purchase requirements, California should continue to work toward removing limitations for the large-scale and complete transition to ZEBs. Early demonstrations have highlighted successes but also identified areas for enhancement or improvement. To achieve a successful transition to 100% ZEB transit fleets in the coming years, additional coordination, focus, and resources are necessary. Specifically, the following areas should be addressed:

- Sustained progress from the vehicle, equipment, and infrastructure manufacturing base is needed to continue driving down costs, improve reliability, and optimize performance.
- Expansion of charging and fueling infrastructure is a fundamental need that will require coordinated efforts and forward-looking planning by transit agencies, utilities, and developers.
- Comprehensive and standardized training programs are needed to develop a highly skilled workforce that can improve the efficiency and cost of maintaining ZEB equipment while creating new jobs and ensuring safety.
- Financial support for purchasing, installing, and operating ZEBs and the related fueling/charging equipment is necessary.

11.2.1 Sustained Vehicle, Equipment, and Infrastructure Progress

Pilot deployments of standard ZEBs have demonstrated successful operation in a variety of transit service, but some deployments of these early-generation products have also indicated that driving range (for BEB), reliability, and service support need continued improvement to fully meet transit agencies' operational needs. ZEB OEMs have been actively working on these enhancements based on the feedback received and lessons learned from early deployments, and are featuring improvements in the newer generations of ZEBs.

Some of the lower availability for early ZEB deployments may be attributed to troubleshooting issues and training maintenance staff, but availability is generally expected to improve as ZEB technologies continue to mature and operators gain more experience with the technologies. Durability/reliability of BEBs and FCEBs also needs to be improved before they are comparable to conventional buses. Variability in daily driving range may pose a near-term challenge for some transit agencies, which will diminish as battery energy density and ranges increase over time. In the meantime, transit agencies may incorporate operational and technical solutions. Operationally, transit agencies may initially choose BEBs for less-demanding routes and may expand driving training. Technically, transit agencies may choose bus models with larger battery packs (extended range), incorporate intermediate fast charging along some routes, or choose FCEBs. Additional near-term progress is expected to help transit agencies achieve full transitions to ZEBs in the coming years.

Besides the progress being made on both battery-electric and fuel cell electric buses, transit agencies are also actively working with charger OEMs, hydrogen fuel providers, and utility companies to deploy more charging and hydrogen fueling infrastructure and prepare for transitioning to 100% ZEB fleets. Deployment of charging and hydrogen fueling infrastructure at the transit agencies requires significant time and resources. Early coordination with these stakeholders for the equipment specifications, site preparation procedures, installation tasks, and optimized charging/fueling strategies is important to produce acceptable designs and protocols that meet the fleet's site and operational requirements and allow for future expansion.

Maintenance costs are also expected to decrease as transit agencies gain familiarity with maintaining and repairing ZEBs, and as replacement parts for propulsion systems become less expensive and more readily available from OEMs and other suppliers.

Numerous commercial ZEB models are available today from multiple bus manufacturers. BEBs are offered with several choices for charging type and energy capacity to meet the wide range of transit agencies' specific needs. Most transit agencies are trending toward selecting plug-in charging and BEBs with larger batteries due to the operational flexibility they provide. Similarly, FCEBs are generally considered to provide a one-to-one replacement option for transit agencies and can be operated and fueled very similar to conventional buses.

11.2.2 Expansion of Charging and Fueling Infrastructure

Based on the early deployment experience, some transit agencies have voiced concerns regarding the expansion of charging and fueling infrastructure. Importantly, transitioning to ZEBs requires new charging or fueling infrastructure that transit agencies are not used to planning for, purchasing, installing, or operating. New infrastructure adds considerable cost and complexity, especially for scaling up a large fleet to ZEBs. It requires coordinated efforts and forward-looking planning by transit agencies, utilities, and developers.

Installing chargers to deploy a small number of BEBs is usually a straightforward process with minimal costs. Expanding from a small pilot fleet to a large fleet of BEBs, however, requires careful planning to scale up the infrastructure in a way that minimizes costs, project timelines, and operational disruptions. Large infrastructure projects requiring utility upgrades can take several months or more than a year to complete, including the necessary permitting. Transit agencies with experience operating BEBs emphasize it is especially important to communicate with the electric utility as early as possible to coordinate on the infrastructure timing and best approach to meet the needs of the electric fleet.

New ZEBs and charging/fueling infrastructure often require additional modifications or upgrades to bus yards, maintenance facilities, and/or the existing utility grid. Depending on the technology and level of total power or system upgrades needed, the upfront costs associated with new ZEB infrastructure can be high for transit agencies, yet it is an essential part of transitioning to ZEBs. Better planning and federal and state funding, along with utility-based incentives to support the expansion of electric charging or hydrogen fueling infrastructure, will be critical to achieving a successful transition to 100% ZEB fleets.

11.2.3 Comprehensive Training Programs To Develop a Highly Skilled Workforce

Another important topic for ZEB implementation is the workforce development and human operations and resources needed to support the physical transition to new generations of bus technology. This is a challenge to find experienced staff, yet it also serves as an opportunity for workforce development. Transit agencies employ various strategies for achieving their training goals, working closely with bus OEMs, BEB charger manufacturers, hydrogen fuel providers, hydrogen station developers, and established training programs for operators, mechanics, and maintenance workers. Many transit agencies also work proactively with fire safety officials on first responder training. OEMs have developed training centers and partnered with community colleges and other institutions to create diverse and robust training programs that will equip individuals with the knowledge and skills necessary to support a mature ZEB industry well into the future. In addition, several training initiatives are emerging at the national and state level. In 2021, CEC's Clean Transportation Program and CARB jointly allocated up to $6.8 million in grant funds for Inclusive, Diverse, Equitable, Accessible, and Local (IDEAL) ZEV Workforce Pilot projects that will provide workforce training and development that support ZEVs, ZEV infrastructure, and ZEV-related commercial technologies in California [14]. Eight entities were awarded under this program. In addition, CARB has instructed CALSTART, who administers the HVIP program, to allocate $250,000 of the HVIP outreach funding to support SunLine Transit Agency's training program at its West Coast Center of Excellence in Zero-Emission Technology. This training program focuses on maintaining and operating ZEBs in public fleets. Public and private organizations, including transit agencies, colleges, private industry, and government agencies, are collaborating with SunLine Transit Agency to develop training and resources for ZEB maintenance, including all kinds of alternative and emerging energy technologies. Investment in this training program could benefit transit agencies and school districts immediately.

Future workforce development efforts should address the following remaining needs for California transit agencies:

- Training programs need to be improved and expanded to reach regional levels.
- More training is needed as more ZEBs are procured and placed into service.
- Transit agencies are seeking partnerships with academic institutions for better organization and delivery of curricula.
- Certificate training programs are desired to establish specific training levels for individual staff on various topics, such as high-voltage electrical and high-pressure gas systems.
- There are needs for greater state support.

11.2.4 Financial Support for ZEB Purchase and Deployment at Early Stage

The most significant challenges to ZEB adoption are the vehicle capital and infrastructure costs in early years, as well as the long-term stability and projection of electricity or hydrogen costs. To date, the capital costs for BEBs and FCEBs are still higher than that of conventional buses, although costs have been decreasing. Depending on the technology and level of total power or system upgrades needed, the upfront costs associated with new ZEB infrastructure can be high, yet it is an essential part of transitioning to ZEBs. Federal and state funding, along with utility-based incentives to support the expansion of electric charging or hydrogen fueling infrastructure, will be critical to achieving a successful transition to 100% ZEB fleets.

11.3 Closing Remarks

This report provides a first-phase comprehensive assessment of the state of zero-emission transit bus implementation in California, with a focus on implementation progress and status of standard ~40-foot transit buses. As previously mentioned, the entire market performance examined under this comprehensive review suggests that the California transit industry is well positioned to proceed with the ICT regulation’s 2023 requirement of 25% of new bus purchases being ZEBs for large transit agencies.

Experience from using zero-emission technologies in transit buses and demonstrating their viability will benefit the market for the same technologies to be used in other heavy-duty vehicle applications, such as school buses, as well as drayage, delivery, and yard trucks, and could possibly serve as a model for other states wanting to achieve zero-emission fleet transition goals. Successful transformation to zero-emission technologies in these various transportation sectors will ensure enormous emissions reductions and advance the long-term health and climate protection goals in California and our nation.

Advancement in these areas will not be possible without continued successful partnership of transit agencies with bus manufacturers, technology providers, infrastructure providers, and the state to better understand transit agencies’ needs and to provide sufficient and adequate support for a smooth and successful transition.

Given the uncertainties associated with the continuing evolution of ZEB and infrastructure technology performance and cost, there is a critical need to have an active program to collect up-to-date data and facilitate communications between key stakeholders including the state, transit agencies, utilities, and the vehicle and infrastructure manufacturing industry. This information base will help inform manufacturers on where to focus improvements, support data-driven purchase and deployment decisions by the transit industry, help the state assess and adapt policies, and inform the research community on where to invest funding to accelerate technology development.

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Appendix

A.1 California Organizations With Active ZEBs

Table A-1. California Organizations With Active ZEBs [35]

#	State	Transit Agency
1.	CA	Alameda-Contra Costa Transit District (AC Transit)
2.	CA	Anaheim Resort Transportation
3.	CA	Antelope Valley Transit Authority (AVTA)
4.	CA	Central Contra Costa Transit Authority (CCTA / County Connection)
5.	CA	Culver City Bus
6.	CA	Foothill Transit
7.	CA	Golden Empire Transit District (GETbus)
8.	CA	Gardena Transit (GTrans)
9.	CA	Los Angeles County Metropolitan Transportation Authority (LA Metro)
10.	CA	Long Beach Transit
11.	CA	Montebello Transit
12.	CA	Monterey-Salinas Transit
13.	CA	Orange County Transportation Authority (OCTA)
14.	CA	Sacramento Regional Transit District (SacRT) and Yolo County Transit (Yolo Bus)
15.	CA	San Diego Metropolitan Transit System (San Diego MTS)
16.	CA	San Francisco Municipal Transportation Agency (SF Muni)
17.	CA	San Joaquin Regional Transit District
18.	CA	Santa Barbara Metropolitan Transit District
19.	CA	Santa Clara Valley Transportation Authority (VTA)
20.	CA	Santa Cruz Metropolitan Transit Districts
21.	CA	Solano County Transit
22.	CA	SunLine Transit
23.	CA	Tri Delta Transit (Antioch Transit/Eastern Contra Costa Transit Authority)
24.	CA	Victor Valley Transit Authority
25.	CA	Yosemite National Park
26.	CA	Visalia Transit
27.	CA	We Drive U, Inc.

A.2 List of Rollout Plans

List of rollout plans submitted to CARB as of September 2, 2021 [1].

Table A-2. Rollout Plans Completed by Large Transit Agencies

Agency
Alameda-Contra Costa Transit District
City of Los Angeles Department of Transportation
City of Santa Clarita
City of Santa Monica, Big Blue Bus
Foothill Transit
Fresno Area Express
Golden Empire Transit District
Golden Gate Bridge, Highway and Transportation District
Long Beach Transit
Los Angeles County Metropolitan Transportation Authority
North County Transit District
Omnitrans
Orange County Transportation Authority
Riverside Transit Agency
Sacramento Regional Transit District
San Diego Metropolitan Transit System
San Francisco Municipal Transportation Agency
San Mateo County Transit District
San Joaquin Regional Transit District
Santa Clara Valley Transportation Authority

Table A-3. Rollout Plans Completed by Small Transit Agencies (Due June 30, 2023)

Agency
SunLine Transit Agency

A.3 Available ZEB Models

Table A-4. List of Available ZEB Models for Standard, Low-Floor-Style Transit Buses

Power Source	OEM	Model	Length (ft)	Curb Weight (lbs)	Gross Vehicle Weight Rating (lbs)	Seated Passengers	Electrical Energy (kWh)	H_2 (kg)	Nominal Range (mi)	Altoona Test Report Number
Electric	ARBOC	Equess CHARGE	30	22,500	33,000	up to 25	350		210	
Electric	ARBOC	Equess CHARGE	35	23,650	33,000	up to 33	437		230	
Electric	BYD	K7M ER	29.9	28,650	37,479	20	313		up to 196	
Electric	BYD	K7M	30.7	23,545	31,967	22	215		up to 158	476
Electric	BYD	K8M	35.8	32,120	43,431	32	391		up to 196	
Electric	BYD	K9M	40.2	32,190	43,431	37	313		up to 157	527
Electric	BYD	K9S MD	40.9	35,140	44,754	42	446		up to 203	441
Hydrogen	ENC	Axess FC	35		44,300	35			260	
Hydrogen	ENC	Axess FC	40		44,300	43		50	260	491
Electric	Gillig	Low-floor BEB	29, 35, 40	29,000		38	444		150	
Electric	Green Power	EV250	30		31,966	25	up to 260		up to 150	
Electric	Green Power	EV350	40	31,320	37,479	40	up to 400		up to 200	
Electric	New Flyer	Xcelsior Charge NG	35	27,600		up to 32	350		179	
Electric	New Flyer	Xcelsior Charge NG	35	27,600		up to 32	440		220	
Electric	New Flyer	Xcelsior Charge NG	40	28,850		up to 40	350		174	
Electric	New Flyer	Xcelsior Charge NG	40	28,850		up to 40	440		213	
Electric	New Flyer	Xcelsior Charge NG	40	28,850		up to 40	525		251	
Hydrogen	New Flyer	Xcelsior Charge H2	41	32,250		40	160	37.5	350	501
Electric	Nova	LFSe	40	30,140		up to 37	76		25	493
Electric	Nova	LFSe+	41			up to 41	up to 564		211–292	
Electric	Proterra	ZX5 35ft	36.9	26,358	42,000	29	225		95–125	
Electric	Proterra	ZX5+ 35ft	36.9	29,658	42,000	29	450		172–240	
Electric	Proterra	ZX5 40ft	42.5	26,649	43,650	40	225		92–120	
Electric	Proterra	ZX5+ 40ft	42.5	29,849	43,650	40	450		163–232	
Electric	Proterra	ZX5max 40ft	42.5	33,149	43,650	40	675		221–329	

A.4 NREL ZEB Evaluations Included in Maintenance Data Meta-Analysis

Table A-5. NREL ZEB Evaluations [103]

Bus Type	Fleet Size	Transit Agency	Model Year	OEM	Model	Nominal Size (ft)	Months of Data Collected
BEB	4	CCCTA	2016	Gillig		30	12
BEB	12	Foothill Transit	2014	Proterra	BE35	35	81
BEB	2	Foothill Transit	2016	Proterra	Catalyst FC	40	48
BEB	14	Foothill Transit	2017	Proterra	Catalyst E2	40	12
BEB	3	KC Metro	2015	Proterra	Catalyst	40	12
BEB	10	Long Beach Transit	2015	BYD		40	12
CNG	8	Foothill Transit	2014	NABI	BRT	40	75
CNG	14	Foothill Transit	2017	New Flyer	Xcelsior CNG	40	12
CNG	8	Long Beach Transit	2014	Gillig		40	12
CNG	10	OCTA	2016	New Flyer	Xcelsior CNG	40	14
CNG	5	SunLine	2011				58
CNG	5	SunLine	2016	New Flyer	Xcelsior CNG	40	31
CNG	5	SunLine	2019	New Flyer	Xcelsior CNG	40	11
Diesel	10	AC Transit	2013	Gillig		40	49
Diesel	5	AC Transit	2017	Gillig		40	12
Diesel	7	CCCTA	2014	Gillig		30	12
Diesel	3	KC Metro	2015	Gillig		40	12
FCEB	10	AC Transit	2019	New Flyer	Xcelsior H2	40	12
FCEB	10	OCTA	2018	New Flyer	Xcelsior H2	40	14
FCEB	3	SunLine	2014	ENC	Axess (AFCB)	40	≤61
FCEB	5	SunLine	2018	New Flyer	Xcelsior H2	40	20
FCEB	5	SunLine	2018	ENC	Axess (AFCB)	40	10-16

A.5 Resources for Transit Agencies Transitioning to ZEB Fleets

American Public Transportation Association (APTA) Zero Emission Fleet Committee: https://www.apta.com/member-resources/committees/clean-propulsion-support-technology/

The Zero Emission Bus Resource Alliance (ZEBRA): http://zebragrp.org/

California Transit Association (CTA) ZEB Task Force: https://caltransit.org/ (CTA home page)

SunLine's West Coast Center of Excellence in Zero-Emission Technology (CoEZET): https://www.sunline.org/alternative-fuels/west-coast-center-of-excellence-in-zero-emission-technology

A.6 Websites for Transit ZEB OEMs

ARBOC: https://arbocsv.com/models/equess-charge/

BYD: https://en.byd.com/bus/

Complete Coach Works (CCW): https://completecoach.com/services-alternative-fuel-electric-conversions/

ENC: https://www.eldorado-ca.com/hydrogen-hybrid-bus

GILLIG: http://www.gillig.com/battery-electric

GreenPower: https://greenpowermotor.com/gp-products/ev350-bus/

Lightning eMotors: https://lightningemotors.com/buses/

New Flyer: https://www.newflyer.com/buses/

Nova: https://us.novabus.com/blog/bus/lfse-plus/

Proterra: https://www.proterra.com/vehicles/zx5-electric-bus/

A.7 IMPLAN Model – Assumptions and Data Sources

Table A-6. Detailed Assumptions and Data Sources for IMPLAN Model

	Model	Sources
INFRASTRUCTURE		
BEB depot chargers	Based on a depot with 95 325-kW chargers and 190 pantographs (320 bus capacity)	Capital cost breakdown: [184] Price normalization: [184] Annual operation and maintenance cost: 3% equipment cost
BEB on-route chargers	Based on construction costs for an average 450-kW charger	Capital cost breakdown: [186] Price normalization: [187,188] Annual operation and maintenance cost: 3% equipment cost
FCEB hydrogen station	Based on an average heavy-duty refueling station, 350 bar via liquid hydrogen pump/vaporization	Capital cost breakdown: [185] Price normalization: [185] Annual operation and maintenance cost: [185]
ZEB MANUFACTURING		
BEB	Based on internal combustion engine bus manufacturing, modified to account for batteries and electric drivetrains	Production structure: [180–182] Demand: rollout plans for the transit agencies [a]
FCEB	Based on internal combustion engine bus manufacturing, modified to account for fuel cells and electric drivetrains	Production structure: [180–183] Demand: rollout plans for the transit agencies [a]
ZEB OPERATION & MAINTENANCE		
BEB	Maintenance: $0.46/mile Efficiency: 2.18 kWh/mi Electricity: $0.1311/kWh + $1.16/kW/month (1,750-kW peak demand) Life: 12 years	Cost breakdown: NREL data for transit agencies Fuel data: VICE model
FCEB	Maintenance: $0.43/mile Efficiency: 8.1 mi/kg Liquid hydrogen: $7.79/kg Life: 12 years	Cost breakdown: NREL data for transit agencies Fuel data: VICE model

[a] For those agencies that did not specify ZEB types in their rollout plans, we assumed that 75% are FCEBs and 25% BEBs.

A.8 IMPLAN Model – Total Employment by Skill Level per Year (Temporary Impacts)

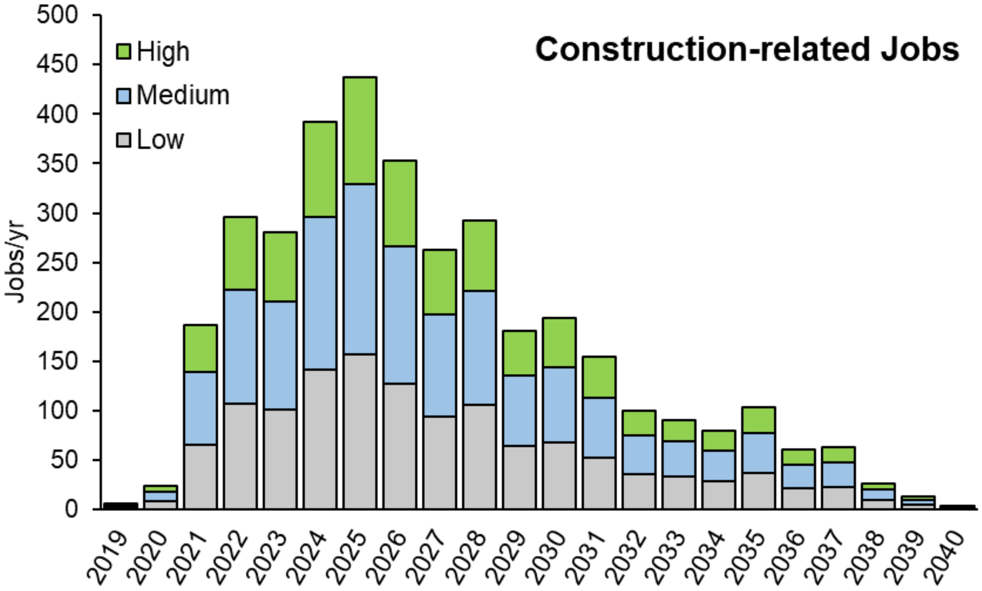

Figure A-1. Construction-related jobs

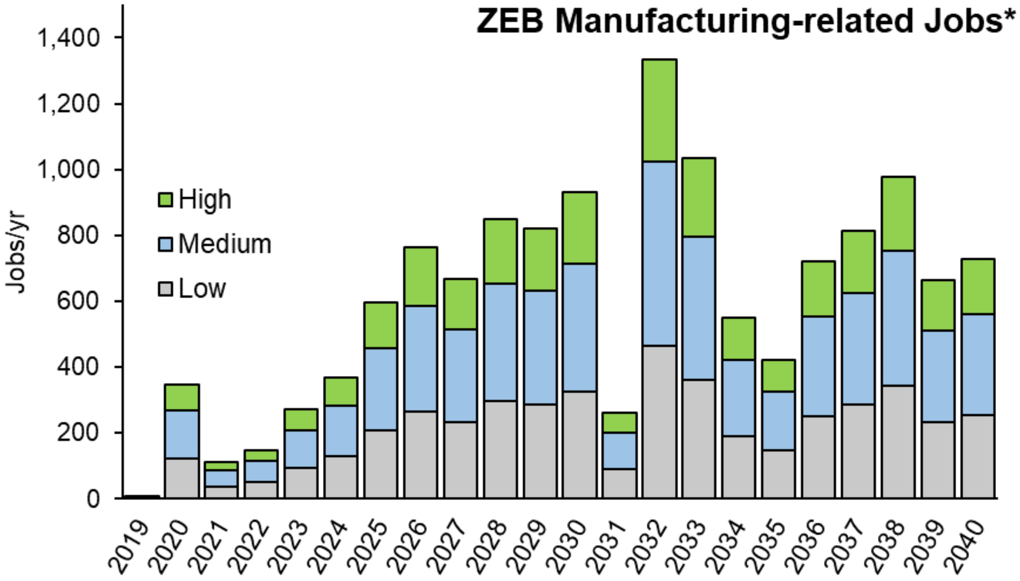

Figure A-2. Manufacturing-related jobs.

* Assuming all ZEB purchases are in California.