California Statewide Transit Agency Deployment Toolkit

In Partnership With:

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The Center for Transportation and the Environment's (CTE) mission is to improve the health of our climate and communities by bringing people together to develop and commercialize clean, efficient, and sustainable transportation technologies. CTE would like to thank the following staff who contributed to this publication:

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Glossary of Terms

Altoona Testing:	Transit buses funded by FTA grant funding must meet FTA's bus test requirements. The testing center is operated by Penn State University near Altoona, PA, earning the nickname of "Altoona testing" for the standard tests covering safety, structural integrity, durability, performance, maintenance, noise, fuel economy, and emissions.
Availability:	Measure of how often a bus is available to be used in revenue service. The National Laboratory of the Rockies (NLR) typically uses the following categories for availability: • In-service (road calls should also be tracked on days when the bus is put into service) • Event/Demonstration • Not used • Training • Not available to be put into service
Battery Electric Bus:	Zero-emission bus driven by electric motors using energy from onboard batteries that are charged from an external source.

Battery Management System (BMS):	Monitors energy, as well as temperature, cell or module voltages, and total pack voltage and adjusts the control strategy algorithms to maintain the batteries at uniform state of charge and optimal temperatures. The BMS is programmed to optimize battery life and set limits so users are not able to damage the battery through use.
Block:	Refers to the daily schedule assignment for an individual bus. A driver schedule is known as a “run.”
Buy America Certification:	Provision requiring that steel, iron, and manufactured goods purchased using federal funding must be produced domestically in the United States.
Charge Management:	Optimization of charging processes to meet service needs and minimize utility costs.
Charge Modeling:	Recommended component of a BEB performance evaluation to understand the capabilities, limitations, and costs of charging alternatives. Charge modeling evaluates the effectiveness of planned charging schedules, based on the specifications of the bus and charging equipment, as well as a transit agency's service plan and electricity rate schedule.

Charging Equipment:	The equipment that encompasses all the components needed to convert, control and transfer electricity from the grid to the vehicle for the purpose of charging batteries. May include chargers, dispensers, controllers, transformers, switchgear, etc.
Charging Station:	The location that houses the charging equipment connected to a utility’s electric service to provide electricity to a vehicle’s battery system through a charging interface.
Commissioning:	Process to verify that the fueling equipment (i.e., charging stations for BEBs, hydrogen fueling stations for FCEBs) functions according to design objectives and technical specifications before approval for routine use. All charging or hydrogen fueling equipment must be commissioned with each bus.
Cryogenic Storage:	Required for the storage of liquid hydrogen at ultra-low temperatures, since the boiling point of hydrogen at one atmosphere pressure is -252.8°C.

Demand Charges:	A charge by utilities that is often based on the highest amount of power (kilowatts) used at a given time. The utility measures demand over a given period of time (i.e., 15-minute increments) and charges the customer based on the highest demand recorded over the billing cycle. Depending on the rate structure, demand rates may also vary by the amount of power used and the time of day or season of the year it is used. Demand charges are put in place to cover the cost of utility infrastructure needed to meet the highest electricity demand at any time, since the electric utility must be able to meet the power demand for all of its customers at the instant that it is required.
Depot Charging:	Centralized BEB charging at a transit agency's garage or maintenance facility. With depot charging, BEBs must be taken out of service to charge.
Dispenser:	Physical unit that delivers fuel (electricity, hydrogen, diesel, etc.) to the vehicle via a conduit and connector.
Duty Cycle:	Information regarding how a vehicle is used, which includes (but is not limited to): hours per day; days per week; total miles; typical load profile; and peak load profile.
Electrolysis:	Method to produce hydrogen fuel where electricity is used to split water into hydrogen and oxygen using an electrolyzer.

Energy:	Quantity of work. While BEBs measure energy directly in kWh, FCEBs and conventional vehicles track fuel consumption (kg of hydrogen or gallons of diesel), which correspond to stored energy and can be converted into common energy units for comparison.
Fleet Transition Plan:	A plan that outlines the timeline, preferred technology, and costs to replace a fleet of conventionally fueled vehicles with zero-emission vehicles. Also includes plans to scale fueling infrastructure over time, to support the incremental deployment of ZEBs
Fuel Cell Electric Bus:	A zero-emission bus that utilizes electric motors, onboard hydrogen storage, a fuel cell system, and batteries. The fuel cell uses hydrogen to produce electricity, with the waste products of heat and water. The electricity charges the batteries, which store energy until needed by the electric drive motor for propulsion and auxiliary loads.
Greenhouse Gas Emissions (GHGs):	Gases in Earth’s atmosphere that trap heat. Common direct GHGs associated with diesel combustion include carbon dioxide (CO2), nitrous oxide (NO2), volatile organic compounds (VOCs), and particulate matter (PM). Other indirect greenhouse gases emitted from combustion include carbon monoxide (CO), other nitrous oxides (NOx), and volatile organic compounds (VOCs). Particulate matter (PM) and all gases listed except carbon dioxide reduce local air quality.

Gross Vehicle Weight Rating:	The maximum total weight as determined by the vehicle manufacturer, at which the vehicle can be safely and reliably operated for its intended purpose.
Hydrogen Fueling Station:	The location that houses the storage, compression, and dispensing equipment to supply fuel to hydrogen fuel cell electric buses. The station may also include hydrogen production equipment.
Inductive Charger:	A method of charging a BEB without a physical connection between the charger and vehicle. Energy is transferred wirelessly using inductive coupling between a magnetic charge coil beneath roadways and a receiving coil onboard the bus. It uses the same principle as wirelessly charging a cell phone, but at a much larger scale.
Key Performance Indicator:	High-level metric selected to measure progress toward an intended result.

On-route Charging:	A method of charging a BEB while the bus is in service, also known as opportunity charging. Characterized by high power (up to 450kW) and short duration (measured in minutes, not hours) to store enough energy to operate until the next charge event. With proper planning, on-route charged BEBs can replenish energy frequently enough to remain in service indefinitely. Chargers typically connect through the use of a pantograph interface on the roof of the bus or an inductive interface under the bus. With short charge durations, multiple vehicles can rely on a single charger, in sequence.
Operating Range:	The distance a vehicle can reliably drive with the energy stored on board. Varies with a given driving cycle and external factors, including ambient temperature, grades, and speed.
Overhead Charger:	Energy transfer to a vehicle through a physical connection between an overhead pantograph arm and charge rails on the vehicle's roof. The moving parts of the pantograph can be on the stationary structure (known as “bus down” because the moving parts are mounted overhead and move down to the bus) or “on the vehicle (“bus up,” currently uncommon in the US). DC energy transfer allows high power rates, up to 450kW. Applications include on-route charging (generally short duration, high power charges) and depot charging (generally lower powers around 150kW for longer durations).

Plug-in Charger:	A method of charging a BEB where energy is transferred from the electrical grid to a vehicle's onboard battery via a plug and receptacle. Typically used for longer duration charges occurring overnight or mid-day between morning and late afternoon blocks. Energy transfer can be AC (up to 19.2kW, not used on large heavy-duty vehicles) or DC (powers range from 24kW to 350kW+).
Power:	The rate that energy is consumed or moved, measured in kilowatts (kW).
Regenerative Braking:	When a vehicle's kinetic energy is captured by the electric motor acting as a generator, slowing the bus and returning the energy to the battery for storage.
Revenue Service:	All scheduled time a bus spends serving passengers, which can also be defined as platform hours minus deadhead and layover time.
Route Modeling:	A software-driven method to assess the operational performance of ZEBs by modeling bus operations on given routes using bus specifications, route profile, and environmental conditions.

State of Charge:	Quantity of electric energy remaining in a battery relative to the maximum rated capacity of the battery expressed in a percentage. This is a dynamic measurement used to express the current level of charge in the energy storage system. A full battery at a relative measurement of 100% SOC indicates that the energy storage system cannot accept further charging; an empty battery at 0% cannot be discharged any further to power the vehicle.
State of Health:	Represents the current condition of a battery or fuel cell compared to the new, beginning of life state; often expressed in a percentage. With respect to a fuel cell, this would include an assessment of power degradation and reduction in fuel efficiency.
Steam Methane Reforming:	Hydrogen production method which produces hydrogen from natural gas (methane).
Switchgear:	Collection of electrical infrastructure, such as circuit breakers, panels, and switches, that receives, distributes, and protects the sites equipment and wiring.
Technical Specifications:	Critical components of bus and charging or hydrogen fueling infrastructure procurements that define technical and performance requirements that satisfy service needs within the constraints of operating conditions.

Transformer:	Electrical equipment that converts high-voltage electricity from the utility grid to a lower, usable voltage for charging electric vehicles.
Utilization:	Comparison of the number of days a bus was put into service to the total days it was available for service. Low utilization could indicate that there are operational issues, such as there not being enough operators trained on ZEBs. Tracking utilization can help identify the root cause of issues and address them.
Zero-Emission Bus:	A bus that emits no tailpipe emissions. Commonly battery electric buses and fuel cell electric buses.

Acronyms List

AC: alternating current
A&E: architectural and engineering
AHJ: authority having jurisdiction
APEP: Advanced Power and Energy Program
APTA: American Public Transportation Association
ARCHES: Alliance for Renewable Clean Hydrogen Energy Systems
ASE: Automotive Service Excellence
BEB: battery electric bus
BESS: battery energy storage system
BMS: battery management system
BTMS: battery thermal management system
Caltrans: California Department of Transportation
CARB: California Air Resources Board
CEC: California Energy Commission
CI: carbon intensity
CMS: charge management system
CNG: compressed natural gas
CTE: Center for Transportation and the Environment
CTTC: California Transit Training Consortium
DC: direct current
DGE: diesel gallon equivalent
DGS: Department of General Services
DOE: Department of Energy
DOT: Department of Transportation
ESG: environmental, social, and governance
EVSE: electric vehicle supply equipment
EV: electric vehicle
FCEB: fuel cell electric bus
FTA: Federal Transit Administration
HFCBC: Hydrogen Fuel Cell Bus Council
HP: horsepower
HV: high voltage
HVIP: Clean Truck and Bus Voucher Incentive Project
H_2: hydrogen

GFO: grant funding opportunity
GVWR: gross vehicle weight rating
ICE: internal combustion engine
ICT: Innovative Clean Transit
IIJA: Infrastructure Investment and Jobs Act
ISO: International Organization for Standardization
KPI: key performance indicator
kWh: kilowatt-hour
kW: kilowatt
LCFS: Low Carbon Fuel Standard
LCTOP: Low Carbon Transit Operations Program
LOTO: lockout/tagout
LH$_2$: liquid hydrogen
NAFTC: National Alternative Fuels Training Consortium
NEVI: National Electric Vehicle Infrastructure
NFPA: National Fire Protection Association
NREL: National Renewable Energy Laboratory; now National Laboratory of the Rockies (NRL)
NTI: National Transit Institute
O&M: operations and maintenance
OEM: original equipment manufacturer
OSHA: Occupational Safety and Health Administration
PEM: proton-exchange membrane
PPE: personal protective equipment
PSPS: Public Safety Power Shutoff
RFP: Request for Proposals
SAE: SAE International; formerly known as the Society of Automotive Engineers
SMR: steam methane reforming
SOC: state of charge
SOH: state of health
TCRP: Transit Cooperative Research Program
TIRCP: Transit and Intercity Rail Capital Program
TWC: Transportation Workforce Center
V2B: vehicle-to-building
V2G: vehicle-to-grid
WCCOE: West Coast Center of Excellence
ZEB: zero-emission bus
ZEV: zero-emission vehicle

ZE: zero-emission
ZEBRA: Zero Emission Bus Resource Alliance
ZEBU: Zero-Emission Bus University

Introduction

Transit agencies across California are planning for and implementing zero-emission bus (ZEB) deployments in response to regulatory requirements, climate goals, and changing operational needs. While ZEB technologies offer significant environmental and public health benefits, they also come with new planning, procurement, infrastructure, and operational considerations that differ from conventional bus deployments. A successful transition and deployment begin with an understanding of ZEB technology and its impact on operations, as well as early coordination across agency stakeholders.

The **California Statewide Transit Agency Deployment Toolkit**, created by the Center for Transportation and the Environment (CTE) in partnership with the California Department of Transportation (Caltrans), is designed to provide agencies with both technical context and practical guidance to support successful zero-emission bus (ZEB) deployments. While the Toolkit includes information applicable to ZEB technologies broadly, some sections focus specifically on either battery electric bus (BEB) and charging considerations, or fuel cell electric bus (FCEB) and hydrogen fueling considerations. Because FCEBs are more nascent than BEBs, more information gaps remain, which this toolkit aims to help address by providing extra resources to bridge these gaps.

The Toolkit is designed to be flexible and applicable across different agency sizes, timelines, and technology pathways. It contains multiple standalone sections, allowing readers to focus on their specific stage of deployment rather than progressing through the Toolkit chronologically. The Toolkit includes the following:

- **Tool 1: Zero-Emission Bus (ZEB) 101**
    - Introduces high-level technology concepts and key differences between ZEB technologies that agencies should be aware of as they begin evaluating their options
- **Tool 2: Step-by-Step Framework for ZEB Deployment**
    - A step-by-step framework to support agencies as they plan and implement ZEB projects, progressing through key deployment stages, from early planning and procurement to station build, workforce training, and ongoing operations. Each step of the framework includes guiding questions, a readiness checklist, and references to additional resources
- **Tool 3: Funding Sources**
    - A select list of government funding programs that support ZEB vehicle procurements, infrastructure development, and related planning efforts applicable to California transit agencies
- **Tool 4: California Hydrogen Market Forecast**

    - A web-based, interactive geospatial mapping tool developed by GreenInfo Network and CTE that projects hydrogen supply and market development across transit agencies in California. This tool is intended to help understand expected hydrogen market trends across transit agencies in California
- **Tool 5: Stakeholder Interviews and CTE Recommendations: Hydrogen Market**
    - An analysis of common barriers to hydrogen deployment and associated recommendations for hydrogen adopters, influenced by discussions with hydrogen stakeholders across California
- **Tool 6: Components of Hydrogen Station Designs: 3D Renderings**
    - 3D renderings of various hydrogen fueling station designs and layouts intended to provide visual representations of the major components that make up hydrogen fueling stations and are intended to help agencies better understand station layouts, equipment configurations, and facility space requirements
- **Tool 7: Hydrogen Station Designs**
    - Example hydrogen station layouts and design concepts developed by TAIT illustrating potential configurations for hydrogen fueling infrastructure and resemble designs that transit agencies can expect to receive from A&E firms in the design planning process

The Toolkit is intended to serve as a reference document to guide stakeholders through the challenges of transitioning to ZEBs. It relies on the experiences and lessons learned from past agencies, as well as the knowledge CTE has acquired through decades of work supporting zero-emission fleet advancement. It synthesizes information from a variety of different resources, including past guidebooks, safety documents, and presentations.

However, while the Toolkit points to many helpful publications, it is not a comprehensive list of all available resources and should be considered a starting point for agencies throughout their deployment process. Agencies are also encouraged to join virtual transit working groups like the Zero Emission Bus Resource Alliance (ZEBRA), the Hydrogen Fuel Cell Bus Council (HFCBC), or the American Public Transportation Association (APTA) Zero Emission Fleet Committee to access and share peer agency lessons learned and research findings.

ZEB Technology Overview

ZEBs operate without combustion and do not produce tailpipe emissions such as carbon dioxide (CO_2). This distinguishes ZEBs from their internal combustion engine (ICE) counterparts, including those utilizing diesel, gasoline, and compressed natural gas (CNG) as a primary energy source.

There are two types of ZEBs that are commercially available today: battery electric buses (BEBs) and fuel cell electric buses (FCEBs). BEBs and FCEBs differ primarily in how energy is stored and supplied to the vehicle. BEBs rely on onboard batteries as the only source of energy for the vehicle, while FCEBs carry hydrogen in the form of gas, which is used by a fuel cell to generate electricity and recharge an onboard battery. Both technologies use battery-powered traction motors that are more efficient than diesel engines. While BEBs and FCEBs both support zero-emission goals, they differ in their operational, fueling, costs, and maintenance considerations. Agencies should evaluate these tradeoffs to determine which technology, or combination of technologies, is best suited to their fleet needs and operating conditions.

The key components of a diesel, electric, and hydrogen fuel cell vehicle are compared in **Figure 1.**

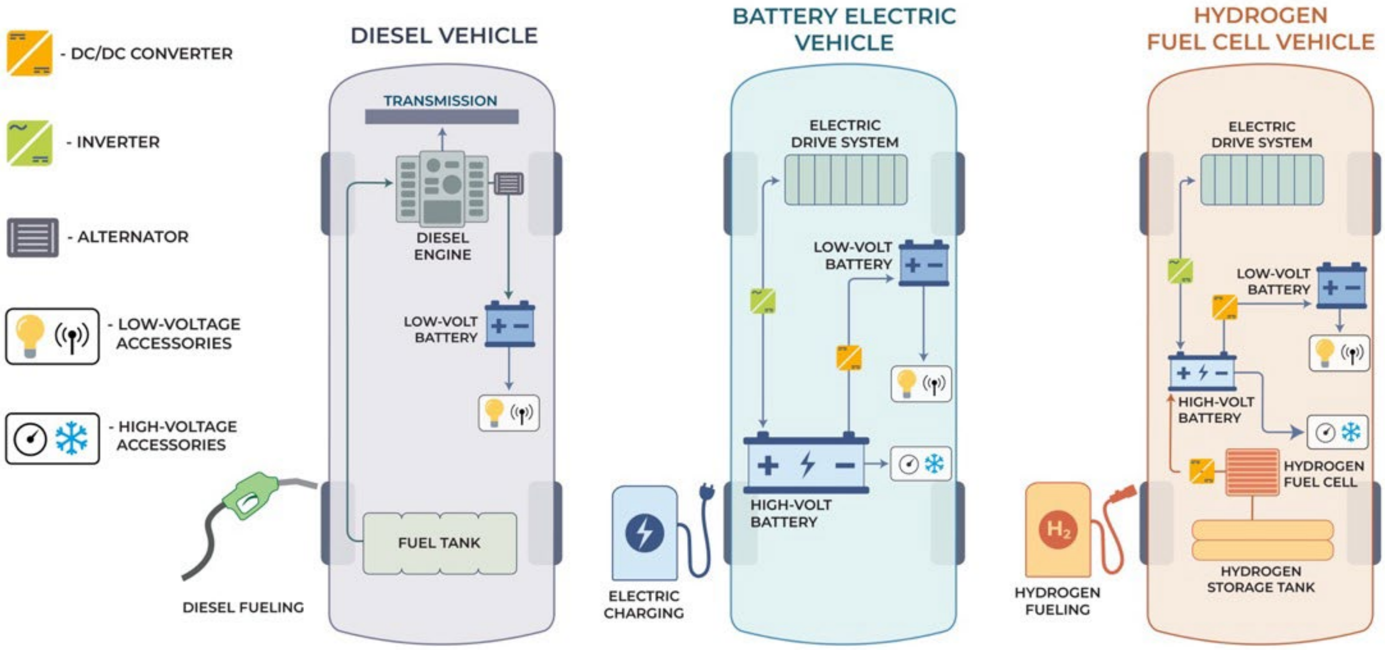

Figure 1 – Diesel, Battery Electric, and Hydrogen Fuel Cell Electric Bus Schematic

Since BEBs store all onboard energy in batteries, which are recharged by an external energy source, the range of these vehicles is limited by the amount of battery capacity that can be stored on board without exceeding the allowable vehicle weight limitations and without eliminating passenger seating. BEBs store significantly less energy on board compared to their internal combustion engine (ICE) counterparts, as seen in **Figure 2.** The energy capacity of FCEBs is significantly higher than that of BEBs because additional energy in the form of hydrogen (H_2) is stored on the vehicle in comparatively light storage tanks. A fuel cell uses the onboard H_2 to recharge a significantly smaller, and therefore lighter, battery. However, FCEBs still have an onboard energy capacity that is lower than that of a diesel vehicle, as seen in **Figure 2.**

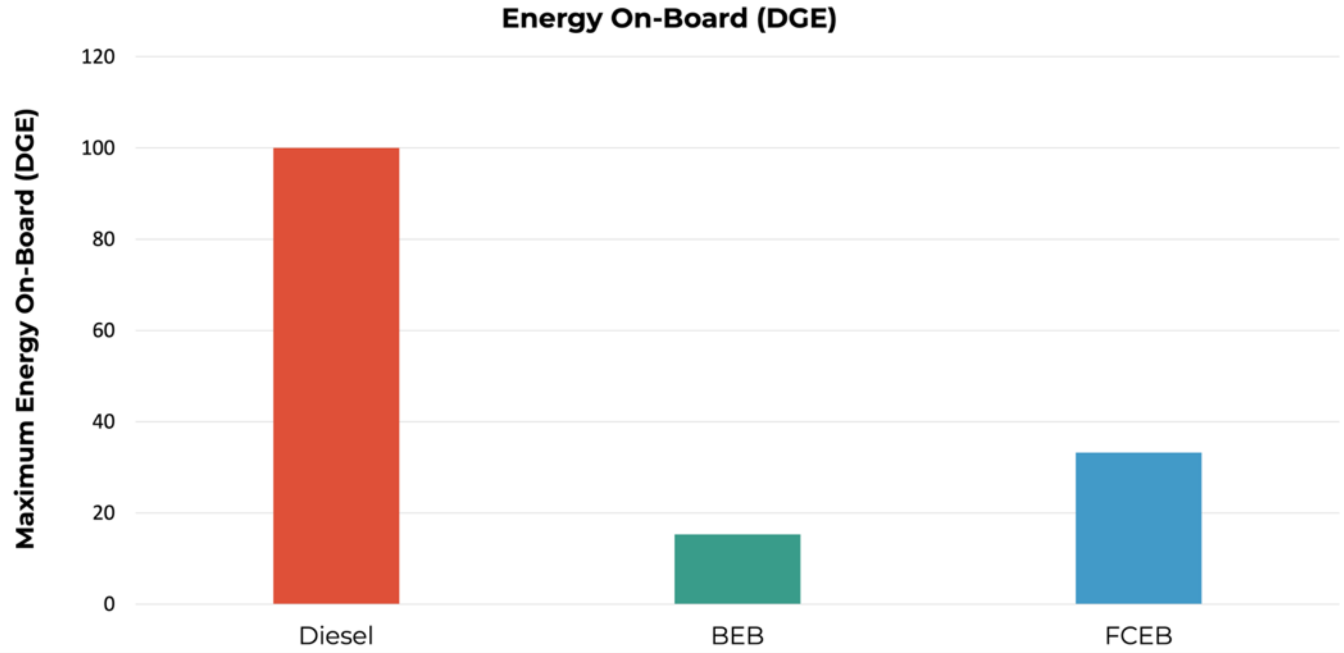

Figure 2 – Comparison of Onboard Energy, as Measured in Diesel Gallon Equivalents (DGE), between Diesel, BEB, and FCEB Technology

In addition to the amount of energy on board the vehicle, it is important to consider how efficiently the vehicle uses that energy. Electric motors, such as those employed by both BEBs and FCEBs, are significantly more efficient than an ICE. This means that although zero-emission technologies have lower onboard energy storage capacity, their more efficient propulsion systems offset some of this difference, as shown in **Figure 3**, which illustrates the miles each vehicle type can travel without refueling.

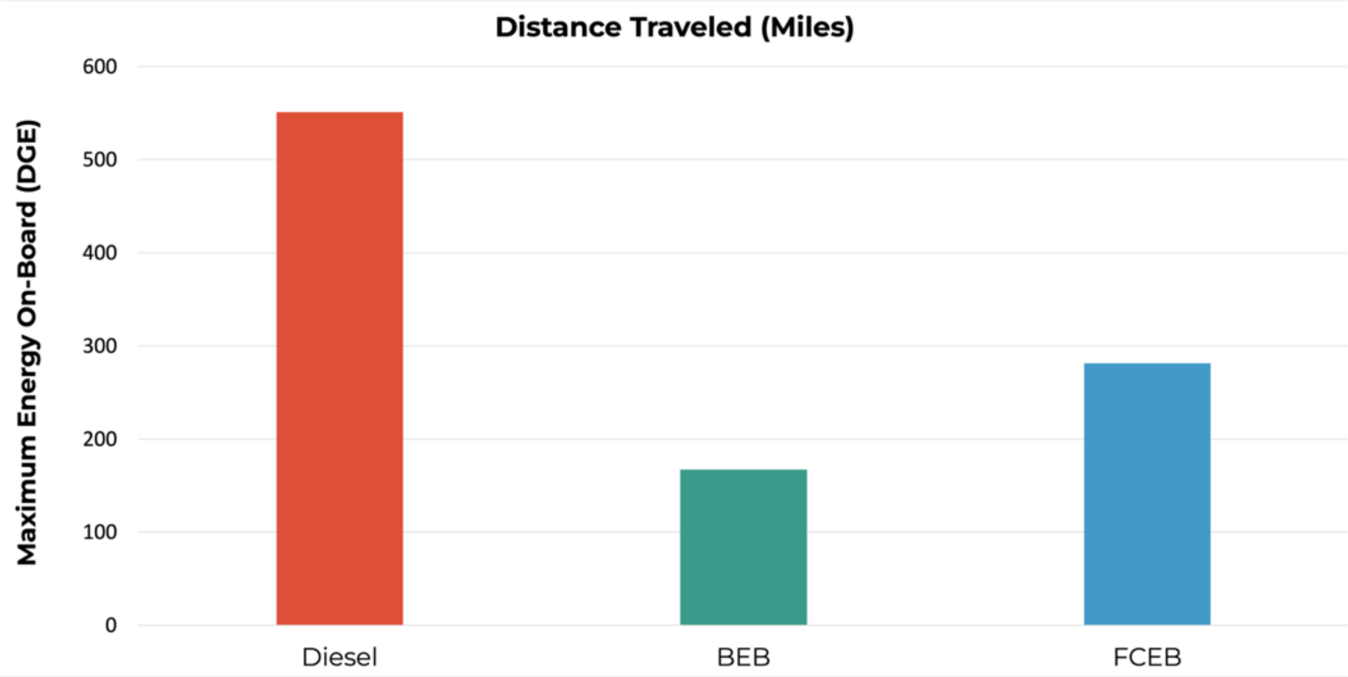

Figure 3 – Comparison of Range for Diesel and ZEB Technology

Although BEBs and FCEBs are more efficient than ICE vehicles, their range is lower than that of an ICE bus. However, approximately 60% of transit blocks are less than 150 miles and easily within the operational ranges of BEBs and FCEBs. It is therefore important to account for this operational difference when planning to transition a fleet to ZEBs.

A full ZEB fleet may include both BEBs and FCEBs, depending on the needs of a transit agency. Electric trolleys with overhead catenary wires are also a viable zero-emission technology.

An overview of available BEB and FCEB technology is provided in the sections below for reference. A summary of BEB and FCEB technology considerations is listed in **Table 1**.

Table 1 – Overview of Battery Electric Bus and Fuel Cell Electric Bus Considerations

CONSIDERATION	BATTERY ELECTRIC BUS	FUEL CELL ELECTRIC BUS
Reliable Range	Around 200 miles in transit service on a single charge (or extended range with on-route charging), dependent on battery size, operating conditions, and weather.	Between 200 and 320 miles in transit service before refueling reliably, but up to 350 miles under certain conditions with standard specifications.
Fueling Technology	Plug-in charging, Overhead conductive charging, or Wireless inductive charging.	Hydrogen storage and fueling station, delivered gaseous or liquid hydrogen, or on-site hydrogen production through electrolysis or natural gas reformation
Capital Costs	BEBs are more expensive than diesel buses in 2026, with BEBs costing approximately 1.4 times more than ICE counterparts. Charging infrastructure costs vary based on type of charging, additional infrastructure required, and utility service. Scalability may be constrained by utility service, parking configuration, and space required for charging equipment and additional infrastructure. Infrastructure cost per bus tends to increase with more BEBs.	FCEBs are more expensive than BEBs in 2026, with FCEBs costing approximately 1.8 times more than ICE counterparts. Fueling infrastructure costs vary and depend on fuel type (gaseous or liquid), fueling rate, storage volume, and dispensing throughput. Infrastructure cost per bus tends to decrease with more FCEBs.
Refueling Considerations	A depot-charged BEB may require 2-4 hours to fully charge, with the entire fleet needing to charge between pull in and pull out. Electricity rates may vary based on the amount of energy used at a given time, as well as the time of day, day of the week, and season of the year. In general, the charging will be cheapest during the utility's off-peak window, which is often overnight. For example, SDGE off-peak rates are 2-3 times cheaper than on-peak rates.[1]	Refueling procedure and time required are slightly slower than diesel buses, but similar to Compressed Natural Gas (CNG). Electricity costs may be significant if producing hydrogen on-site. Fuel costs will vary based on production method, type of fuel (liquid or gaseous), or delivery distance.

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[1] "Steps for Selecting the Best Pricing Plan." San Diego Gas & Electric, n.d.

BEB and Charging Infrastructure Overview

BEBs use onboard battery packs to power all bus systems. BEBs generally have no tailpipe emissions; however, some transit agencies utilize an auxiliary fuel-fired heater to avoid using energy stored in the battery to run an electric heater and therefore preserving vehicle range in cold climates. Chargers may use plug-in, overhead conductive, or in-ground inductive charge interface. Any type of charger may be used at the depot or on route, however, the charge rate may differ depending on the requirement and application.

When procuring BEBs, agencies first need to understand the service requirements and range needs for each route. There are two primary strategies for extending range: 1) increasing onboard energy storage by incorporating larger battery packs; or 2) supplementing range with high-power pantograph charging. Adding batteries allows buses to operate for longer periods between charges but can increase vehicle weight, cost, and charging time. Alternatively, on-route pantograph charging enables buses to recharge in short intervals throughout the day, reducing the need for large battery capacity but requiring additional charging infrastructure and careful operational planning. The selection and necessity of these strategies depend on route characteristics, scheduling constraints, and range needs.

Industry Average 40’ BEB Characteristics in 2026*

- Battery capacity: 250–686 kWh
- Reliable range in transit service: 200+ miles on a single charge
- Capital costs: $1.1 million for base bus
- Charging approach: 50–200 kW plug-in chargers, typically used for overnight depot charging; 150–300 kW pantograph chargers at the depot; and 300–450 kW pantograph chargers for on-route opportunity charging while in service
- Fuel economy: 1.8 kWh per mile (low HVAC use in conditions 50–80°F); 3.5 kWh per mile (high HVAC use in conditions >95°F or <35°F)

* Example 40’ bus characteristics are provided for educational purposes and are not intended to represent any specific model or all available configurations.

Three options exist for BEB charging technology: plug-in charging, overhead conductive charging, and wireless inductive charging. Any of these types of chargers can be used to charge BEBs either at the depot or at on-route charging stations. Typically, plug-in chargers are primarily used to charge buses at the depot and overhead conductive or wireless inductive chargers are used to charge buses on-route. However, the appropriate charging technology and operation will depend on fleet size, charger power, route characteristics, and available space. Overhead or inductive charging may be necessary for large-scale BEB fleets with limited space at the depot for chargers.

A BEB charging station will typically include (1) transformer, (2) switchgear, (3) chargers, and (4) dispensers (as shown in **Figure 4**). Additional equipment may be required due to the size of the deployment, requirements from the electric utility, and the charging method. For example, a single transformer and switchgear may support multiple chargers, and one charger may have more than one dispenser. The electric utility is typically responsible for the grid and transformer assets, while the transit agency is typically responsible for the switchgear and other remaining charger assets.

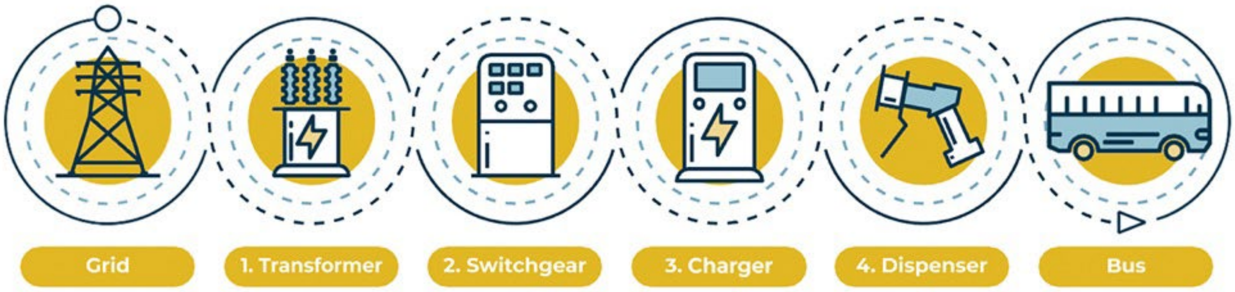

Figure 4 – Generalized Charging Station Schematic

When selecting charging infrastructure, transit agencies must consider their route demands (e.g., speed, grade, stops,), bus service or blocking demands (e.g., deadheads, duration, and frequency), seasonal temperatures, passenger loads, available parking space and power, layover or transit center locations and space, and utility rate schedules and costs. Transit agencies may choose a combination of chargers and charging approaches, utilizing both depot and on-route charging, to fully meet their needs.

Integrating charging infrastructure into transit operations necessitates careful planning. BEB fueling infrastructure requires space and power. At scale, power demands will be significant. One should conduct a thorough analysis of current and future ZEB plans in order to install solutions that are scalable and make the most out of the existing facilities. Agencies will need to balance infrastructure decisions with the understanding that the market is rapidly maturing, and future solutions may better accommodate an agency's needs. It is recommended to speak with the utility provider to understand what incentives or pilot programs they might offer to support the purchase, design, or installation of fueling infrastructure.

FCEB and Hydrogen Infrastructure Overview

FCEBs utilize onboard hydrogen storage, a fuel cell system, and batteries. The fuel cell uses hydrogen to produce electricity, also producing waste products of heat and water. The electricity charges the batteries, which powers the bus. To further improve efficiency, the waste heat can be used to help heat the cabin.

FCEB operation is similar to diesel bus operation, due to their similar range and fueling approach. FCEBs may be close to a 1:1 replacement for conventionally fueled buses. However, FCEB bus and infrastructure costs are currently higher than diesel buses and BEBs.

Industry Average 40' FCEB Characteristics in 2026*

- Hydrogen Storage Pressure: 350 bar
- Hydrogen Storage Capacity: 37.5 kg for base model, 56 kg for extended range
- Fuel cell power: 85–120 kW
- Battery capacity: 50–120 kWh
- Reliable range in transit service: 220–320+ miles
- Capital costs: $1.5 million for base bus
- Fuel consumption: 20–25 kg per day
- Fuel economy: 7–9 miles per kg

* Example 40' bus characteristics are provided for educational purposes and are not intended to represent any specific model or all available configurations.

A hydrogen fueling station operates similarly to a CNG fueling station. A hydrogen fueling station will typically include a (1) hydrogen delivery system, where hydrogen is delivered by a supplier or produced on-site, (2) hydrogen storage tank(s), (3) vaporizer (for liquid storage), (4) compressor, (5) chiller, and (6) dispensing system that delivers the fuel to the vehicle **(Figure 5).**

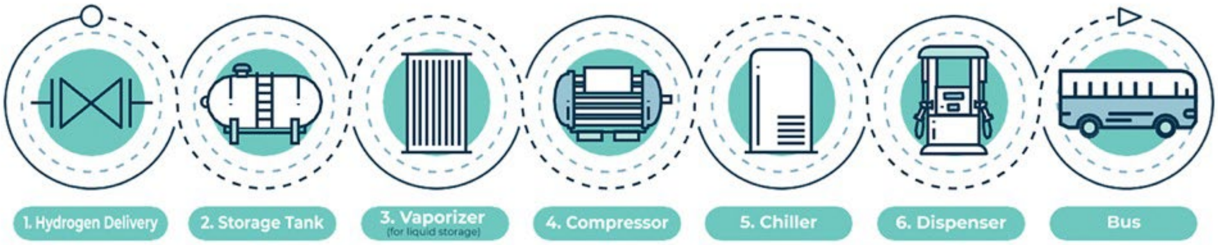

Figure 5 – Generalized Hydrogen Fueling Station Schematic

Gaseous hydrogen storage will require an integrated design with both low-pressure and high- pressure storage. Liquid hydrogen storage is more common for transit applications, as it allows for higher storage capacity. FCEBs available in the U.S. all require hydrogen to be dispensed at 350 bar (H35). See **Figure 6** for examples of the equipment needed for gaseous hydrogen delivery, liquid hydrogen delivery, and on-site hydrogen production. While **Figure 6** uses electrolysis as an example for on-site hydrogen production, natural gas reformation can also be used to produce hydrogen.

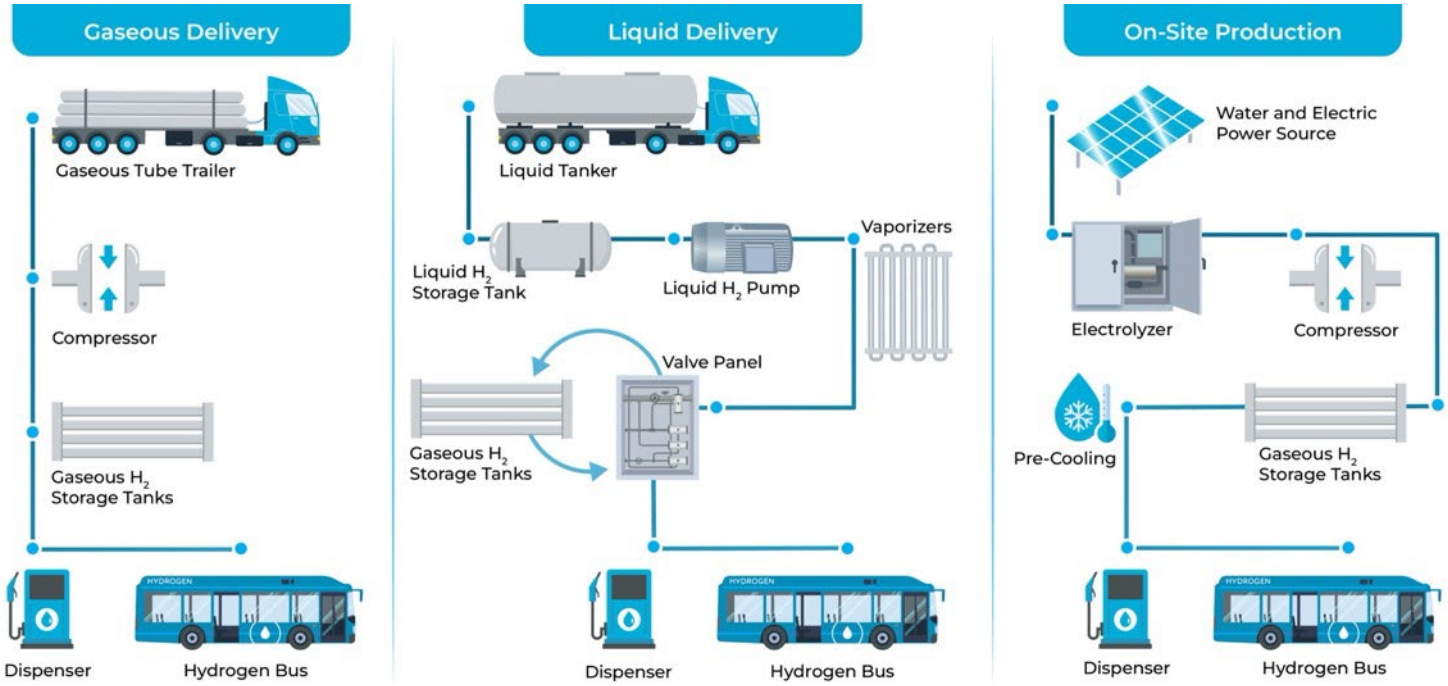

Figure 6 – Summary of Hydrogen Fueling Station Delivery Option

It is important to note that the hydrogen fueling station for buses will not be compatible with most hydrogen fueling stations for light-duty fuel cell vehicles, which require hydrogen to be dispensed at 700 bar (H70). Many retail hydrogen stations that dispense at 700 bar can also dispense at 350 bar.

A summary of hydrogen fueling station considerations is shown in **Table 2.**

Table 2 – Summary of Hydrogen Fueling Source Consideration

Type of Structures	Fueling Mediums	Production Methods
• Permanent (all piping and electrical equipment below ground) • Semi-permanent (all piping and electrical equipment above ground) • Temporary (rented or leased mobile trailer)	• Liquid • Gaseous	• Liquid or gaseous delivery • On-site generation through electrolysis or natural gas reformation

Upon completion, a hydrogen fueling station will look and operate much like a traditional CNG fueling station. In addition to the fueling pumps depicted, the hydrogen storage, compression, and production equipment, if utilized, would be located nearby.

While the initial investment in a hydrogen fueling infrastructure may be significant, scaling up hydrogen fueling infrastructure may be less costly on a per bus basis and less land-intensive than scaling up battery charging infrastructure. Some equipment expansion may be needed, but the total footprint of a hydrogen fueling station is similar to a diesel or CNG station. For smaller FCEB deployments and during a fleet transition period, the facility will need fueling stations for both conventionally fueled vehicles and FCEBs. As transit agencies phase out non-ZEBs, hydrogen fueling stations could occupy the existing footprint dedicated to diesel or CNG fueling after the transition.

Tool 1:

Zero-Emission Bus (ZEB) 101

This section is intended to expand on key ZEB concepts discussed in the introduction of this toolkit. This tool is not meant to recommend specific solutions or replace detailed planning or education. Instead, it establishes important terminology, introduces high-level technology concepts, and highlights key differences between ZEB technologies that agencies should be aware of as they begin evaluating their options. Agency needs and operating feasibility vary widely from agency to agency.

Battery Electric Bus Technology and Charging Fundamentals

Energy Fundamentals

Power vs Energy

When working with ZEBs, it is important to understand kilowatts (kW) and kilowatt-hours (kWh), which are used to measure power and energy respectively.

Power is the rate at which work is done. ICE vehicles commonly compare power using units of horsepower (HP). ZEB motors are often rated in kilowatts. A kilowatt is a unit of power used to measure the transfer of electricity and is equivalent to 1,000 watts or approximately 0.75 HP. Watts are the unit for power used by the International System of Units.

Energy is the capacity for doing work. A kilowatt-hour is a unit of energy. In the U.S., it is often used on electric utility bills when reporting electricity delivered in the billing period (the energy used). On ZEBs, battery capacity is commonly reported in kilowatt hours, just like an ICE vehicle's fuel storage capacity is rated in gallons.

One kilowatt-hour is equivalent to the energy delivered at a rate of one kilowatt for one hour. In the absence of any efficiency losses, a vehicle charging at 20 kW for two hours will receive 40 kWh of energy in that time.

Energy Storage

Agency staff accustomed to working with ICE buses likely measure their fuel consumption (energy used) and dispensing in gallons of gasoline or diesel. Those using compressed natural gas may use diesel gallon equivalents (DGE) or kilograms. Energy storage capacity is measured by the tank size–how many gallons of gas or diesel the fuel tank can hold.

BEB energy storage is measured in kilowatt-hours (kWh) stored in the battery while FCEBs report kilograms of hydrogen stored in the tank (similar to CNG buses). For perspective, a gallon of diesel contains approximately 37 kWh of energy. A kilogram of hydrogen contains approximately 33 kWh of energy—notably similar to diesel. Keep in mind that the overall propulsion system efficiency impacts how much stored energy is used for propulsion.

Batteries are advertised in terms of “nameplate capacity,” a measure of the absolute maximum amount of energy the battery can store. In practice, not all of this energy is available to the user. To protect battery life, keep the battery in a stable operating range, and minimize battery degradation mechanisms, some capacity is software locked by the manufacturer. The amount of energy made available to the user is the “usable battery capacity,” sometimes referred to as the “usable battery energy.” When evaluating technologies, usable battery capacity is the more relevant metric, as it reflects actual performance in the field. While useable battery energy scales with nameplate capacity, avoid looking at nameplate capacity alone because the amount of energy kept in reserve is not standardized and varies between battery designs and manufacturer strategies.

Batteries

High-Voltage Batteries

All transit buses, including ICE vehicles, use low voltage (12V) batteries to power accessories such as lights and radio systems. A distinguishing characteristic of both BEBs and FCEBs currently built for the U.S. market is the use of onboard high voltage (HV) batteries, which supply power to the electric drive system. HV batteries are generally between 400V and 800V and some companies refer to them as “traction batteries.” HV batteries use lithium-ion battery cells and serve as the primary onboard energy storage system, analogous to a fuel tank on a conventional vehicle. State of charge (SOC) is used to describe what percentage of a battery's current capacity is currently stored and available for use.

Energy Density and Range

Today’s lithium-ion batteries used in BEBs hold less energy per unit of mass compared to the fuel in diesel, gasoline, natural gas, and hydrogen vehicles. However, because electric drivetrains are more efficient, a more helpful measure for vehicle performance is vehicle range per unit of energy rather than energy density alone.

There are both practical and regulatory limitations to how large BEB batteries can be. Adding additional mass increases energy storage but also reduces fuel economy and pushes the vehicle’s weight closer to its design limits. State and federal regulations limiting gross vehicle weight rating (GVWR) limit the energy capacity of batteries and range of BEBs compared to both FCEBs and ICE vehicles. Battery technology is continuously improving with ongoing research and commercial investment in energy density, including solid-state batteries.

Additionally, efforts have been made within California to loosen weight limits on power units for zero-emission vehicles (ZEVs).[2]

BEB range varies with ambient temperature, topography, route duty cycle (speed profile), passenger load, vehicle weight, driver behavior, and traffic conditions. Ambient temperature is often the largest contributor to range reduction, especially in cold climates where it's regularly below freezing. While combustion engines have abundant waste heat available to heat the passenger cabin, BEB propulsion systems are significantly more efficient and do not have adequate waste heat to contribute to cabin heating. Electric heaters are used in the winter and draw energy from the battery that would otherwise power the propulsion system, resulting in reduced vehicle range. This impact can be partially mitigated by using an auxiliary fuel-fired heater.

Degradation

Lithium-ion batteries degrade over time with normal use. State of health (SOH) is used to measure what percentage of a battery's original capacity is available as a result of degradation. For example, if a battery's SOH is 80%, its energy capacity at a full SOC is 80% of its original capacity at the time of purchase.

Battery degradation is influenced by many factors including:

- Calendar age, with performance declining over time regardless of usage
- The rate at which a battery is charged or discharged
- The number of charging cycles
- Storage temperatures
    - Batteries stored at temperatures warmer than 35°C (95°F) will experience faster degradation, as the rate of unwanted chemical reactions within the battery occurs at faster rates at higher temperatures
    - Storage temperatures below 32°F should also be avoided because cell freezing causes damage to some battery chemistries
- Storage at high SOCs or low SOCs
    - Storage at high SOC (above 80%) or low SOC (below 20%) can increase the degradation rate because the battery is at the highest or lowest voltage of its operating range
    - To extend battery life, consult your vehicle manufacturer. Many recommend storage between -20°C and +35°C (-4°F to 95°F) and 20% to 40% SOC whenever operationally possible to help extend battery life

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[2] California Department of Transportation. *Ex Zero-Emission Vehicle Truck Access*. California Department of Transportation, n.d. https://dot.ca.gov/programs/traffic-operations/legal-truck-access/ex-zero-emission-vehicle.

CTE recommends checking with the vehicle manufacturer for model-specific guidance regarding long-term vehicle and battery storage. Agencies should familiarize themselves with their battery warranty terms and conditions and account for replacement and disposal costs in lifecycle cost assessments. Agencies should understand the warranty duration (often at the 20% degraded mark which generally occurs around 6 years), how state of health is defined, and how energy throughput and low state of charge events are factored into the warranty. Agencies should take degradation into account when planning for how BEBs are deployed over their lifecycles. BEBs can operate on shorter blocks with degraded batteries when they can no longer complete blocks they are assigned when first entering revenue service.

Battery Safety

BEB batteries present different hazards than ICE vehicles, and these risks can be mitigated through a combination of engineered and operational means.

Battery Fires

A conventional vehicle fire is typically battled by using water to starve the fire of oxygen, smothering and extinguishing it. However, lithium-ion batteries supply both fuel and oxygen during a fire, so the internal source of oxygen means a lithium-ion battery fire cannot be smothered, and water can only be used as a means of heat removal. Once a failure has spread beyond a single battery cell, the main goal is to prevent the spread of fire to additional vehicles or facilities. Facility sprinkler systems can help to suppress fires, but they may need to be upgraded to deliver more water over a longer period of time. Codes and standards are evolving to catch up to the new requirements of having large batteries on vehicles. Agencies should perform fire modeling for BEB facility projects and establish standard operating procedures for responding to BEB fires. CTE recommends engaging local fire inspectors early in a project to be aware of local codes and challenges.

Figure 7 – Battery Fire Suppression Considerations

The figure above depicts the three components of regular fire, showing that the removal of any one component can be effective in suppression. On the bottom, the battery fire supplies both fuel and oxygen, so heat is the only component that can be removed.

Detecting Battery Malfunction and Failure

Some failure modes of battery cells cause them to experience both a rise in temperature and a voltage drop. While not all cell failures result in a fire, detecting these changes can help identify a potential hazard before a fire occurs, particularly if a single cell failure generates enough heat to damage adjacent battery cells. The battery management system (BMS) monitors individual battery cell voltages, system electrical resistance, temperatures inside the battery pack, and system SOH. Some BMS designs can notify vehicle operators and fleet managers if and when issues arise. The BMS also communicates with the battery thermal management system (BTMS), responsible for monitoring and controlling battery cooling and heating, which are used to maintain optimal battery temperature and keep batteries within a safe operating range. As an added layer of safety, gas detection systems can identify when a cell has failed and off-gasses, then notify operators and fleet managers in the event that a cell has failed and could potentially lead to a larger event.

It is important to work with your bus manufacturer to understand the conditions under which the detection systems are operating, and when they are not operational, i.e., the bus is on or off, connected or not connected to a charger, charging or not charging, etc.

Additional Hazard Mitigation Systems

Ground fault detection systems monitor for unintended electrical contact between the high-voltage system and the vehicle body and automatically shut the system down if a fault is detected. Fuses also provide a backup layer of protection by breaking the circuit when experiencing excess current, preventing further damage.

Operational Best Practices

- Establish telematics alert systems and standard operating procedures for ZEB fires
- Keep buses on when feasible to ensure alert systems function in the event of an emergency
- Keep staff onsite during charging events to respond to incidents
- When ZEBs are damaged or awaiting service, park them away from people, facilities, and other buses
- Perform initial BEB charging outside using a low-power (50 kW) charger after battery system maintenance
- Request and observe OEM-provided guidance for long-term ZEB storage
- Open garage doors in the event of an indoor ZEB fire

- Do not move ZEBs that are on fire unless directed by first responders
- Review facility and vehicle hazards with the local Authority Having Jurisdiction (AHJ) and a qualified fire protection engineer

BEB Charging Types

Electric vehicle supply equipment (EVSE), also commonly referred to as chargers or charging stations, delivers energy to vehicles for storage in the onboard battery. There are multiple types of EVSEs available today, providing different options based on how fast charging is needed, often a function of battery size and duty cycle. The section below describes different EVSE types currently on the market and their relevant applications.

AC Charging

Alternating current (AC) charging is common on passenger vehicles, vans, cutaways, and school buses. However, it is no longer provided on any new U.S. transit buses. For these use cases though, AC charging is the lowest power and lowest cost option for charging electric vehicles (EVs). AC charging delivers AC power to the vehicle, so the AC to DC conversion happens on the vehicle. The highest charge power supported by the standard used in North America, J1772, is 19.2kW. Getting full power requires all equipment rated for 19.2kW: the circuit for the EVSE, the EVSE itself, and the hardware on the vehicle. If any of those three key components are not rated for 19.2kW, charge power is limited to the lowest of the three.

DC Charging

Direct current (DC) charging is common on all EV types, including transit buses, cutaways, vans, and school buses. DC charging delivers a higher, faster flow of power compared to AC charging and is well suited for vehicles that have short refueling windows or very large energy storage capacity (like transit buses). In DC charging, the power conversion of the grid-supplied AC power to battery-required DC power happens offboard the vehicle, so the charger provides DC power to the vehicle at the voltage required by the battery. This allows for higher power charging at up to 350kW because larger power conversion hardware can be used; unlike AC charging, where the power conversion hardware is on the vehicle, DC charging does not have the same limitations on weight and size.

Peak power is a function of the EVSE's capability (generally between 24kW and 350kW) and how fast the vehicle is designed to charge. It is important to match the DC charger's output voltage operating range with the vehicle's voltage operating range to avoid compatibility issues. Notably some chargers are limited to a 500VDC output, and some vehicles have battery systems around 700VDC. It is also important to understand how much power the vehicle can accept when deciding what power charger to purchase. For example, if a bus cannot accept more than 150kW from a charger, a charger rated higher than 150kW will not charge it any faster than 150kW. Another consideration with DC charging is that one charging cabinet can often be used to charge multiple vehicles via multiple dispensers. For example, if a charger is rated for 150kW and has two dispensers, it may be able to deliver 75kW to each dispenser at the same time or provide full power to one at a time. Each design has its own nuances; the charger's internal hardware may limit how the power can be split to specific values.

Going through the transition planning process helps planners select charger power and architecture to meet their needs. DC Charging power level selection, including how to consider growing fleets, facility costs, utility upfront costs, and operational costs based on utility rate tables is discussed further in later steps of the toolkit.

Battery Charge Curves

Lithium-ion batteries cannot receive peak power for the entire range of battery SOC. As more energy is added and SOC increases, risk of battery degradation mechanisms increases. Additionally, overcharging risks increase as the battery approaches 100% SOC, which could create unstable chemistry conditions. To mitigate, battery control systems are programmed to follow charge power limits that change with SOC. Most vehicles on the market today will experience a drop-off in charge power at roughly 70% to 90% during a DC charge. The exact behavior is highly dependent on the battery design and other vehicle limiting factors in charge rate. This is an important consideration when calculating charge times – while a linear approximation can be used for low power AC Charging, higher power DC Charging will take longer to charge from 80% to 100% SOC compared to from 60% to 80% SOC. **Figure 8** shows a generic DC charge curve for a typical vehicle today. The two lines show a high-power charge and a low-power charge. Note, the high-power charge experiences a greater power reduction at high SOC because it reaches the battery's charge limits earlier than the lower power charger.

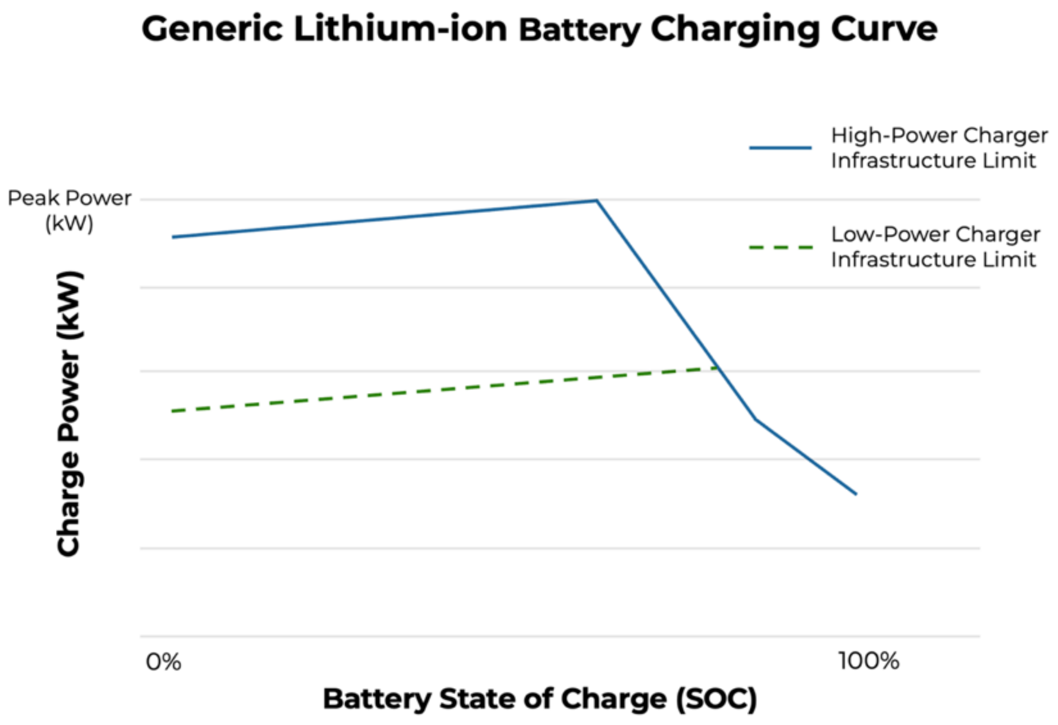

Figure 9 – Graph of Generic Lithium-ion Battery Charging Curve

Charger Dispenser Options

Plug-In Charging

Plug-in charging describes both AC and DC charging because it involves physically connecting a cord with plug to the charge receptacle on a vehicle. Plug-in charging is the most common way to charge EVs, driven by reliability, dominant market share, ease of use without complex alignment requirements, and lower cost than other methods. The biggest downsides to plug-in charging are the need for cord management to avoid running over cords and plugs, a maximum power limit of approximately 350kW, and reliance on a person to physically plug the vehicle in. While plugging in the vehicle is not difficult, it can add time and reduce the effectiveness of a short-duration charge in the middle of transit service, also known as “opportunity charging.” Options for automated charge connection may be better suited for opportunity charging on tight timetables and offers higher charge powers, with the tradeoffs of higher cost and increased complexity.

DC Charging in North America is currently split between three different industry standards, all with unique plugs: CCS-1 (also known as SAE J1772), CHAdeMO, and

NACS ("North American Charging Standard," also known as Tesla Supercharger or J3400). As of 2026, no U.S. passenger vehicles are sold with CHAdeMO charge ports, despite its use on some of the earliest EVs in the 2010s. Adapters between CCS-1 and NACS adaptors entered the market in 2024, available today for approximately $250. The U.S. passenger vehicle market is now split between CCS1 and NACS as the primary charge port standards on new vehicles, both of which support comparable power levels. NACS offers smaller packaging and a less bulky connector, which is preferred by some consumers for aesthetic reasons. The transit bus and school bus markets currently all use CCS-1 with no public plans to add NACS. Cutaways on the market today use CCS-1, although NACS has been announced for some future models. While the market is far from settled on which DC standard will become the norm in the long run, adapter options and EVSEs with multiple plugs to support either standard have reduced compatibility issues. Standard selection is driven by vehicle availability (which standard is supported by the manufacturer) or existing infrastructure.

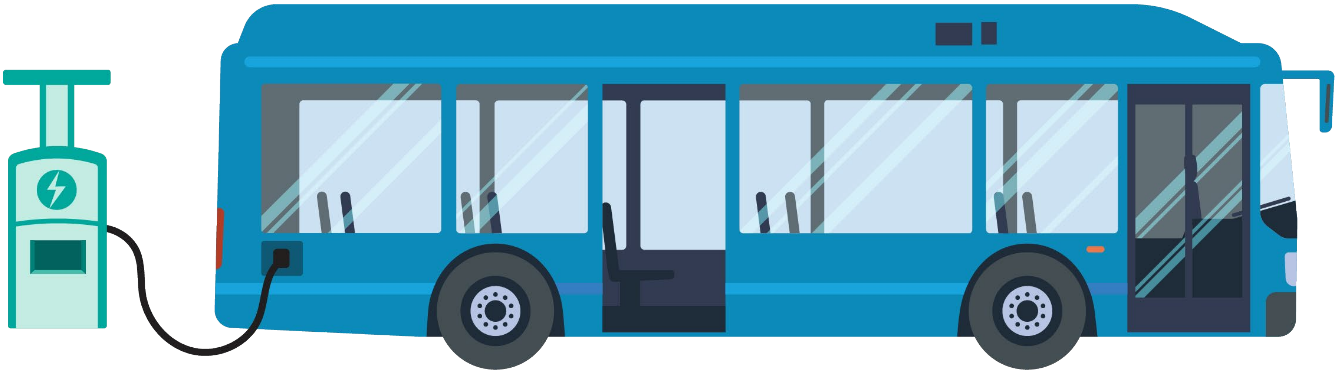

Figure 10 – Plug-In Charging Graphic Reference

Pantograph Charging

Overhead pantograph charging uses an industry standard interface (J3105) consisting of an overhead mounted charging arm that lowers to connect to charge rails mounted on a transit bus' roof. J3105 calls for WiFi communications to pair vehicles and pantographs. Some, but not all, implementations have required an additional RFID system to match buses and pantographs when WiFi crosstalk occurs in tightly spaced layouts. It is important to set robust requirements during sourcing, based on the unique layout and spacing of a given yard for pantograph charging, to source a system designed to work in a given layout. Pantograph charging speeds exceed those of plug-in charging, with options of 400kW+ available in 2026, which makes this a good option for on-route or opportunity charging. It is important to note that the vehicle must be optioned with overhead roof rails from the factory, and peak charge power will vary between different vehicle models. At this time, pantograph charging is not available on other vehicle types aside from transit buses. The higher power capability and automated connect and disconnect system make pantograph charging an attractive option for short charges during layovers at transit centers.

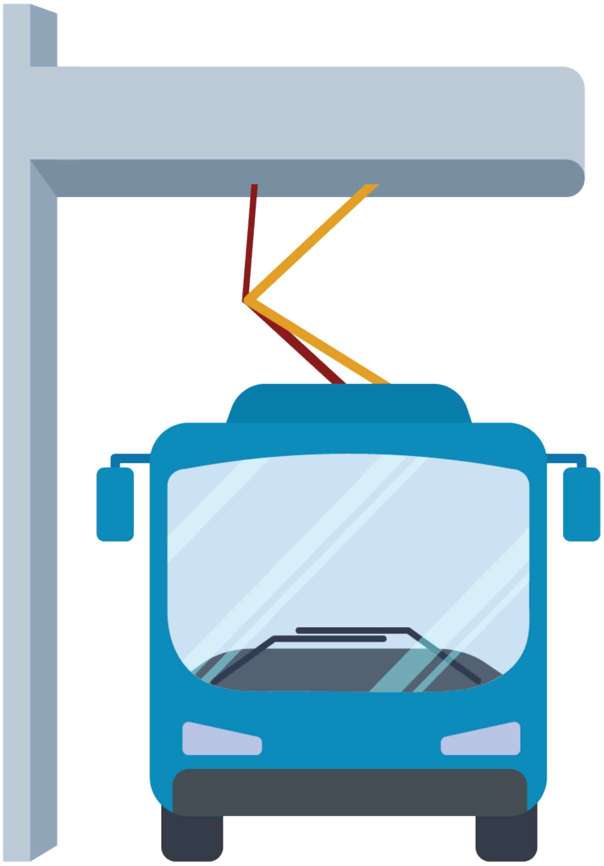

Figure 11 – Pantograph Charging Graphic Reference

Figure 12 – Inductive Charging Graphic Reference

Inductive Charging

Inductive charging allows for both depot and on-route “opportunity” charging but has different infrastructure requirements compared to other charging methods. Inductive charging requires ground coils and vehicle coils that transfer power across an air gap, meaning no physical connection is made (just like when wirelessly charging a cell phone). The vehicle coil output is AC power, meaning the vehicle manufacturer must support adding an onboard rectifier to convert from AC to DC. Key advantages of inductive charging include higher-power charging compared to plug-in charging, no need for operators to manually connect EVSE to BEBs to charge, no cable management concerns, and no overhead infrastructure that can cause height restriction concerns in shared spaces or aesthetic concerns in some communities. Currently, it is not possible to share an inductive charging cabinet with multiple ground coils in the same way plug-in or pantograph chargers can share a power cabinet. Power options for 200kW+ are available in 2026, with higher powers potentially available in the future. This power is high enough to potentially be an option for on-route or opportunity charging under certain conditions.

Bidirectional Charging

Bidirectional charging allows the energy stored in an EV to be used to power other loads. Presently, there are no applications of bidirectional charging in the transit space. School buses are currently used in the field for vehicle-to-grid (V2G). V2G charging allows the EV to send energy back to the grid, thus acting as support during peak demand or power outages. Select passenger vehicles, but no buses, currently support V2B (vehicle-to-building) using energy from a vehicle to provide backup power to a building disconnected from the grid during an outage. Both technologies allow EVs to be mobile energy storage units that increase resiliency.

Future development in bidirectional charging can potentially increase an agency's resiliency, as the additional energy provided by their vehicles can be used to power community centers or other critical care facilities during emergencies. In addition, enrolling in a V2G program, such as the Emergency Load Reduction Program in California, creates potential revenue for agencies from utilities.[3] Agencies simply need to charge their vehicles during off-peak hours and return power to the grid during on-peak hours. However, utilizing V2G technology requires vehicles to be both stationary and charged. Therefore, bidirectional charging may not be suitable for agencies whose vehicles do not have a lot of downtime. Utility coordination and buy-in are essential aspects of any bidirectional charging deployment connecting to the grid. The management and deployment of V2G technology will require additional software systems and potentially additional or different charging hardware.

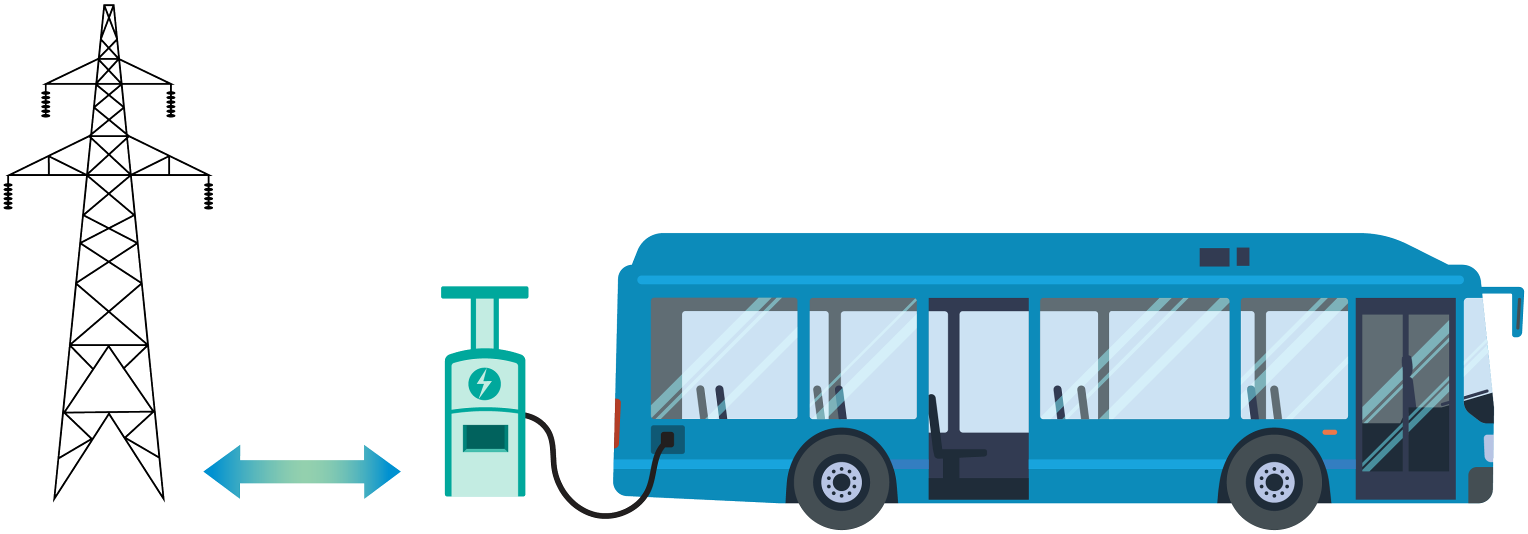

Figure 13 – Bidirectional Charging Graphic Reference

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[3] "Emergency Load Reduction Program in California." California Energy Commission, 2027.

Resilient Charging Design Considerations and Practices

There are several reasons agencies may be interested in exploring resilient or off-grid charging options. One potential reason is that as agencies transition to BEB fleets, site resilience becomes increasingly important to maintaining reliable service during grid outages, natural disasters, or other emergencies. Incorporating resilient energy strategies early in facility planning can reduce operational risk when external power supplies are unavailable. This is especially important for agencies that have mandatory emergency response requirements. Another potential reason is that the local utility grid may not have sufficient capacity to support adding the necessary amount of power to an agency's site; therefore, off-grid charging is the only option for meeting the power needed to achieve a successful ZEB deployment. Additionally, it is possible that the capacity is available from the utility grid, but the cost may be higher, or the available power may be from non-renewable sources and therefore is not aligned with an agency's carbon reduction goals. Producing power onsite may therefore give an agency more independence in managing operating costs and fuel carbon intensity (CI).

Resilient charging designs allow for energy to be delivered to BEBs without reliance on traditional utility-side electrical infrastructure and are frequently used in situations where utility capacity is insufficient to meet agency demand, impacted by unexpected outages, or if new infrastructure is cost-prohibitive and/or subject to extended lead times. There are a variety of resilient charging approaches, two of which are microgrids or generators. Generators cost significantly less than microgrids, but microgrids are more robust and have multiple benefits including lower operating costs and emissions outputs. These two options are described in more detail below.

Microgrid Design and Practices

Microgrids enable off-grid charging while providing on-site load management and operational flexibility. Microgrids decide where power comes from, when to store or use it, and when to disconnect from the grid. The microgrid controls and manages the following energy resources:

Battery Energy Storage Systems (BESS)

BESS can store and later supply electricity to chargers without drawing power from the utility grid while charging. These systems are typically charged via on-site renewable energy production or when low-cost grid power is available. The BESS can then deliver energy to support charging during outages, or when charging is needed when grid power cost is at peak, or at grid-constrained sites. Because vehicles are already essentially very large batteries, storing energy to charge vehicles for an outage is generally not practical, except for a small number of critical vehicles.

Mobile/Temporary Charging

Mobile/temporary charging units are not permanently installed and have the flexibility to be moved or removed. These are typically used for pilot deployments or throughout the construction phases of projects and are designed to support a limited number of vehicles. Mobile chargers could be relocated between different facilities to support charging needs during resilience events.

On-Site Renewable Generation

On-site generation using renewable power options, such as solar photovoltaic systems utilizing solar panels, can be used to provide off-grid power for charging. This approach is typically paired with BESS to support consistent charging operations.

Backup Generators

Another off-grid charging option is to produce power using a generator. Backup generators powered by diesel, renewable diesel, natural gas, or hydrogen can supply electricity to chargers during outages or where utility service is unavailable. While effective for emergency or temporary use, generator-based charging may conflict with emissions reduction goals and is generally not intended as a long-term solution.

Design Considerations

Regardless of the charging approach, agencies should design their sites to support critical charging loads that are required for both regular service and emergency response. Off-grid systems should be sized to accommodate worse-case operating conditions and fleet growth. Agencies should also consider space requirements, cost differences, build and permitting timelines, and safety considerations early in the design process.

Benefits and Drawbacks

Off-grid charging adds resiliency, particularly in emergencies such as Public Safety Power Shutoffs (PSPS). They can also enable BEB transitions in cases where a local utility provider has insufficient capacity to meet demand, allow transit agencies greater control over their utility rates, and provide low to zero

CI[4] electricity if an agency chooses to produce electricity at its facility using renewable sources.

Microgrids and generators are additional infrastructure elements that will add to overall costs. Depending on which resilience approach is selected, the power may not be fully zero-emission and could conflict with an agency's zero-emission goals.

Scaling Up

After a successful pilot, agencies may begin scaling up their ZEB fleet and supporting infrastructure. As ZEBs become an increasing percentage of the fleet, planning becomes even more important. From an internal planning perspective, agencies should be aware of an important threshold that occurs when the percentage of ZEBs in the fleet exceeds the spare ratio. This is an important horizon because it's the point in the agency's fleet transition where the success of the technology directly impacts their ability to meet pullout. As previously mentioned, it is highly recommended that an agency develop a ZEB Transition Plan before that point.

Agencies must continue to ensure that bus and charger OEMs can provide adequate response times for service and replacement parts to avoid unplanned downtime. Agencies should also make considerations for BEB site resilience to ensure that the BEBs can operate in the event of a power outage. As much as possible, agencies should also try to apply learnings from their pilot experience and replicate successes from that deployment while also adjusting their approach to try to avoid any issues that may have been encountered in the pilot phase.

As the size of the ZEB fleet grows, there are several key coordination efforts that need to occur. For BEBs, three of these are related to infrastructure: ensuring there is sufficient space in the yard for the necessary charging infrastructure, planning for yard disruptions during charger installations, and ensuring that the utility will be able to meet power demands. To ensure there will be sufficient space for the chargers, agencies may want to hire contractors to assess the yard and create a site layout. Agencies should also consider how many total charger installation projects will be necessary to meet the needs of the final quantity of BEBs that will eventually be in the fleet. The agency may plan to add chargers each time BEBs are added to the fleet, but this could mean that the yard will be repeatedly disrupted by charger installation projects. Agencies should plan how to minimize disruption to the yard.

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[4] *California Air Resources Board. Grams of Carbon Dioxide Equivalent (CO2e) Greenhouse Gas Emissions per Megajoule of Electricity*. California Air Resources Board, n.d. https://ww2.arb.ca.gov/resources/documents/apply-lcfs-fuel-pathway.

Finally, to ensure sufficient grid-side power, agencies should plan for grid-side infrastructure upgrades multiple years in advance of large-scale BEB deployments and account for long lead times for items such as transformers in deployment planning. Agencies should also place special emphasis on managing utility costs, which can include charging off-peak, staggering charging to avoid demand charges, and negotiating with utilities for better rates, if possible.

Fuel Cell Electric Bus and Hydrogen Fueling Infrastructure

Fuel Cell Systems

Typically, when people discuss the fuel cell within a FCEB, they are referring to a suite of components that collectively operate as a fuel cell system. This system can include multiple fuel cell stacks, an air compressor, power conditioning components, and a humidifier. Current U.S. FCEBs use proton-exchange membrane (PEM) technology. PEM fuel cells generate electricity by removing the electrons from hydrogen molecules. These electrons produce an electric current, which is used to power components or charge batteries on the vehicle. The charged hydrogen molecules also react with oxygen from the air and produce water as a byproduct, which exits the FCEB via the tailpipe. This process also generates some heat. Many fuel cells are assembled together to create a fuel cell stack; there may be multiple stacks within a single fuel cell system[5].

Fuel Cell Degradation

Stack performance degrades over time due to normal wear and contaminants, which can reduce the power output and efficiency. Agencies should familiarize themselves with their fuel cell warranty terms and conditions and account for refurbishment and/or replacement costs in lifecycle cost assessments. Fuel cell stacks are often replaced every six years. Agencies should monitor the efficiency and power output of the fuel cell over time to identify potential impacts to operations before they occur.

Fuel Cell Safety

The main safety risks associated with the fuel cell system are related to high-voltage components and the presence of hydrogen. Anyone who may be involved in the maintenance of a FCEB or the fuel cell system should receive high-voltage and hydrogen safety training to avoid any potential risks from these factors. A technician working on the fuel cell system should also ensure that the vehicle is in a facility, maintenance bay, or outdoor location configured to safely conduct maintenance activities on hydrogen-powered vehicles. Although not directly part of the fuel cell system, it should be noted that while the hydrogen within the fuel cell is typically at relatively low pressure (less than 120 psi), hydrogen on board the vehicle is stored in high-pressure tanks (5000

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[5] U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. *Fuel Cell Systems*. U.S. Department of Energy, n.d. https://www.energy.gov/eere/fuelcells/fuel-cell-systems.

psi). Technicians working on the vehicle should receive safety training for handling high-pressure systems.

FCEB Battery Components and Hybrid Systems

Today's FCEBs use a hybrid system that pairs a fuel cell with a high-voltage battery. The fuel cell provides power as needed to charge the battery, while the battery discharges to support dynamic loads needed by the electric propulsion motor for accelerating or climbing grades. The battery also stores energy produced from regenerative braking. Although smaller than BEB batteries, FCEB batteries operate similarly and introduce comparable high-voltage safety and lithium-ion fire risk considerations.

Hydrogen Fueling

Hydrogen Production Pathways for Transit Applications

Hydrogen used to fuel FCEBs is currently delivered to transit agencies or produced on-site. The most common hydrogen production method is steam methane reforming (SMR), carried out at a central, large-scale facility, which produces hydrogen from natural gas (methane) at a relatively low cost. Small-scale reformers do exist, but they can be challenging to deploy in transit applications. Often, reformers function best at steady-state, and transit agencies typically have inconsistent off-take throughout the day with a defined fueling window. Additionally, SMR is associated with greenhouse gas emissions unless paired with carbon capture.

There are also electrolytic pathways for hydrogen production. Electrolysis produces hydrogen by using electricity to split water into hydrogen and oxygen. Any electricity can be used, including from the local grid or on-site production from renewable or low-carbon electricity. While producing hydrogen on-site from an electrolysis system will typically have higher capital costs and electricity demands than delivered hydrogen solutions, producing hydrogen on-site may offer reduced emissions and fuel price stability compared to delivered solutions.

Like other large-scale hydrogen production pathways, biomass-based processes or industrial byproduct hydrogen, may also supply transit fueling markets in certain regions. These are less common, and their suitability is location specific.

Onboard Hydrogen Storage

Transit FCEBs typically use roof-mounted, high-pressure tanks to store gaseous hydrogen at a pressure of 350 bar. When discussing the amount of fuel in a tank to communicate the range of a vehicle, hydrogen is typically described in kilograms (kg), a unit of mass. Mass is preferred over pressure because the pressure within the hydrogen storage tanks varies with ambient temperature. A typical 40 ft transit bus has a hydrogen storage capacity of 37.5 kg, but options are available to expand storage and, by extension, range. In addition to range, hydrogen storage size and placement impacts vehicle weight and passenger capacity. Agencies should consult with the OEM to understand if additional storage capacity is needed to meet performance requirements.

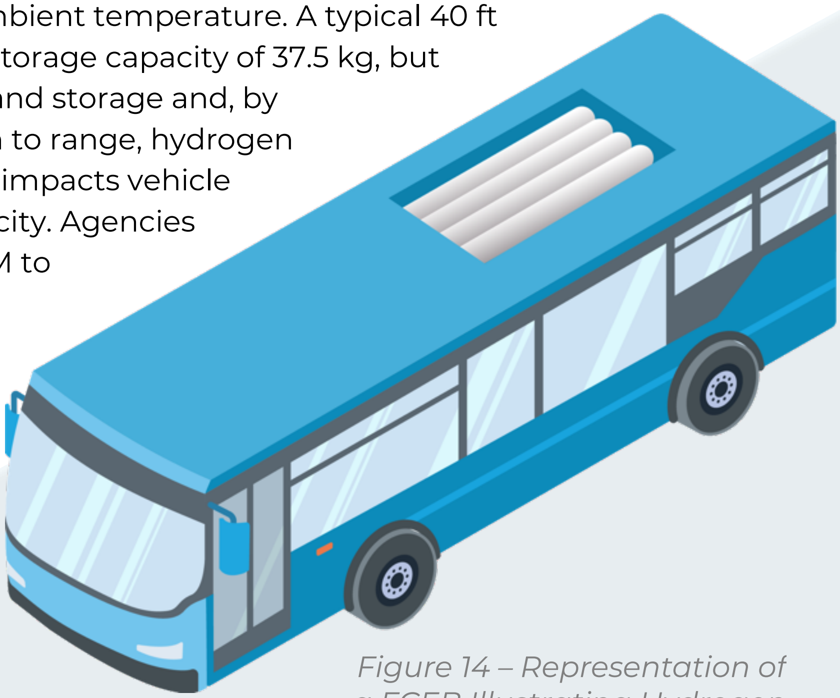

Figure 14 – Representation of a FCEB Illustrating Hydrogen Storage On-Top of the Vehicle

FCEBs utilize gaseous hydrogen as a form of energy storage because it stores significantly more energy per mass than current battery chemistries used in BEBs, offering extended range without contributing to large vehicle weight increases. Research is underway to develop FCEB designs that eliminate high-voltage traction batteries, further reducing overall weight.[6]

700 bar systems are used in passenger vehicles and heavy-duty trucks but are not currently used for transit buses, although there is potential for future market development. This is an important consideration if a transit agency is considering including public access hydrogen fueling as part of a hydrogen station design. However, 700 bar fueling is likely more expensive than 350 bar fueling.

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[6] FuelCellsWorks. “Center for Transportation and the Environment to Lead Innovative Battery-Free Fuel Cell Bus Project.” *FuelCellsWorks*, 15 Nov. 2024, https://fuelcellsworks.com/2024/11/15/fuel-cells/center-for-transportation-and-the-environment-to-lead-innovative-battery-free-fuel-cell-bus-project.

Hydrogen Dispensing Equipment and Facility and Station Operations

The following section provides an overview of hydrogen fueling stations. FCEBs in the U.S. currently accept hydrogen solely in gaseous form; however, hydrogen fueling stations can accept liquid and/or gaseous hydrogen deliveries depending on their design. Liquid hydrogen is much denser than gaseous hydrogen, allowing a much greater mass of hydrogen to be stored in the same volume. This means that a liquid tanker can carry more fuel than a gaseous tube trailer, and a liquid storage tank can store more hydrogen than gaseous ground storage with the same volume. For example, a typical liquid tanker might carry 4,000 kg of hydrogen, but a typical tube trailer may only store 400 kg of hydrogen (depending on the trailer model). Since the buses require gaseous hydrogen, hydrogen stations that receive and store liquid hydrogen must also include systems to convert the hydrogen to gaseous form and adjust it to the appropriate pressure for the bus to accept. Examples of fueling station layouts, including key components of gaseous storage-based and liquid storage-based stations, are provided in **Tool 6** and **Tool 7**.

Hydrogen Fueling Stations

One key decision impacting hydrogen station configuration is whether the main hydrogen storage system will be gaseous or liquid. The main factor impacting whether an agency decides to procure a liquid or gaseous hydrogen storage system is often the expected hydrogen demand for the fleet. While liquid hydrogen is often cheaper than gaseous and can be stored in a smaller footprint for a given mass, it is very difficult to store liquid hydrogen at very cold temperatures (liquid hydrogen is a cryogenic fluid and must be stored at -423 degrees Fahrenheit). This means that if the station is over-sized for a bus deployment, there will often be losses of hydrogen fuel that can lead to high fuel costs (described in more detail in the *Boil-Off Loss Management* section below). For this reason, smaller deployments tend to be more suited to gaseous storage, while larger deployments may find liquid hydrogen to be more economical.

There are three general levels of hydrogen infrastructure options as illustrated in **Table 3**. The options are as follows:

Level 1 (Gaseous) - For a pilot program of approximately one to five FCEBs, a small-scale gaseous solution is sufficient, with gaseous hydrogen being delivered via tube trailer.

Level 2 (Gaseous or Liquid) - When the deployment size increases up to 15 FCEBs, a gaseous solution is still viable, but the station configuration will need to be more involved, requiring an integrated skid-mounted solution with a compressor, pre-cooling equipment, and dispensers. However, the hydrogen can still be delivered via tube trailer.

Agencies with approximately 15 to 20 FCEBs, which are expected to consume approximately 375-500 kg of hydrogen per day, should begin to consider liquid as opposed to gaseous hydrogen. The equipment for liquid hydrogen can be more complex, with a liquid tank, liquid pump, vaporizer, pre-cooling, and dispenser. Hydrogen will be delivered in liquid form in a tanker from a centralized production plant.

Level 3 (Liquid) - Agencies with approximately 50 to 150 FCEBs should consider a large-scale liquid solution. Large-scale liquid solutions include large liquid tanks (15,000 gallons or greater), vaporizers, liquid pumps, gaseous buffer storage, and dispensers, all mounted on a concrete pad. Similar to the smaller fleets, liquid hydrogen can still be delivered to this type of station in a tanker from a centralized production plant.

Table 3 – Hydrogen Fueling Station Configurations by Scale and Fleet Sizes

Type of Structure	Sample Configuration	Fuel Delivery Method	Optimal Fleet Size Supported
Level 3: Large-scale Station	Large liquid hydrogen tank (15,000 gallons or greater), vaporizers, liquid pumps, gaseous buffer storage, and dispensers all mounted in place on a concrete pad	Liquid – Tanker from centralized production plants	50 – 150 buses
Level 2: Medium-scale Station	Liquid: Integrated, trailer-mounted solution with a liquid tank, liquid pump, pre-cooling, and dispenser	Liquid – Tanker from centralized production plants	15 – 20 buses
	Gaseous: Integrated, skid-mounted solution with a compressor, pre- cooling equipment, and dispenser, typically connected to a gaseous tube trailer for supply	Gaseous – Tube trailers or generated on-site through electrolysis or natural gas reformation	5 – 15 buses
Level 1: Small-scale Station	Gaseous systems can be as simple as a hose with a regulator	Gaseous – Tube trailers	1 – 5 buses

Aside from fleet size, there are several other important considerations that influence the optimal station configuration for an agency. For example, station reliability and fuel supply reliability can affect which hydrogen option is the best fit. Fuel supply reliability is strongly influenced by an agency's proximity to hydrogen production and liquefaction facilities as well as access to multiple production facilities, particularly for small- and medium-scale solutions, which typically lack redundant systems. Stations should be designed with redundant systems and include a clear plan for preventive maintenance, a list of critical spares to be maintained on-site, and a defined corrective maintenance response protocol.

An agency's long-term deployment goals are also critical to sizing a station appropriately. If an agency is committed to expanding its FCEB fleet over time, it is important to select a fueling solution that can scale as the hydrogen fleet grows.

Historically, transit agencies have typically secured funding to design and construct a large-scale liquid hydrogen station to support the expected final FCEB fleet size. The advantage of this approach is that it requires a single capital investment and then the agency can add FCEBs to the fleet in future years without further infrastructure upgrades. The disadvantage to this approach is that if a liquid station is designed to support 50 FCEBs and the agency only has 5 FCEBs for multiple years, the station will have significant boil-off. There have been reports of agencies losing over 40% of the fuel purchased to boil-off when the station is oversized for the fleet.

Today, there are more modular systems available in the market for small-scale stations and medium-scale stations. For example, some products include a skid-mounted dispenser and pre-cooling system that can be initially connected to a high-pressure tube trailer. Over time, infrastructure can be built out to include gaseous ground storage, compression, on-site production, or a liquid storage and pumping system. Planning upfront for a modular station build-out could reduce initial capital investment and allow an agency to adapt its plans more easily as bus procurement schedules change.

It is important to note that FCEB transit buses are currently designed to fuel at 350 bar, so any fueling solution procured by an agency for bus fueling should specify fueling at this pressure.

Dual Pressure Hydrogen Dispensers

More common in retail fueling stations, dual-pressure hydrogen dispensers offer fueling at both 350 and 700 bar. Just as 350 bar fueling is standard for medium- and heavy-duty vehicles, including transit buses, 700 bar fueling is standard for light-duty vehicles such as passenger cars and some heavy-duty vehicles. Agencies may wish to consider installing a dual pressure dispenser if they intend to purchase light-duty fuel cell vehicles or offer public dispensing.

Boil-Off Loss and Management

Specific to hydrogen fueling solutions using liquid storage, boil-off occurs when liquid hydrogen evaporates into gas due to increases in temperature. Liquid hydrogen is a cryogenic fuel, meaning that it must be stored at very low temperatures (-253°C) to remain in a liquid state. When liquid hydrogen warms, it boils, which increases pressure inside the bulk storage tank. When the pressure exceeds a certain level, hydrogen gas must be vented to prevent overpressure, resulting in the loss of fuel. The three main sources of heat input in a hydrogen station are during the liquid hydrogen offload process, heat conducted through the tank, and the liquid hydrogen pump cool-down process.

Transit agencies with permanent liquid hydrogen fueling stations in service have reported losses between 10–40% of purchased hydrogen due to boil-off. Thankfully, there are ways to reduce the losses. There are two main strategies for combating boil-off: equipment strategies and operational strategies. Equipment strategies involve adding additional technologies to a station that help to mitigate losses, while operational strategies are actions the agency can take when using their station to reduce boil-off. Some of these strategies have solely been proposed because of the observed losses at existing stations and may not have been deployed at transit agencies.

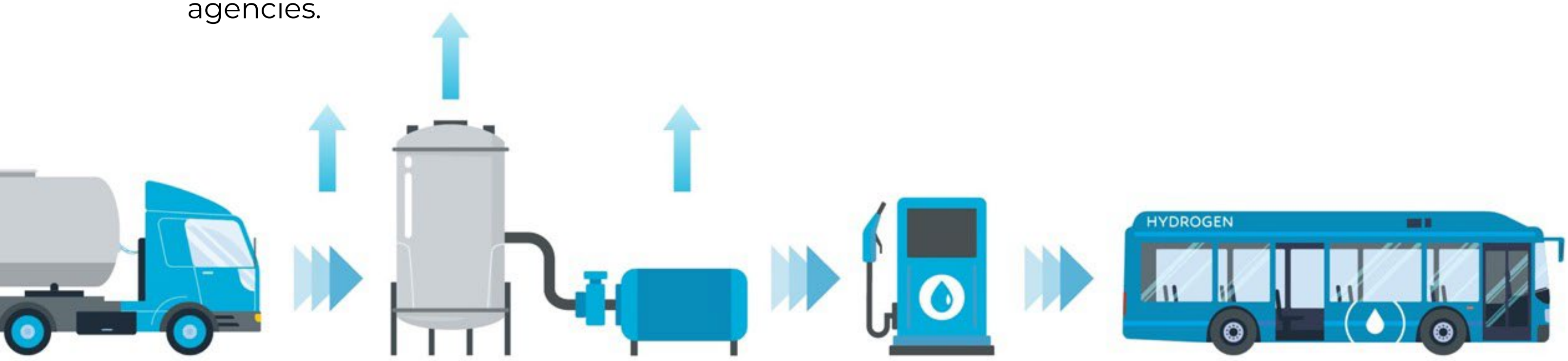

Figure 15 – Boil-Off Gas Graphic Reference

Equipment Strategies for Minimizing Boil-Off

Delivery Offloading Pump

The typical process for transferring liquid hydrogen is through pressure equilibrium, which can result in the loss of 10–20% of delivered hydrogen. Agencies can mitigate some fuel losses during offloading by using a cryogenic offloading pump as opposed to relying solely on existing pressure differentials.

Boil-Off Compressors

Boil-off gas compressors draw gaseous hydrogen resulting from boil-off from cryogenic storage tanks into pressurized gaseous storage. Boil-off gas compressors have the potential to mitigate some boil-off losses; however, they increase the capital and operating costs of a station, along with expanding its footprint. Agencies considering a boil-off gas compressor solution should account for maintenance costs and uptime when evaluating vendor proposals. Additionally, there can be a complex interplay between the minimum pressure the compressor requires to operate and the pressure required in the bulk liquid storage tank to operate the liquid pump. All of these elements must be evaluated to determine the expected boil-off captured by the compressor and whether the recovered fuel costs justify the initial capital expenditure, as well as maintenance and operating costs. To date, this technology has not been deployed in transit applications.

LH2 Pump Innovation

One of the major heat inputs contributing to boil-off is the station pump. The station pump typically contributes to boil-off losses during cooling and during actual pumping operations. First, the pump must be cooled to push hydrogen through it. Because of this, several companies have developed cryopumps that require a less significant cool-down process. Innovations include vacuum-insulated cryopumps and submerged cryopumps, where the cryopump itself is submerged in a cryogenic fluid. Second, hydrogen can be lost during the actual pumping process. New solutions in innovative pump design (i.e., improving pump seals) aim to minimize these losses. To date, there have been limited transit deployments of these technologies.

Tank Refrigeration

An internal cooling system can be installed within a station storage tank to minimize hydrogen losses due to boil-off. This system is designed to reduce heat gain. However, tank refrigeration requires additional equipment and capital investment, and there have been limited deployments in transit applications to date. As a result, the cost-effectiveness of this approach remains uncertain, particularly because the system requires significant electricity consumption.

Operational Strategies for Minimizing Boil-off

Back-to-Back Fills

If pumping equipment must be cooled prior to fueling, minimizing the number of cool-down events is critical to reducing losses. Planning to fuel multiple buses during a single fueling window limits how often the pump must be cooled and helps reduce excess boil-off associated with repeated cool-down events.

Station Utilization

Higher utilization can reduce the loss of boil-off gas, as more frequent deliveries keep the hydrogen in the tank colder. High throughput reduces the likelihood of multiple cool-down events.

Contracting Practices to Reduce Boil-off

Station designers are ultimately responsible for maximizing station performance. In order to minimize boil-off, agencies should include performance requirements relating to boil-off in their equipment solicitations and hold station providers accountable in contract language. Staying up to date with developments in hydrogen fueling can help agencies set realistic expectations regarding boil-off when issuing a solicitation.

It is also important to recognize that some vendors will not agree to meet boil-off performance requirements unless they are contracted for both station operation and fuel supply. This is because the fuel delivery process can be a significant source of heat input, and the pressure in the hydrogen bulk storage tank impacts the delivery process. Without oversight of both elements, some vendors will not commit to keeping boil-off below a certain threshold.

Scaling Up

True to any ZEB technology scale-up, as FCEBs make up a larger percentage of the fleet, an important threshold is reached when the percentage of ZEBs in the fleet exceeds the spare ratio. As previously mentioned, it is highly recommended that an agency develop a ZEB Transition Plan before that point. Agencies also must continue to ensure that bus and fueling station OEMs can provide adequate response times for service and replacement parts to avoid unplanned downtime. Though less critical than for agencies reliant on BEB charging infrastructure, agencies with a hydrogen fueling station may also want to plan for backup power for the hydrogen fueling station to ensure FCEBs can continue operating in the event of a power outage, since the fueling station also requires electrical power to function. As much as possible, agencies should also apply learnings from their pilot experience and replicate successes while adjusting their approach to avoid any issues that may have been encountered during the pilot phase.

As agencies increase the quantity of FCEBs beyond the pilot phase, they typically begin considering the installation of permanent hydrogen fueling infrastructure. If possible, the agency should select a solution that will have sufficient capacity for the remainder of their planned FCEB fleet. This means that the infrastructure scale-up for FCEBs may be completed within a single project.

Tool 2:

Step-by-Step Framework for ZEB Deployment

This tool, organized as a step-by-step framework for ZEB deployment, begins with evaluating agency priorities and progressing through education, planning, procurement of vehicles and infrastructure, infrastructure build, workforce training, and deployment evaluation. Each step builds on the last and includes targeted questions, readiness checklists, and a list of existing resources that are designed to support agencies throughout each step of the process. Readers who are new to ZEB technologies are encouraged to start from Step 1 before proceeding to the next steps. However, agencies with more ZEB knowledge or experience may choose to move directly to the step that most aligns with their current stage of deployment. A consolidated readiness checklist from each step can be found in the **Appendix**:.

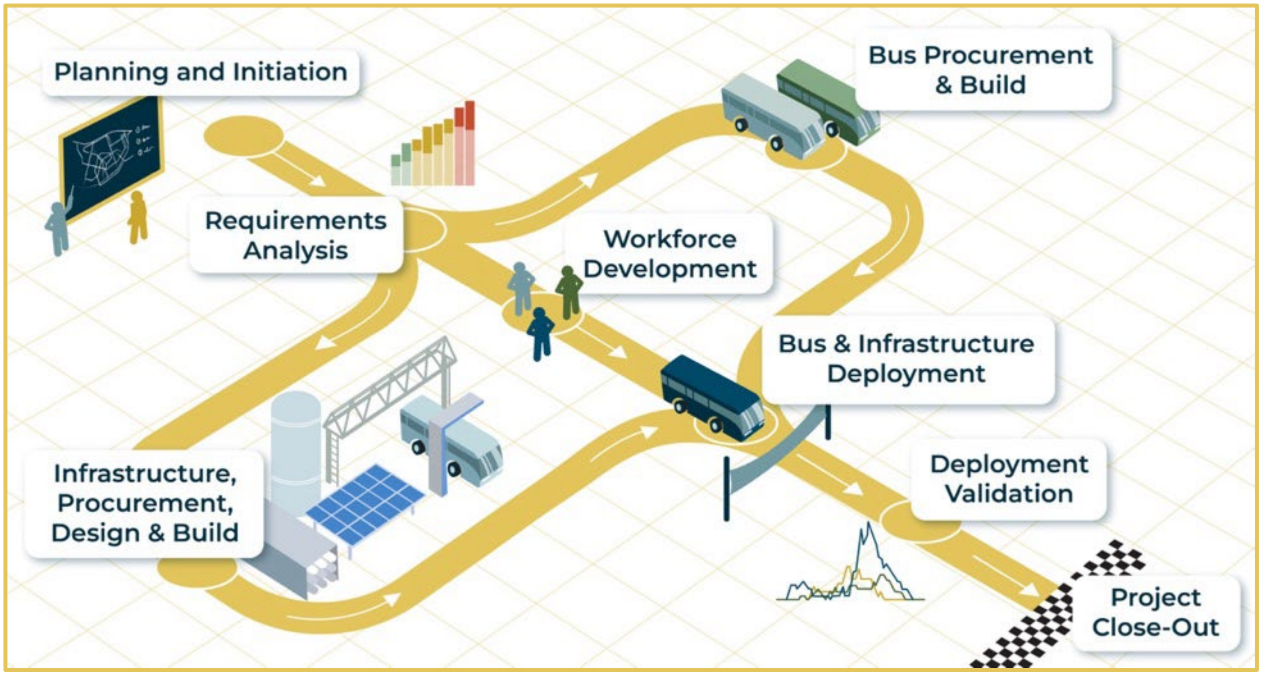

Figure 16 – CTE's Smart Deployment Methodology

Step 1:

Evaluate Agency Motivations

Regardless of prior zero-emission experience, agencies should have a thorough understanding of their internal goals before planning a ZEB deployment. For example, a ZEB transition may be motivated by regulatory requirements, such as the California Air Resources Board's (CARB) Innovative Clean Transit (ICT) regulation or based on more aggressive agency-wide or city-wide decarbonization goals. This knowledge will help determine how the transition is scaled and the timeline for transitioning fleets to 100% zero-emission. This effort will likely require early coordination with board members and across departments. If applicable, agencies should consult any existing transition plans and make updates as needed.

Key Questions to Consider:

Agency Goals

- What are the agency's motivations for transitioning to ZEBs?
  - Is the agency motivated primarily by compliance with CARB's ICT regulation?
  - Does the agency have internal environmental, social, and governance (ESG) goals?
- Is the immediate goal to focus on developing a plan to transition the entire fleet to ZEBs?
- Is the immediate goal to deploy a ZEB pilot?
  - Does the agency want to pilot newer zero-emission technologies or focus on established technologies?
- What is the timeline for transitioning to ZEBs?
- Which vehicles are in the scope of the transition?
  - Fixed route? Commuter? Paratransit? On Demand? Non-revenue?
- How will the agency gauge success?

Stakeholders

- Who at the agency will lead ZEB efforts?
- What are the agency's internal capabilities for managing a ZEB transition planning and/or deployment effort?
- Who are the key internal and external stakeholders to include in ZEB planning efforts?
- Is the Board supportive of the agency's goals and ambitions?
- Are there community groups, businesses, elected officials, or other organizations that will support or challenge the agency's zero-emission goals?

Technology Considerations

- What is the agency's comfort level with ZEB technology?
- What does the agency expect in terms of the general cost impact of a ZEB deployment?
- Does the agency have any requirements or preferences for how green/renewable/carbon-intensive the ZEBs' fuel (electricity or hydrogen) is?
- What is the agency's experience with high-voltage and/or high-pressure systems related to hybrid or gaseous propulsion technologies?

Checklist Before Moving to the Next Step:

- ☐ Agency’s zero-emission goals are documented
- ☐ Board and executive priorities are understood and aligned
- ☐ Applicable regulations and legislative requirements are defined
- ☐ Key stakeholders have been identified

Suggested Resources to Reference:

- Innovative Clean Transit (ICT) Regulation Fact Sheet (CARB)
- Local and/or regional climate action plans

Step 2:

ZEB Education and Agency Stakeholder Engagement

This step is focused on introducing agency stakeholders to key concepts and developing an understanding of available ZEB technology options to inform later planning decisions.

Agencies should ensure that staff at all levels of the organization are educated regarding ZEB concepts, including vehicle technologies, energy sources, facility requirements, and maintenance considerations, as needed. During this step, agencies should also document any department-specific concerns regarding zero-emission technologies. Introducing ZEBs into an agency's fleet affects service planning, daily operations, maintenance, procurement, facility planning, safety, resilience, budgeting, workforce needs, and long-term planning. Agency-wide education helps ensure stakeholders understand both how ZEB technologies function and how they differ from internal combustion engine (ICE) technologies. When planning for ZEB deployments, agencies should evaluate the extent to which these differences may create challenges for different departments involved in operating new buses. Staff at all levels of the organization should be included in this step so that any questions or concerns can be identified and addressed early in the process.

There are a variety of educational resources available to learn more about ZEB technologies. Key ZEB topics are covered in **Tool 1**. Additionally, the list of suggested resources provided at the end of this step include additional information about the ZEB technologies discussed in this toolkit. Along with self-education, agencies are encouraged to visit peer agencies that have deployed ZEBs to see buses and infrastructure in operation and hear from peers about their experiences. If conducting this level of research and internal education is not feasible for an agency given its existing staff capacity, the agency should consider hiring additional staff or contracting with consultants to support this effort.

Learning about new technologies can be daunting, especially when they are constantly evolving and decisions around them have long-term financial and operational impacts. Some guiding questions that agencies should be able to answer before developing a transition plan and/or deploying ZEBs are provided below.

Key Questions to Consider:

Vehicles

- What vehicle models are currently available?
- What are the general strengths and weaknesses of each technology solution?
- What solution types are mature versus emerging?
- How might adding ZEBs to the fleet affect internal operations?
- Will the ZEB deployment be part of or separate from regular fleet replacement schedules?

Fuel

- What fuels or energy sources are required for each ZEB technology?
- Who are the major providers of the fuels that serve the agency's region?
    - For hydrogen providers: is gaseous fuel available for delivery? At what pressures? Is liquid fuel available? What is the resiliency of these supply sources?
- What is the fueling mechanism for the ZEB type(s) under consideration at a high level?
- What are the pros and cons of different hydrogen production and delivery pathways?
- What are the basic safety considerations associated with each fuel or energy type?
- How might ZEB fueling or charging impact current fueling operations?

Facilities

- What types of fueling infrastructure are required to support ZEBs?
- How do facility needs differ between incumbent technologies, BEBs, and FCEBs?
- What general space and safety considerations are associated with ZEB facilities?

Maintenance

- How might adding or updating maintenance facilities to accommodate ZEB maintenance impact the fleet overall?
- How do maintenance needs differ for ZEBs?
- Is there a need for additional maintenance tools and equipment?

Workforce Development

- What new safety considerations and skills are required for each ZEB technology?
- What are the general workforce development implications for each ZEB technology?

Agency Specific

- Who are the key stakeholders within the transit agency? Which staff within each department are considered key stakeholders?
- Are there existing forums within the transit agency for convening key stakeholders?
- What capital and operating budgets do the agency have available for ZEB-related costs?
- What types of funding may be available for a ZEB deployment?
- What is the agency's current knowledge base and comfort with respect to ZEBs?
- What resources are best suited to filling gaps in the agency's knowledge of ZEBs?

Checklist Before Moving to the Next Step:

- ☐ Current fleet composition and service information are documented and up to date
- ☐ Knowledge gaps have been identified
- ☐ A plan to address knowledge gaps has been created
- ☐ ZEB basics and the differences between ICE buses, BEBs and FCEBs are understood across staff levels
- ☐ Key questions and concerns from internal stakeholders have been documented
- ☐ Strategies to address key questions and concerns from stakeholders have been identified
- ☐ Vehicle and infrastructure solution options have been reviewed
- ☐ Peer agency sites where ZEBs are operating have been visited
- ☐ Agency's internal capabilities for executing ZEB deployment are understood
- ☐ Agency has developed a plan to hire or contract for additional support as needed

Suggested Resources to Reference:

- Guidebook for Deploying Zero-Emission Transit Buses (CTE)
- Zero-Emission Bus Transition Planning Guidebook (CTE)
- ZEB 101/ZEB 201 Courses (CTE)
- Guidebook for Deploying Battery Electric Buses (FTA)
- Guidebook to Low and ZE Transit Buses (DRPT)
- Zero Emission Bus Technology Resources (APTA)
- Joint Office of Energy and Transportation Resources (Joint Office)
- Web-Based Hydrogen Safety Resources (Hydrogen Tools)
- Hydrogen Resources (GO-Biz)
- Electric Bus Basics (U.S. DOT)
- Alternative Fuels Data Center: Electric Vehicle Charging Stations (U.S. DOT)

Step 3:

Planning Your Transition and Deployment

After developing basic knowledge of ZEB technology, agency stakeholders can begin considering which technologies may be well suited to their specific operating context. This step focuses on identifying and working through foundational planning questions that inform propulsion technology selection and deployment strategy. Agencies may begin by planning a pilot deployment to test zero-emission technology or by creating a ZEB transition plan, including feasibility requirements analyses and preliminary evaluations of capital and operating requirements and budgets for their full fleet, before initiating a pilot. For agencies that want to test out the technology and have not yet committed to converting a large portion of their fleet to ZEBs, starting with the pilot may be a good option. However, CTE strongly recommends beginning with the development of a transition plan if the agency intends to transition a significant portion of its fleet to ZEBs, as this can help optimize the pilot phase.

Regardless of whether a full transition plan has been finalized, CTE recommends that agencies begin their ZEB deployments with a ZEB pilot consisting of less than 10% of their total fleet. Typically, a pilot consists of 2-10 vehicles, which allows an agency to learn about the technology in the context of its operations while keeping the proportion of its fleet that is composed of ZEBs below the FTA's required spare ratio. This also enables agencies to meet service requirements in the event that issues arise that keep a pilot vehicle from operating in revenue service.

The planning step focuses on narrowing down which vehicle and fueling options make the most sense for the agency and developing an implementable strategy for achieving the agency's zero-emission goals. This requires weighing the tradeoffs between different technologies, further discussed in **Tool 2: Step 2** and **Tool 1**, with consideration for the agency's specific service needs. This step may also require identifying what additional analysis or stakeholder engagement is needed before moving into procurement. This step is where regulatory timelines, funding availability, and compliance strategies begin to shape decision-making.

If creating a robust transition plan is not feasible for an agency given existing staff capacity, the agency should consider hiring additional staff or contracting with consultants to support this effort. Agencies can also join virtual transit working groups like the Zero Emission Bus Resource Alliance (ZEBRA), the Hydrogen Fuel Cell Bus Council (HFCBC), or the American Public Transportation Association (APTA) Zero Emission Fleet Committee to access and share peer agency lessons learned and research findings.

Transition Planning

Before converting a significant portion of a fleet to zero-emission technology, an agency should conduct a ZEB transition planning analysis to create a feasible, informed plan to convert their fleet. CTE's Transition Planning Methodology example is shown in **Figure 17**. Most agencies likely already have plans to replace their fleet with incumbent technologies; however, a zero-emission transition plan is about identifying opportunities to replace retiring vehicles with ZEBs, based on technical and financial feasibility.

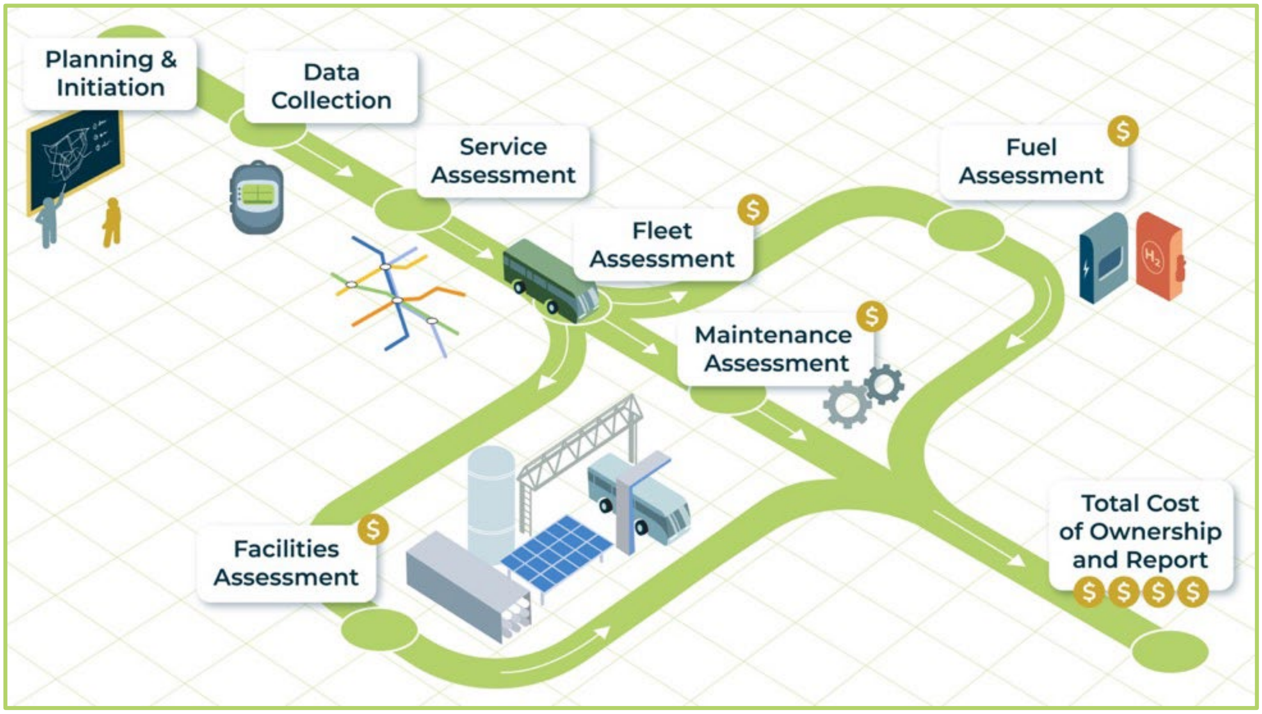

Figure 17 – CTE's Transition Planning Methodology

ZEB transition planning will also identify the incremental cost of transitioning compared to baseline agency fleet costs over time, which allows agencies to predict future funding gaps and plan to secure additional funds. Exploring multiple transition scenarios (i.e. fully BEB fleet without on route charging, fully BEB fleet with on route charging, fully FCEB fleet, mixed BEB/FCEB fleet, etc.) can help an agency determine which ZEB technology mix is the best option for their specific needs by checking each transition scenario's feasibility to meet agency service needs and then exploring fleet, fuel, facilities, and maintenance costs as well as operational considerations for each. With an understanding of feasibility, cost, and operational considerations for each scenario, an agency can weigh the opportunities and challenges associated with each option and choose which one will be the best fit. The transition plan also establishes an agency goal and helps align all stakeholders on the next steps for ZEB deployments. Transition plans should be revised at least every two years to capture the impacts of technological advancements, service modifications, fleet expansions, cost changes, and transition project schedule updates.

CTE recommends that, at minimum, a transition plan include the following assessments:

Service Assessment

Whether planning for a pilot deployment or conducting a full fleet transition plan, it is important to consider whether a given ZEB technology will be able to meet the range and performance requirements of an agency's service.

ZEBs have variable range under different operating conditions. The reliable range in transit service for a BEB today is approximately 200 miles on a single charge, while a FCEB today can support travelling more than 300 miles. However, vehicle range will differ across agencies due to route characteristics (speed, stop frequency, grade), passenger load, climate, driver behavior, and battery or fuel cell state of health (SOH).

A feasibility analysis, the key stage of the service assessment, looks at the energy needed to complete a block and compares that to the available energy of a bus type planned for the block. Understanding feasibility starts with activities such as data collection, reviewing vehicle specifications, and block analysis. Agencies are encouraged to utilize route modeling tools and review publicly available data from nearby agencies that have deployed ZEBs to gain an understanding of how vehicles may perform in their operations. In some cases, it may even be possible to borrow a ZEB from a nearby agency to run tests on specific routes to determine performance compatibility. Feasibility may change over time as technology improves. As a result, more routes and blocks may become feasible. The feasibility analysis should be considered in determining the vehicle replacement plan and the future fleet composition.

To deploy ZEBs on longer or more strenuous routes that are determined infeasible with BEBs or FCEBs, agencies may need to consider purchasing additional buses, adjusting blocks, redesigning routes, or incorporating midday or on-route charging/fueling. Agencies may wish to seek professional guidance to understand service feasibility prior to deploying zero-emission technology.

Fleet Assessment

The **Fleet Assessment** develops a projected timeline for the replacement of current buses with ZEBs that is consistent with the agency's fleet replacement plan and considers any feasibility limitations that were identified in the Service Assessment. This assessment also includes a projection of fleet capital costs over the transition lifetime. The timeline can be optimized with regard to any state mandates, like CARB's ICT regulation, or to meet agency goals, such as minimizing cost or maximizing service levels. The assessment generally assumes that buses are replaced with ZEBs of the same length as the incumbent buses currently in operation. The plan can also consider the impact of known or anticipated service and fleet modifications. As mentioned previously, it is recommended that the agency plan for the first ZEB deployment to be a relatively small pilot deployment. This should be built into the fleet procurement schedule. An example graph showing fleet composition results from CTE's Fleet Assessment is shown below in **Figure 18**.

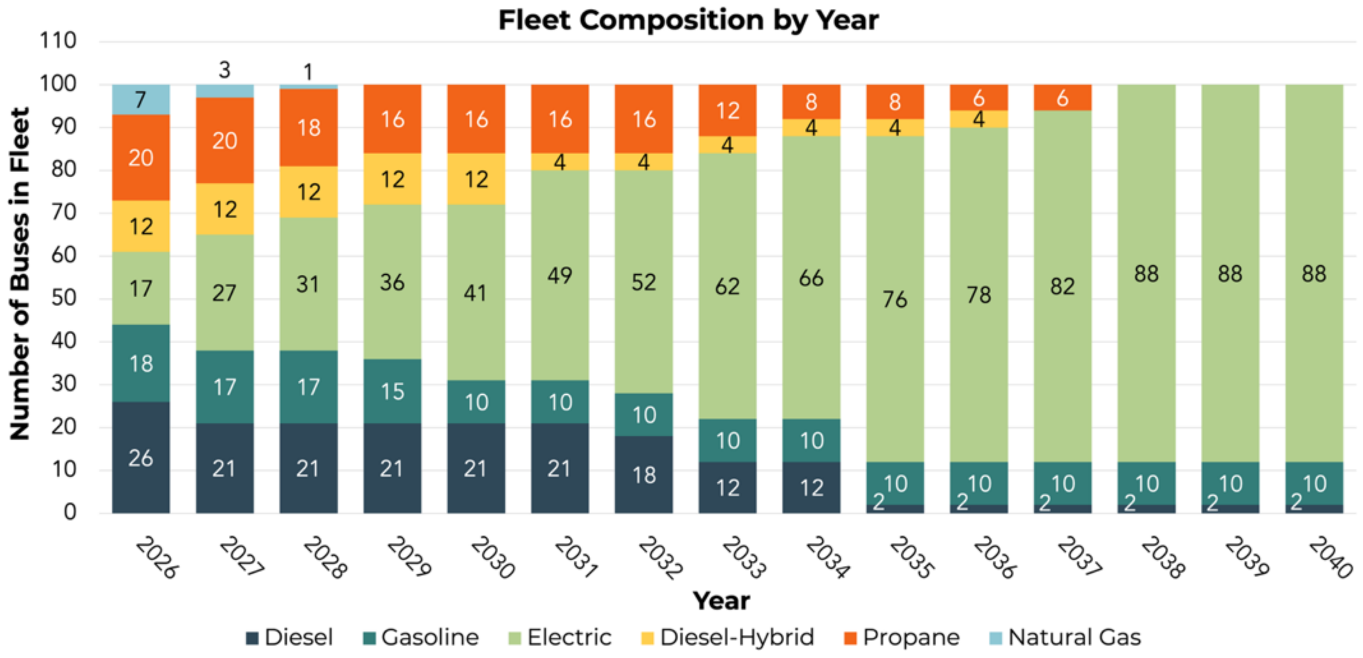

Figure 18 – Fleet Assessment Results & Annual Fleet Composition by Fuel Type Example

Fuel Assessment

The **Fuel Assessment** merges the results of the Service Assessment and Fleet Assessment to determine annual fuel requirements and associated costs. The Fuel Assessment calculates energy costs through the full life of the transition, including for the agency's incumbent technology buses. As current technologies are phased out in later years of the transition, the Fuel Assessment calculates the changing energy requirements for ZEBs. The Fuel Assessment also provides emissions savings and a total energy cost over the transition lifetime. An example graph showing annual energy use results from CTE's Fuel Assessment is shown below in **Figure 19.**

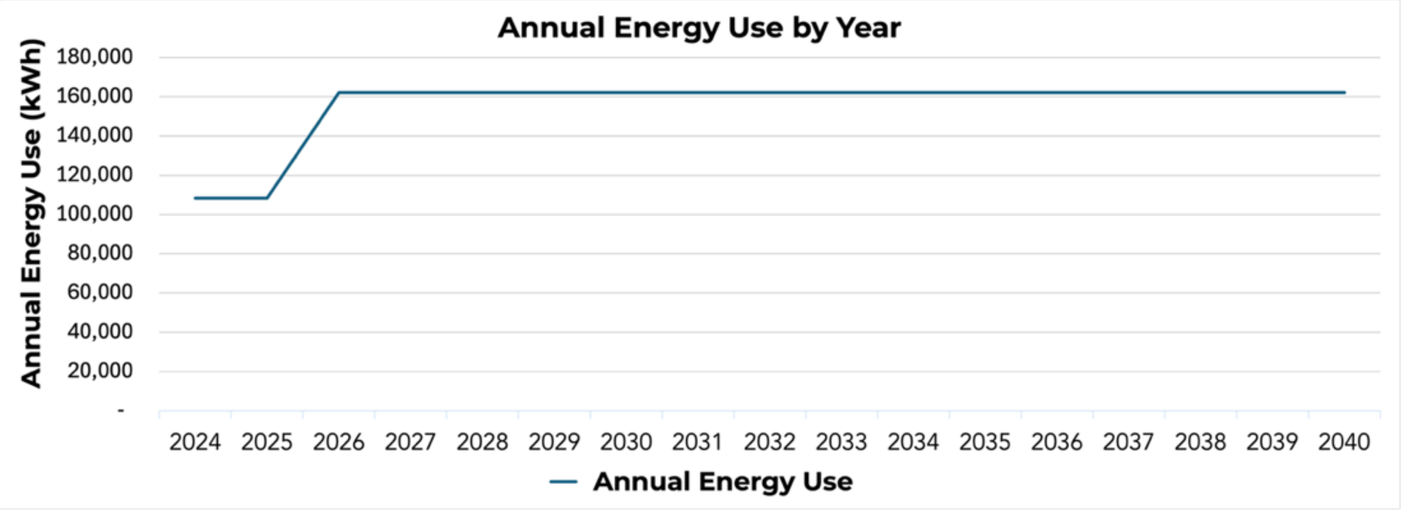

Figure 19 – Fuel Assessment Results & Annual Energy Use Example

Facilities Assessment

The **Facilities Assessment** determines the necessary infrastructure to support the projected zero-emission fleet based on results from the Fleet Assessment and Fuel Assessment. The Facilities Assessment determines the number, scope, and timeline of infrastructure projects needed to meet the fleet procurement schedules defined in the Fleet Assessment and the incremental fueling capacity required based on the Fuel Assessment. The result provides hydrogen and/or battery electric infrastructure requirements and calculates associated capital costs. The estimated energy demand over time should be communicated to the local utility so that it can be built into their demand plans to ensure sufficient power will be available when it is needed. An example graph showing infrastructure procurement plans from CTE's Facilities Assessment is shown below in **Figure 20**Figure 18.

For agencies deploying approximately four or fewer BEBs, a common approach is to plan for 150 kW per bus, assuming each bus has its own charger. As deployments scale beyond four buses, many agencies find that two BEBs can share a charger and plan for approximately 75 kW per bus. This recommendation assumes a single charging location.

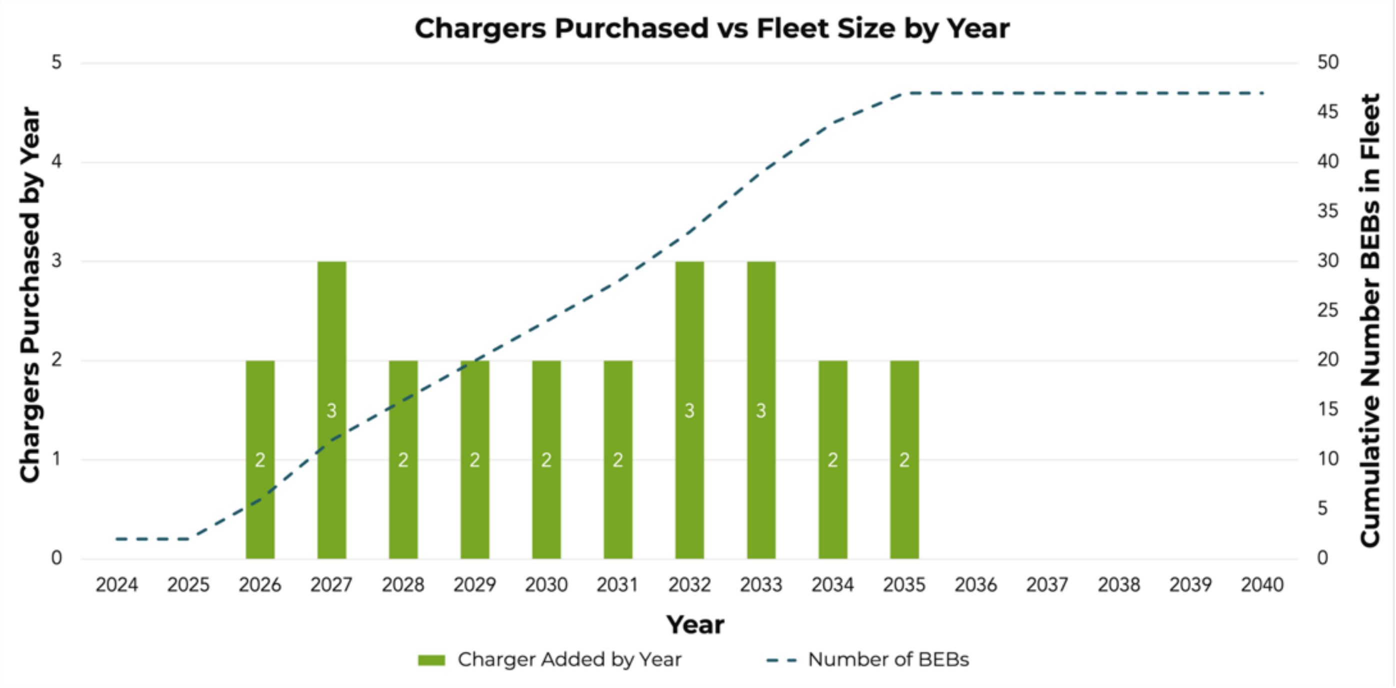

Figure 20 – Facilities Assessment Results & Annual Infrastructure Purchases Example

Maintenance Assessment

The **Maintenance Assessment** calculates all projected fleet maintenance costs over the life of the project. This includes costs related to incumbent technology buses remaining in the fleet, as well as new ZEBs. FCEBs will often require mid-life fuel cell overhauls, whereas BEBs will often require mid-life battery replacements. An example graph showing annual maintenance cost results from CTE's Maintenance Assessment is shown below in **Figure 21**.

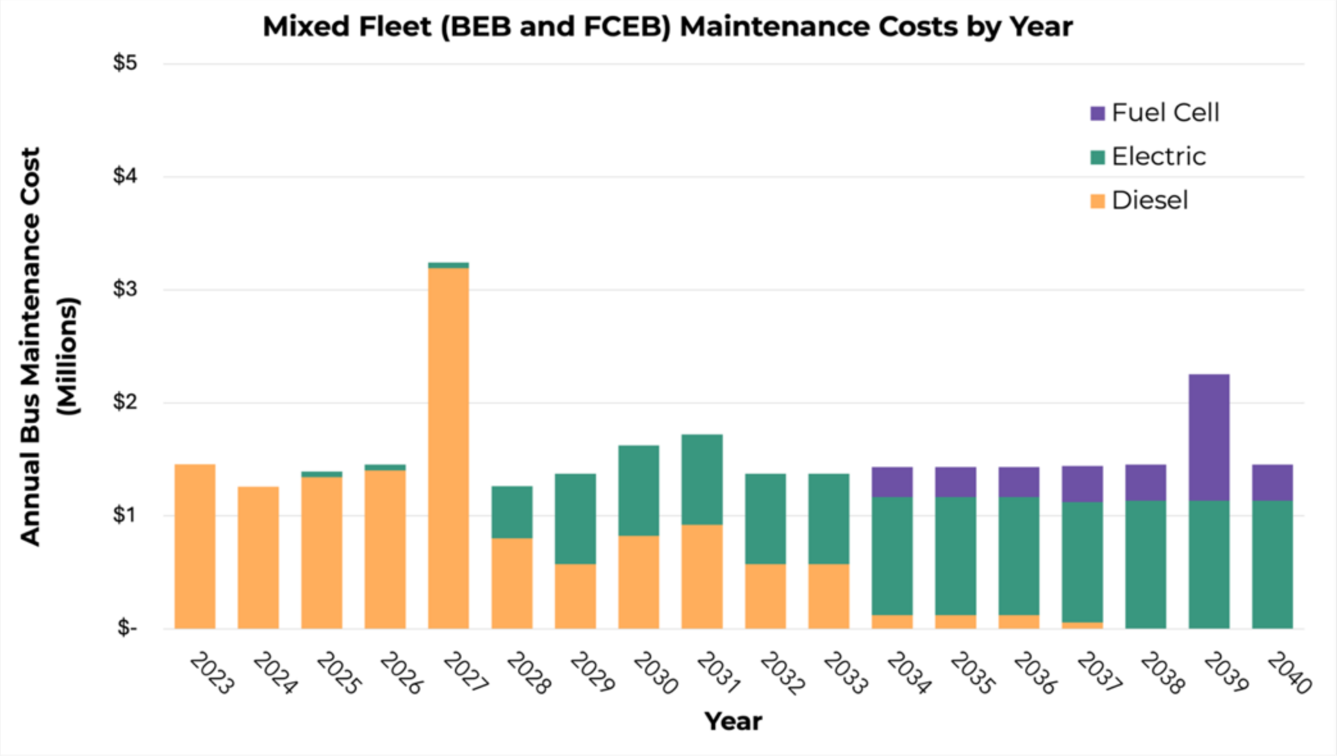

Figure 21 – Maintenance Assessment Results & Fleet Maintenance Costs Example

Total Cost of Ownership Assessment

The **Total Cost of Ownership Assessment** compiles results from the previous assessment phases and provides a comprehensive view of all associated costs over the transition lifetime. ZEBs are associated with higher vehicle capital costs but potentially lower operating costs compared to incumbent technologies. Incremental costs will vary depending on existing site conditions and agency-specific needs. The Total Cost of Ownership Assessment should also account for changes in costs, such as those resulting from inflation, over the course of a transition or the impact of financing capital procurements, if necessary. Agencies should pursue regional, state, and federal funding to support their zero-emission deployments. A list of potential funding sources is included in [Tool 3].

Scenario Analysis

The Transition Planning process described above can be repeated to analyze and compare different deployment scenarios (i.e., baseline, BEB-only, FCEB-only, mixed fleet, etc.) to help agencies better understand their technology options and to compare the Total Cost of Ownership between ZEB transition scenarios. Scenario Analysis helps agencies make a more informed decision and fully understand what is required to transition to a ZEB fleet.

More information about ZEB Transition Planning best practices can be found in the Zero-Emission Transition Planning Guidebook.[7]

Deployment Planning

The Transition Plan will outline the need for several ZEB vehicle and infrastructure procurement and deployment projects over the course of the transition period. Once an agency is ready to start actively planning for a specific ZEB project, there are additional planning steps that occur to 1) confirm that the assumptions made in the transition planning process are still accurate and 2) confirm additional details that were not necessary at the transition planning phase.

Selecting Buses and Infrastructure

At this point of the planning step, agencies that have not already decided on a technology type should understand the pros and cons of BEB vs. FCEB technology evaluated against the agency’s specific considerations of route feasibility, infrastructure needs, fueling availability, costs, funding sources, and stakeholder approval. These factors should be considered holistically to determine which technology type will be most suitable to meet the agency's long-term goals.

After the technologies have been evaluated and selected, agencies can begin the process of developing vehicle and infrastructure specifications that meet agency service requirements. Establishing specifications upfront reduces the risk of procuring buses or fueling infrastructure that do not meet agency standards or goals.

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[7] Center for Transportation and the Environment. Zero-Emission Bus Transition Planning Guidebook. CTE, n.d. https://cte.tv/post/zero-emission-bus-transition-planning-guidebook.

Understanding Utility-Side Constraints and Implications for ZEBs and Infrastructure Solutions

Before initiating procurement of ZEBs and supporting infrastructure, agencies should contact the local power utility company and ensure that the site has sufficient power available for the new equipment. Adding chargers or hydrogen fueling equipment with on-site power requirements will impact an agency's electricity demand, making early and ongoing coordination with utility providers a crucial step of the planning and deployment process. This is especially critical for agencies considering BEB technology, but agencies looking to deploy hydrogen fueling stations should still discuss whether their site has sufficient capacity to accommodate the load from a hydrogen fueling station[8]. Early coordination can help reduce project risk, align expectations, and inform realistic deployment schedules across stakeholders.

Agencies should confirm with the utility whether existing grid-side electrical infrastructure can support anticipated increases in demand from chargers and/or hydrogen fueling equipment. This includes understanding available service capacity, transformer constraints, substation proximity, and whether utility upgrades will be required to equip the yard with sufficient power. If upgrades are necessary, utilities may need to prepare the site to accommodate additional space for new electrical equipment, conduit routing, trenching, breaker panels, or switchgear, depending on the infrastructure requirements. Utility side upgrades often take longer than the sitework that the agency has full control over, which can result in utility upgrades being the critical path item for the deployment timeline. Therefore, it is critical to highlight the importance of agencies confirming power availability and/or utility upgrade timelines before initiating a ZEB procurement.

Agencies should also reference existing utility engagement guides, energy demand estimation tools, and peer agency case studies to better understand the nature of these discussions. Agencies can work with utility providers to understand how increased demand may affect existing electrical infrastructure, project timelines, and operating costs. Utilities can help agencies calculate potential electricity consumption by forecasting peak demand loads, annual energy consumption, and sometimes offering load management strategies or available programs to offset capital costs.

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[8] *Power Requirements for Hydrogen Fueling Stations*. Technical note, n.d. *Some liquid stations may require 600–1000 amps, 3-phase, 480VAC power depending on fleet size.*

Stakeholder Approval

Stakeholder approval and organizational buy-in of the transition plan and each planned procurement are critical steps in the planning stage, as ZEBs carry long-term operational, cost, and workforce implications that affect all levels of the organization. Agencies are encouraged to engage with key stakeholders early and ensure that all applicable departments are consulted in planning activities. Formal review and approval of plans across stakeholders ensures that the plans reflect agency priorities, budgeting considerations, and workforce impacts. Confirming organizational buy-in of the transition plans prior to the procurement stage can help reduce the likelihood of project delays and limit revisions to initial plans.

BEB-Specific Deployment Planning Considerations

Required infrastructure elements to support BEB deployments may include:

- Fueling equipment
  - Electric vehicle supply equipment (EVSE)
- Site work
  - Site designs
  - Electrical upgrades, i.e., transformers, switchgear
  - Canopies and/or parking reconfiguration
  - Duct banks
  - Construction & Installation
- Maintenance facility upgrades
- Land acquisition (if the existing facility cannot accommodate ZEB fueling)
- Professional services
- Additional staff or consultants

Recurring and operational costs to support BEB deployments may include:

- Training
- Non-warranty maintenance
- Spare parts and consumables
- Fuel (electricity) costs
- Charge management software (CMS)
- Charge monitoring and maintenance services

Utility Coordination: Estimating Electrical Demand and Power Needs

At this stage of planning, the exact number of chargers and their power levels may still be undecided. This should not deter agencies from continuing to coordinate with their utility. Coordinating with the utility is an iterative process and often begins by discussing current power availability at a given future charging site. These conversations can help inform whether it is possible to meet the power demands of a given BEB deployment within the site's existing capacity.

The charger power needed to support each BEB depends on the rated output power of the selected chargers and how they are configured to deliver energy to one or more buses. DC plug-in chargers used for transit vehicles commonly range from approximately 50 kW to 350 kW. Charger power selection is driven by three factors: vehicle battery size, time available to charge, and vehicle charge power acceptance.

A simple way to approximate the minimum required charge power is to divide the energy needed by the available charging time. For example, if a vehicle has a battery with 500 kWh of usable energy and has 5 hours to charge, a charger with a minimum power of 100 kW would be required. However, this does not tell the full story, as it does not account for whether the vehicle is rated to receive 100 kW of power or whether it can sustain that power for the entire charging event.

In practice, higher power or additional charging time is needed to account for reduced charging rates toward the end of the session. All lithium-ion batteries experience reduced charge power as they approach a full state of charge (100% SOC). The "taper" occurs automatically and is programmed into vehicle control systems to protect battery life and prevent overcharging. The reduction in power is also influenced by the charger's rated power; when connected to a higher-power charger, the same vehicle may begin tapering at a lower SOC than when connected to a lower-power charger. The exact charging behavior varies by each vehicle model in the market.

To estimate electrical power, the efficiency of the charger must also be considered. DC charger power is typically advertised from the perspective of the vehicle; it is what the charger is capable of outputting after converting the grid AC into DC power for the vehicle. This AC to DC power conversion is not without loss in the form of heat generated. Utilities, however, are concerned with the total power drawn from the grid before these losses occur, as this determines both infrastructure sizing and monthly energy costs. As a general rule of thumb, adding approximately 10% to the DC charging capacity provides a reasonable estimate of the required utility-side power. Keep in mind, many DC EVSEs advertise a higher peak efficiency than 90% (many advertise roughly 97%), but efficiency across the entire range of EVSE operating voltage is not often available. If better data is available, this 10% factory can be reduced. As an example, if a site has determined three 100kW DC chargers meet their charging needs, they will require approximately 330kW of power when all operating simultaneously at peak power (3 x 100kW x 1.10). If the capacity is too low to accommodate these chargers, the site will either need to be upgraded by the utility, or the agency can elect to use lower power chargers with the understanding that the buses will charge more slowly.

Space Considerations

It is important to consider yard space requirements for new infrastructure, including BEB charging stations and electrical equipment, as well as vehicles pulling up to fueling equipment. Agencies should also consider maintenance space requirements for storing tools and parts for these new vehicle types, as well as clearance for top-of-bus maintenance. Space constraints may necessitate the purchase or lease of additional land or facilities. Professional service firms can assist agencies with optimizing depot and on-route charging infrastructure development.

FCEB-Specific Deployment Planning Considerations

Required infrastructure elements to support FCEB deployments may include:

- Fueling equipment
    - Hydrogen storage and dispensing equipment
- Site work
    - Site designs
    - Electrical upgrades, i.e., transformers, switchgear
    - Duct banks
    - Construction & Installation
- Maintenance facility upgrades
- Land acquisition (if the existing facility cannot accommodate ZEB fueling)
- Professional services
- Additional staff or consultants

Recurring and operational costs to support FCEB deployments may include:

- Training
- Non-warranty maintenance
- Spare parts and consumables
- Fuel (Hydrogen) costs
- Maintenance service
- Equipment leasing costs (if electing to lease fueling equipment)
- Insurance (if not covered under the agency’s self-insurance)

Estimating Hydrogen Demand

In addition to assessing route feasibility from the perspective of available onboard energy, agencies considering FCEBs should perform a demand analysis based on expected block mileage and vehicle fuel efficiency to understand anticipated fleet-wide hydrogen consumption, which can be used to inform budgeting, fuel supply agreements, and station specifications.

The number of FCEBs, daily volume demand (expressed in kg consumed per day), average and maximum fuel demand per vehicle, time available to refuel, and capital and operating costs will influence the primary form (liquid or gas) in which hydrogen is stored at an agency's facility. These factors will also play a role in determining the source of hydrogen, either delivered or produced on-site. In cases where demand is particularly low, such as a single bus pilot scenario, a fuel-as-a-service model, in which fuel is not permanently stored on-site but rather dispensed directly from a delivered gaseous tube trailer, may be better suited to agency operations. Different types of fueling stations and hydrogen storage methods are discussed further in **Tool 1**.

Fuel Supply Planning

Once an agency has a general idea of both its fuel demand and the method by which hydrogen will be delivered or produced, the agency can seek informal estimates of fuel cost. Projected demand, delivery frequencies, and per-kilogram fuel costs can be used as inputs in estimating recurring total costs over the course of a deployment.

Both the cost and availability of gaseous and liquid hydrogen vary regionally, and delivery costs often increase proportionally to the distance between fuel production sites and agency facilities. Delivered liquid hydrogen is often less expensive than delivered gaseous hydrogen due to its higher density but can be lost to evaporation over time when stored in bulk quantities. Currently, the only producers of liquid hydrogen servicing the California market are located in the Las Vegas and Southern California regions. Therefore, transit agencies north of the Bay Area will likely pay an upcharge due to the long delivery distance. Agencies should identify current and planned hydrogen sources within their area before finalizing a decision to deploy FCEBs.

If the agency is subject to requirements governing the carbon intensity (CI) of its fuel supply, staff should consider both production pathways and opportunities to utilize Low Carbon Fuel Standard (LCFS) credits when evaluating available fuel sources.

Agencies may wish to tailor the size of initial hydrogen deployments to match locally available fuel sources, explore on-site production, or focus initial deployments on BEB technology if delivered hydrogen is not locally available or exceeds available budget for fuel costs.

Utility Coordination: Electrical Needs and Electricity Consumption Calculation for a Hydrogen Station

Power requirements vary by station type. Some hydrogen fueling solutions may not require power to dispense fuel, and others may be paired with a solar array. For a large-scale hydrogen deployment, agencies will likely require a large liquid hydrogen tank of 18,000 gallons (4,824 kg) or greater, with vaporizers, liquid pumps, gaseous buffer storage, and dispensers. Such a station may require between 600 and 1,000 amps of 480V 3-phase power.

Space Considerations

It is important to consider yard space requirements for new infrastructure, including space for the hydrogen storage and compression, access for fuel delivery, and area for FCEBs to access dispensing equipment and any walls/fencing and setbacks required by local codes. Planning for fuel delivery may also require certain clearances around the fueling station to meet safety requirements and to ensure the fuel delivery vehicles have sufficient turning radius to navigate the yard. Agencies should also consider maintenance space requirements for tool and parts storage for these new vehicle types, as well as clearance for top-of-bus maintenance. Space constraints may necessitate the purchase or lease of additional land or facilities. Industrial gas companies or planning and engineering firms can help with understanding equipment and spacing requirements for FCEB fueling stations. Refer to **Tool 6** and **Tool 7** for example FCEB fueling station layouts.

More information about ZEB deployment best practices can be found in the Guidebook for Deploying Zero-Emission Transit Buses.[9]

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[9] Center for Transportation and the Environment & Transit Cooperative Research Program. Guidebook for Deploying Zero-Emission Transit Buses. CTE, 2020. https://cte.tv/post/guidebook-for-deploying-zebs

Key Questions to Consider:

Vehicle and Technology Fit

- Which technologies can meet the agency’s service requirements?
- Does the agency have operational characteristics that may influence the suitability of each technology (e.g., climate, terrain, route lengths)?
- What vehicle types are commercially available and feasible within the agency’s operations?
- Would the agency prefer to conduct pilot deployments to gain experience with ZEB technology?
    - Does the agency feel comfortable with technology pilots, demonstrations, or phased developments?
    - What are the main questions that the pilot deployment is designed to answer?

Fueling and Charging

- What are the agency’s fueling windows (time available to fuel between bus pull-in and bus pull-out)?
- Is the agency open to on-route or midday charging for BEBs?
- Can the utility meet the minimum onsite power requirements necessary to support the fleet?
- Is the agency located somewhere with reasonable access to a gaseous or liquid hydrogen supply?
    - If gaseous, what supply pressures are available?
- Which hydrogen fuel providers serve the agency’s region?
- What is the expected market growth for hydrogen in the agency's region?

Maintenance and Facilities

- Do existing facilities have constraints related to space, power availability, ventilation, or safety?
- What facility modifications may be needed at a high level, and how might they affect operations?
- What changes to maintenance practices, staffing, and training would be required for each technology?
- Are there workforce or labor considerations that may affect deployment timing or approach?
- What safety procedures or certifications may be needed?

Costs and Funding

- What is the current operating budget?
- How much capital does the agency currently have for its ZEB rollout?
    - What ZEB fleet and fuel costs can the agency reasonably afford?
- How much ZEB funding does the agency reasonably expect to be awarded in the next 10–15 years?
- How quickly does the agency need to procure buses to meet its zero-emission goals?

Resilience and Emergency Response

- What are the agency’s local emergency response requirements?
    - How might emergency response requirements impact technology selection and planning?
- How much of the agency’s fleet is expected to respond during a natural disaster?
- What resiliency measures will need to be in place in the event of a power outage at different ZEB fleet sizes?

Technical and Administrative Capabilities

- Who will be responsible for managing ZEB research, procurement, and deployment projects?
- Does the agency need to hire additional staff or consultants to support ZEB planning and deployment or does the agency already have existing staff with the time and skills required?
- What are the projected timelines to deploy buses and infrastructure, and will the agency be able to coordinate both so that buses and fueling/charging stations will be available at the same time?
- What are the agency's goals for KPI reporting and what data is available?

Checklist Before Moving to the Next Step:

- ☐ A formal transition plan has been created
- ☐ Regulatory timelines have been included in long-term planning
- ☐ Feasible ZEB technology options have been determined based on operational and facility considerations
- ☐ Initial meetings with the utility provider have been conducted
- ☐ Pilot projects, phased deployments, or mixed fleets have been considered
- ☐ High-level fueling, charging, and facility needs have been evaluated
- ☐ Preliminary maintenance and workforce impacts have been identified
- ☐ Initial cost considerations and funding opportunities have been reviewed
- ☐ Safety and emergency response plans have been identified
- ☐ Board and executive approval to pursue the proposed ZEB transition plan and deployment approach have been received
- ☐ Projected timelines to deploy buses and infrastructure are feasible and coordinated to ensure fuel supply is readily available to operate buses

Suggested Resources to Reference:

General Resources

- Zero-Emission Bus Transition Planning Guidebook (CTE)
- Guidebook for Deploying Zero-Emission Transit Buses (TCRP/CTE)
- Modernizing Transit Fleets: A Guidebook to Low- and Zero-Emissions Transit Buses (DRPT)
- Checklist for Engaging Your Utility on Fleet Electrification (APTA)
- Preparing to Plug in Your Bus Fleet: 10 Things to Consider (APTA)
- Guidebook for Deploying Battery Electric Buses (FTA)
- RouteE: Route Energy Prediction Modeling Tools (NREL)
- Route Energy Prediction (RouteE) Powertrain Validation Report (NREL)
- Bus Testing Reports (Altoona)
- Microgrids: Best Practices for Zero-Emission Bus Resiliency (CALSTART)
- Joint Office of Energy and Transportation Resources (Joint Office)
- dsgrid: Demand-Side Grid Toolkit (NREL)
- Agency specific utility websites
    - Investor-owned utilities: Pacific Gas & Electric, Southern California Edison, San Diego Gas & Electric
- How to Decide on Hydrogen vs. Battery Buses (NCATT)
- Total Cost of Ownership and Cost Modeling Tools (NREL)
- Annual Hydrogen Evaluation (CARB)
- Diagram and Components of Hydrogen Stations (see **Tool 6** and **Tool 7**)

California Incentive Programs

- VW Environmental Mitigation Trust Funding
- HVIP: Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
- Carl Moyer Memorial Air Quality Standards Attainment Program
- Low Carbon Transit Operations Program (LCTOP)
- California Energy Commission Clean Transportation Program
- EnergIIZE: Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles

Federal Funding Opportunities

- California Transportation Agency IIJA Dashboard
- National Electric Vehicle Infrastructure Program (NEVI)
- FTA's Low or No Emission Grant Program
- Funding Sources (see **Tool 3**)

Step 4a:

Bus Procurement and Build

Once agencies have finalized their fleet plans with confirmed vehicle technology types, infrastructure and fueling needs, costs, and stakeholder approvals, they can begin the process of procuring the vehicles and infrastructure. These processes should run in parallel, with the goal of having buses delivered just in time for the infrastructure commissioning. **Step 4a** will focus on the details of the bus procurement, while **Step 4b** will focus on the infrastructure considerations. The following section touches on the intricacies of ZEB procurements and guides agencies on specification development, procurement methods, and procurement timing to ensure a smooth procurement process.

Specification Development

FTA has been encouraging transit agencies to accept standard model buses with standard configurable options and to eliminate customizations to improve the U.S. bus market for OEMs. Nevertheless, agencies are still able to select from options that are already engineered into the bus design to ensure the buses meet their specific preferences. This is true for both incumbent technology and ZEBs. In any procurement, agencies should ensure that the procurement process and vehicle specifications comply with all applicable federal, state, and local regulations, codes, ordinances, and guidance; operability within the intended environment; adherence to contract requirements; and manufacturing in accordance with industry standards and best practices. Beyond these baseline expectations, however, agencies may include limited additional specifications for vehicles that will ensure the equipment meets the agency's specific needs.

For ZEBs, some options that might warrant special consideration include extended warranties, communications systems, added energy storage capacity, maintenance contracts, recommended spare parts, and any maintenance tools or equipment that are unique to ZEBs. Agencies should also consider defining telematics requirements in support of post-deployment performance evaluations.

Agencies should also assess their in-house capabilities and the availability of third-party vendors to ensure that ZEBs and associated infrastructure remain operational.

BEB-Specific Specification Development Considerations

For BEBs, agencies should understand the energy demands and range requirements needed to meet planned service prior to procurement. The charging strategy, whether depot or on-route, should also be defined in advance, along with key considerations such as charger type, power levels, and the physical location and configuration of the charging interface (e.g., plug placement) to ensure operational compatibility between the buses and charging equipment. Additionally, agencies should determine auxiliary system needs, such as heating, which can impact energy demands and vehicle performance, particularly in colder climates.

FCEB-Specific Specification Development Considerations

For FCEBs, one option that the agency should consider specifying is whether the buses will allow for communication with the hydrogen fueling station. This requires that the bus be equipped with a device that measures onboard tank temperature and communicates with the fuel dispenser about the conditions on board the vehicle. This can allow the buses to be filled more quickly since it is an added safety feature that adds confidence that the tanks aren't being overfilled.

Bus Procurement Approaches

There are two primary approaches an agency can take for its bus procurement that comply with federal requirements for competitive procurements: 1) procuring through a state contract or 2) through a request for proposals (RFP), either individually or as a joint procurement with other agencies. Agencies should compare the two methods to determine which aligns closer with their deployment goals and is consistent with their procurement policy. RFPs allow agencies to specify the technical and performance requirements that best satisfy their fleet, so this may be preferable for agencies with unique procurement requirements. However, since many of the terms have already been negotiated in state contracts, this method is generally preferred by OEMs because they require less time and labor to reach the contracting phase, which also makes state contracts more appealing for agencies with limited staff dedicated to procurement. In addition, state contracts fulfill the federal rules for competitive procurement and still allow for configuration at the contracting phase.

Although less common, a third procurement approach option is to name bus and/or infrastructure OEMs in proposals to federal programs that allow for naming partners, such as the Low or No Emission Grant Program and the Grants for Buses and Bus Facilities Competitive Program. Since the proposal is evaluated as a whole, agencies are allowed to contract with named partners without additional procurement steps if the project is awarded, as the evaluation of the proposal already met the definition of a competitive procurement.

OEM and market availability reports can aid in an agency's decision-making as they prepare to transition to ZEBs. Agencies should always seek current information pertaining to industry assessments of supply chain risks. Member organizations such as ZEBRA and HFCBC provide access to peer agency experiences with parts availability and lead times. Additionally, agencies must consider parts availability throughout the procurement process. Including OEM parts availability in contract language may reduce parts challenges. Warranty language should be unambiguous, and battery disposal should be considered during ZEB procurement. Contract terms related to warranties, performance guarantees, parts availability, training, and technical support are particularly important for ZEB procurements.

BEB-Specific Procurement Approach

Agencies may choose to procure BEBs and charging infrastructure through separate solicitations or as part of a single RFP or state contract. Combined procurements can streamline procurement and project management efforts and may be well-suited for agencies seeking a turnkey ZEB infrastructure solution. However, combined procurements can also result in higher vendor pricing and reduced flexibility in technology selection. If an agency opts to procure buses and infrastructure separately, it is critical to ensure that vehicle delivery timelines align with infrastructure construction and commissioning to avoid stranded assets.

FCEB-Specific Procurement Approach

It is currently uncommon for FCEBs and hydrogen fueling infrastructure to be procured through a single procurement.

Bus Procurement Timing

BEB-Specific Procurement Timing

When planning a BEB procurement, agencies should consider how facility readiness and electrical infrastructure timelines may influence the procurement timeline. If the existing facility design and electrical capacity are sufficient, facility modifications and grid-side upgrades may not be needed. However, if extensive utility upgrades are required, they could extend for multiple years and impact the vehicle procurement schedule.

BEBs may take 12 to 18 months from purchase order to delivery.

FCEB-Specific Procurement Timing

When planning a FCEB procurement, agencies should consider how facility readiness and hydrogen infrastructure timelines may influence the procurement timeline. If the agency already has access to a suitable hydrogen fueling station or can rely on nearby fueling, FCEB deployment can proceed without major delays. However, if a new on-site hydrogen fueling system is required, development and installation of the station will significantly influence the vehicle procurement schedule.

FCEBs may take 18 to 24 months from purchase order to delivery.

Key Questions to Consider:

Procurement Methods

- Does the agency's procurement department allow for purchasing from a state contract?
- Does the agency have access to an applicable state or cooperative contract?
- Does a state contract meet the project's timeline and funding requirements?
- Do the agency's buses require customization or performance requirements beyond what a state contract supports?
- Would a competitive RFP better align with agency goals, timelines, and risk tolerance than a state contract procurement?
- Does the selected procurement approach comply with federal and state funding requirements?
- Has the approach been reviewed by procurement, legal, and finance staff?

Scope and Technical Requirements

- What are the performance requirements of the vehicles?
- Will vehicles and charging/fueling infrastructure be procured together or through separate contracts?
- What risks are the agency responsible for, and which are the vendors responsible for?
- What contractual provisions will be necessary to reduce or mitigate the risks?
- What are the anticipated lead times and how will delivery timelines for vehicles and infrastructure be aligned?
- Does the scope address all the necessary design, permitting, testing, and commissioning steps that will be required to meet successful project completion and meet all agency and relevant state or local AHJ requirements?

Checklist Before Moving to the Next Step:

- ☐ Procurement strategy and contracting mechanisms for vehicles have been defined and approved, and carried through to vendor selection and issued purchase order
- ☐ Roles and responsibilities for design, construction, commissioning, and performance testing have been clearly assigned for buses and infrastructure
- ☐ Scope and performance requirements have been clearly defined
    - Warranties address fuel cell and battery performance guarantees
- ☐ Bus delivery timelines align with planned construction and commissioning of fueling infrastructure
- ☐ Contracts for vehicles have been executed or authorized and define the testing protocols that will be used to verify performance expectations are met prior to acceptance

Suggested Resources to Reference:

- Procurement Guidebook (FTA)
- FTA Buy America / Build America, Buy America (FTA/EPA)
- Altoona Testing (FTA)
- State Contracts
    - California State Contracts/Leveraged Procurement Agreements
    - Florida State Contracts
    - Georgia Statewide Contracts
    - Virginia Statewide Contracts
- Washington State Transit Bus Contracts
- Zero Emission Bus Resource Alliance (ZEBRA)
- Hydrogen Fuel Cell Bus Council (HFCBC)
- Guidebook for Deploying Zero-Emission Transit Buses (TTCRP/CTE)
- Guidebook for Deploying Battery Electric Buses (FTA)
- Market Assessment Reports (CALSTART)
- Cost Estimation for FTA Funded Transit Projects (FTA)

Step 4b:

Infrastructure Procurement, Design, and Build

Once agencies have determined their deployment plans and vehicle technology needs, they reach the infrastructure procurement, design, and build stage of the deployment. At this point, there are still many details that will need to be addressed to ensure the infrastructure is functional, effective, and code-compliant based on the chosen technology.

Although separate efforts, vehicle procurement and delivery should align with infrastructure commissioning and facility modifications to ensure that agencies can operate and maintain their vehicles once they arrive. Since infrastructure buildouts often take longer than the time required to build a bus, it is crucial that agencies coordinate infrastructure schedules ahead of bus delivery schedules to prevent buses from arriving without fueling or charging capability. Agencies should therefore begin planning infrastructure and fuel procurement efforts and drafting solicitation materials up to two and a half years ahead of the target commissioning date for bus deployments.

> ***Facility modification timing:***
> For both BEB and FCEB fueling installations and associated facility upgrades, modifications take an average of 12 to 18 months from notice to proceed to completion.

Infrastructure Procurement

BEB-Specific Charging Infrastructure Procurement

For charging infrastructure procurement, specifications might include charger type, software capabilities, charger/dispenser ratio, and power requirements. As stated above, agencies may choose to procure buses and charging infrastructure through separate solicitations or as part of a single RFP or state contract. Combined procurements can streamline procurement and project management efforts and may be well-suited for agencies seeking a turnkey ZEB infrastructure solution. However, combined procurements can also result in higher vendor pricing and reduced flexibility in technology selection. If an agency opts to procure buses and infrastructure separately, it is critical to ensure that vehicle delivery timelines align with infrastructure construction and commissioning.

Charging infrastructure procurement timing:

For BEB charging infrastructure procurements, installation timelines vary based on charging technology. Depot chargers typically take 6 to 12 months to install from notice to proceed to completion.

FCEB-Specific Hydrogen Infrastructure Procurement

For hydrogen station procurement, hydrogen fueling stations are not currently listed on state schedule contracts and are typically procured via an RFP. Hydrogen fuel can be procured jointly or separately from a procurement for fueling infrastructure; however, these efforts must be coordinated to ensure that fuel and station vendors are compatible and to optimize station design and fuel delivery methods for cost and operational effectiveness. Some vendors that offer both dispensing technology and fuel delivery may limit which vendors can deliver fuel to their equipment. Agencies may consider issuing a single solicitation for both fuel and infrastructure but contracting separately to allow increased flexibility in fuel pricing as market conditions evolve.

For hydrogen fueling infrastructure, agencies should focus on developing a performance-driven specification rather than dictating methods for achieving desired performance. Specifications can be shaped by space limitations (in part constrained by a facility's operating logistics), fueling window, expected fuel demand, desired state of fill, throughput, number of back-to-back fills, minimizing boil-off losses, scalability needs, redundancy and resiliency, communications requirements, capital expenses, and operations and maintenance (O&M) expenses. Agencies should also ensure that fueling stations and maintenance facilities address safety needs such as fire detection, gas detection, emergency shutoff, and visual and audible alarm systems.

Hydrogen fueling infrastructure procurement timing:
For hydrogen fueling infrastructure procurements, timelines vary primarily depending on station design. A small-scale, temporary gaseous solution might take three to six months to install from notice to proceed to completion, a permanent gaseous solution supporting ten buses might take 12 to 15 months, and a large-scale liquid solution might take 18 to 24 months.

Infrastructure Design Plans

Agencies will need to determine the necessary infrastructure design to support their planned zero-emission fleet. Infrastructure must be designed to meet the fueling capacities of the fleet, as well as be constructed with adequate time to meet the fleet procurement schedule. This step cannot be completed until after the procurement is complete, as site planning is dependent on the type of chargers or fuel procured.

Agencies will need to work with their selected design firm to create site plans to better understand the potential impacts of new infrastructure. Site plans should include scaled drawings of the infrastructure, single-line diagrams of electrical plans, and potentially cost estimates as well. Engaging with local permitting agencies early in this stage is critical, as the permitting and design processes are interdependent; design drawings are needed to obtain permits, and feedback from permitting authorities is often incorporated into design revisions. Agencies should also consult with local AHJs on permitting timelines to ensure the infrastructure procurement schedule is realistic.

BEB-Specific Charging Infrastructure Design Plan Considerations

For BEB infrastructure, the design may include depot or on-route charging, using plug-in, overhead conductive, or wireless inductive charging, based on the agency’s procurement choices. For agencies including on-route charging, infrastructure design plans will need to be created at the on-route charging site as well as at the depot charging site. Since on-route charging will occur at a different location than depot charging, these sites will likely have different permitting and building timelines. There may also be a need to redesign the maintenance garage and bus yard to accommodate additional maintenance equipment, tooling, and chargers. Power needs can be significant based on the size of the operation.

Depending on whether an agency has an existing design contractor or in-house design capabilities, as well as the nature of its planned infrastructure solution, an agency may need to procure design and installation services separately from supporting equipment. Construction projects may be subject to different internal bidding requirements.

FCEB-Specific Hydrogen Infrastructure Design Plan Considerations

National Fire Protection Association's (NFPA) hydrogen detection code NFPA-2 dictates setback requirements for hydrogen stations, which are dependent on the state of the fuel (liquid or gas), pressures, pipe diameters, etc.

During the deployment planning stage, the agency will have determined whether to fuel with liquid or gaseous hydrogen, and whether it will be delivered to the station or produced on-site. These decisions will impact how the station is designed to ensure compliance with all applicable codes and standards. In addition, designs must consider operational and spacing requirements.

Infrastructure Buildout

The infrastructure buildout phase includes site preparation, equipment installation, and utility coordination to make sure that the station meets permitting and safety requirements. Agencies should track construction progress against the initial schedules and budgets, confirm compliance with approved designs, and manage timelines to ensure that infrastructure is built and operational so buses can be fueled or charged upon delivery. To ensure schedule adherence, agencies should also keep an open line of communication with AHJs about local permitting timelines.

Codes and Standards

During station construction and commissioning, agency contractors should confirm that all infrastructure is constructed in accordance with state, local, and national building, fire, electrical, and safety codes adopted by an agency's local AHJ. Agencies should maintain coordination with AHJs, including fire departments and building officials, to confirm approval prior to commissioning. AHJs are the ultimate authority regarding code compliance and can recommend measures above and beyond code. AHJ knowledge of ZEB-specific code considerations will vary depending on whether an authority has had previous deployments of ZEBs within its jurisdiction.

In some cases, agencies may have the ability to self-certify code compliance. Agencies should always prioritize safety when self-certifying and may wish to contract with a third-party code expert if their existing professional engineers are unfamiliar with the applicable technology.

For a comprehensive list of BEB-related codes and standards, refer to the Advanced Power and Energy Program's (APEP's) Battery Electric Vehicle Charging Standards List.[10]

For a comprehensive list of FCEB-related codes and standards, refer to H2Tool's Hydrogen Fuel Cell Codes and Standards Dashboard[11] or the Appendix: Regulations, Codes, and Standards section of the Draft GO-Biz Hydrogen Permitting Guidebook.[12]

Maintenance Facility Upgrade Needs and Design Considerations

Transitioning to zero-emission technologies comes with new facility codes and standards, unique workplace safety needs, and potential facility modifications to accommodate specialized maintenance equipment, tooling, and processes. Facility upgrades may vary significantly depending on the type(s) of buses currently maintained versus the type of buses they will maintain in the future. Agencies should document the types of equipment, tooling, workspaces, warehousing, and safety features that already exist in their maintenance facilities to understand the upgrades needed to maintain ZEBs. This section highlights key considerations related to ZEB maintenance facilities but is not exhaustive. Agencies should coordinate early with AHJs, planning and engineering service providers, vehicle and infrastructure manufacturers, and internal safety staff to ensure facilities are designed and operated safely and in compliance with all requirements. Since both BEBs and FCEBs include high-voltage batteries, many facility considerations will be applicable to both technologies. Examples of facility considerations for ZEBs are Include:

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[10] Advanced Power and Energy Program (APEP), University of California, Irvine. *On-Road Medium- and Heavy-Duty Zero-Emission Vehicle Fueling and Charging Standardization Assessment*. Apr. 2024, https://www.apep.uci.edu/MHDV/pdf/White_Paper_Final.pdf

[11] H2Tools, Pacific Northwest National Laboratory. *Hydrogen Fuel Cell Codes & Standards*. 2026, https://h2tools.org/hydrogen-fuel-cell-codes-standards

[12] Governor's Office of Business and Economic Development. *Draft GO-Biz Hydrogen Permitting Guidebook*. State of California, 2026, pp. 53–59. https://business.ca.gov/wp-content/uploads/2026-Draft-GO-Biz-Hydrogen-Permitting-Guidebook.pdf
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Fire Suppression Systems

Lithium-ion batteries come with fire risks that differ from conventional fuels. Fire detection and suppression systems may need to be evaluated or upgraded. Upgrades will need to be consistent with local code requirements and fire department guidance.

Storage for Spare Parts and Batteries

Agency facilities may need additional storage areas for spare parts and batteries. Designated battery storage areas are necessary to avoid accidental contact with high-voltage batteries. Storage areas should consider fire safety requirements and access restrictions.

Vehicle Rooftop Access for Maintenance

ZEBs commonly house key components on the roof, including HVAC systems, high-voltage batteries, and hydrogen storage tanks. Agencies preparing to maintain vehicles with roof-mounted components should make provisions for fall protection, commonly in the form of scaffolding or a rail system. Systems should allow for two staff members to work in tandem for safety.

High-Voltage Work Areas

Staff must be trained to work in garages where high voltage work is performed; even those not working directly on high voltage systems need awareness training. To restrict access to areas where high voltage system access is possible, consult Occupational Safety and Health Administration (OSHA) best practices and required equipment. Specific warning signs, portable barriers, and shepherd's hooks are examples of new equipment present in garages working on ZEBs. Additional PPE including insulated gloves and specialized clothing and/or shoes and special tools for use on high voltage systems are also required.

BEB-Specific Facility Upgrade Needs and Design Considerations

BEB facilities will include charging equipment exclusive to battery electric technology. Along with the general ZEB considerations listed above, key design considerations include:

Lift and Equipment Requirements

BEBs are typically heavier than conventional buses due to their battery weight. Agencies may need to upgrade vehicle lifts, jacks, and floor slabs to accommodate the higher gross vehicle weights.

Charging Space

Adequate space is required within and around maintenance facilities for bus charging. Facility layouts should consider charger placement, clearance requirements, and related impacts to maintenance operations. Agencies may also consider mobile chargers, which are smaller than overnight chargers used in the bus yard for overnight charging. Mobile chargers also have wheels so that they can be easily moved from one bay to another. However, each bay will require a high voltage (i.e., 240V) outlet to connect the charger.

FCEB-Specific Upgrade Needs and Design Considerations

FCEB facilities must also address hydrogen safety, including gas detection and ventilation. Agencies with CNG deployment experience are likely familiar with some of the considerations generally applicable to facilities utilizing pressurized gaseous fuels. However, staff should stay informed and trained on FCEB-specific safety protocols, as hydrogen presents unique hazards and handling considerations that differ from other gaseous fuels. Along with the general ZEB considerations listed above, key considerations for hydrogen vehicle facilities include:

Venting and Ventilation

Hydrogen is a lighter-than-air gas that rises rapidly when released. Maintenance facilities may require enhanced ventilation, roof venting, or open-air design features to prevent hydrogen accumulation.

Defueling

Depending on the category of repair being performed and whether an agency's facility is considered a major or minor repair garage, FCEBs may need to be defueled prior to performing maintenance activities. Defueling requires the use of specialized venting equipment to ensure that hydrogen fuel is safely depressurized and released away from people and facilities.

Ignition Sources and Explosion-Proofing

Facility designers should evaluate potential ignition sources, including electrical equipment and lighting, and apply appropriate separation distances. Depending on facility designs and local safety codes, explosion-proof electrical systems may be required in areas where hydrogen could be present to prevent the ignition of flammable gas. Heating systems serve as another potential ignition source and must operate below code-defined temperatures.

Hydrogen Flame and Gas Detection Systems

Hydrogen fires are nearly invisible in daylight, making flame detection systems an essential component of both maintenance facilities and fueling stations. Facility designers should also make provisions for hydrogen gas detection in the event of leaks, and both gas and flame detection systems should be tied to facility alarm systems. Alarm systems should be both visible and audible and distinguish between different hazards, including hydrogen and other gas leaks. In addition, agencies should coordinate detection, alarm, and notification strategies with local emergency responders during facility planning and design.

Agencies seeking support during the bus procurement and infrastructure build stages of deployment should consider hiring additional staff or contracting with consultants to assist with these efforts.

Key Questions to Consider:

Infrastructure Procurement

- What infrastructure components must be procured (chargers, hydrogen infrastructure, electrical upgrades, compression/storage equipment, etc.)
- What are the performance requirements of the infrastructure?
- Are requirements scalable to support future fleet growth without overbuilding?
- Will vehicles and charging/fueling infrastructure be procured together or through separate contracts?
- What are the pros and cons of procuring through a single contract or multiple procurements?
- For charging infrastructure, is purchasing off a state contract a viable option?
- Can the infrastructure fuel the buses in the required time to meet service needs?
- Does the selected procurement approach require technical compatibility between vehicles and infrastructure?
- Who is responsible for design, installation, commissioning, and performance testing of charging or hydrogen infrastructure?

Infrastructure Design

- What facility modifications are needed?
- Is there sufficient space for planned ZEBs and the related infrastructure?

Station Build

- Has the agency completed the site selection process?
- Does the agency have a construction manager identified?

Safety Considerations

- Do maintenance bays require modifications to meet safety codes and standards?
- How can the agency upgrade facilities to account for ZEB-related safety risks?

Checklist Before Moving to the Next Step:

Infrastructure Procurement

☐ Procurement strategy and contracting mechanisms for infrastructure have been defined and approved, and carried through to vendor selection and issued purchase order
☐ Vehicle procurement and infrastructure timelines are aligned
☐ Fueling process and partners have been determined
☐ Utility coordination is on-going and any needed service upgrade timelines have been confirmed
☐ Warranties and performance expectations for infrastructure components have been clearly defined
☐ Contracts for infrastructure elements have been executed or authorized and define testing protocols that will be used to verify performance expectations are met prior to acceptance

Infrastructure Design

☐ Fueling station and facility designs (30%, 60%, 90%, 100% design completion milestones) have been received and reviewed by all stakeholders
☐ Facility space limitations have been analyzed
☐ Facility modification needs have been documented and planned for
☐ Construction timelines have been received

Station Build

☐ All required permits have been secured
☐ Infrastructure has been installed and commissioned
☐ Additional equipment needs for daily operations and maintenance (overhead levers or gantry cranes to remove overhead components, scaffolding, fall protection, defueling equipment, etc.) have been considered

Safety Considerations

☐ Safety systems have been installed
☐ Emergency response plans have been updated (including establishing who needs to be notified, the type of response expected, and communication protocols)

Suggested Resources to Reference:

- Guidebook for Deploying Zero-Emission Transit Buses (TCRP/CTE)
- California Building Standards Code (Title 24)
- Codes and Standards for Zero-Emission Vehicles (NFPA)
- Codes and Standards for Zero-Emission Vehicles (SAE)
- Codes and Standards for Zero-Emission Vehicles (ISO)
- Zero-Emission Medium- and Heavy-Duty Charging and Fueling Standardization Assessment (APEP)
- Zeroing in on Zero-Emission Buses Report (CALSTART)
- Fuel Cell Electric Bus Evaluations (NREL)
- Guidebook for Deploying Battery Electric Buses (FTA)
- ZEB 101/201 Courses (CTE)
- Hydrogen Safety Resources (Hydrogen Safety Panel)
- Hydrogen Permitting Guidebook (GO-Biz, Draft)
- Hydrogen Station Components: 3D Renderings (see **Tool 6**)
- Hydrogen Station Design Examples (TAIT) (see **Tool 7**)

Step 5:

Preparing for Service (Commissioning, Acceptance and Validation Testing, Workforce Development, Safety, and Emergency Preparedness)

Commissioning

Commissioning evaluates newly constructed infrastructure and confirms that everything is working as intended and is ready to support fueling and maintenance operations. This stage includes site, vehicle, and infrastructure inspections, testing, safety verification, and final approvals from local authorities and utilities. Agencies should confirm that operating changes, emergency response procedures, and staff training are finalized before fully placing the infrastructure and vehicles into service.

Acceptance and Validation Testing

Testing new technology and analyzing performance under real-world conditions can build confidence and expose any challenges to address before formally putting buses and infrastructure into service. Before fully accepting the buses, the agency should test them to ensure they are meeting all performance requirements and test criteria outlined in the contract. After acceptance, which is a contractual requirement, agencies should validate operational performance (i.e., range and efficiency) to confirm that the buses can successfully complete their planned service. Variances may require agencies to adjust their ZEB service plan prior to placing buses into revenue service.

BEB-Specific Acceptance and Validation Testing Considerations

Agencies can verify charger compatibility by connecting chargers to buses to confirm a successful charging interface. A commissioning and testing scheme should test combinations of charger power splitting, CMS control, and different vehicle models. The results of these performance tests may inform the agency of commissioning challenges or existing issues that need to be addressed prior to deployment.

FCEB-Specific Acceptance and Validation Testing Considerations

Agencies can perform a “stress test” of their hydrogen fueling station by fueling an agreed upon number of buses with an appropriate amount of fuel in a reasonable time frame as part of the full station acceptance process. The specific numbers for the evaluation should be established with the station provider ahead of testing and included as a performance requirement in the station contract.

Workforce Development, Safety, and Emergency Preparedness

An important part of planning for a zero-emission transition is understanding training needs and ensuring the workforce is prepared for the new technology. For a successful transition, bus operators, maintenance technicians, and first responders must all be qualified to work with ZEBs. Training is crucial not only to ensure that staff are safe working with ZEB-specific systems, but also to maximize ZEB performance and uptime. Driver behavior has been shown to have a significant impact on vehicle efficiency, and having staff qualified to maintain ZEBs and supporting infrastructure will be necessary to ensure vehicles are able to meet pullout.

Identify Workforce Stakeholders

Before identifying skill gaps and purchasing trainings, agency leaders should align with the key stakeholders involved in equipping their workforce to operate and maintain zero-emission technology. Critical workforce partners may include local unions, community colleges, vehicle OEMs, charger and hydrogen refueling infrastructure provider OEMs, subsystem OEMs, and training consortiums. Some agencies may also contract out vehicle operations or maintenance to a third-party provider and should ensure that their partners are willing and able to develop the skills and facilities necessary to maintain all planned technologies.

To begin, agencies should analyze the gaps between current workforce skills and future skills required to operate and maintain ZEBs. This gap analysis will determine additional training requirements. Once this has been determined, agencies can use the information to develop a training plan for their workforce. This plan can be executed using training resources supplied by the ZEB OEM, charging equipment vendors, or local, regional, and national training organizations, such as the California Transit Training Consortium.

When building and delivering workforce development programs, agencies should consider the following best practices:

- Tailor zero-emission training programs to agency needs with consideration for bus, charging infrastructure, and hydrogen fueling station design
- Training plan should be a combination of hands-on activities and classroom instruction
- Hands-on and oral instruction should be supported by training manuals and other forms of written instruction, such as safety data sheets and documented emergency procedures
- Recurring training classes should adhere to agency standards, but are recommended every one to two years for operators, maintenance technicians, and first responders
- Communicate the introduction of zero-emission technology to agency employees outside of those who are directly involved to promote buy-in

Bus Operators

Bus operators typically receive initial training from the vehicle's OEMs upon delivery of the bus and prior to vehicle deployment. Bus operators must be trained on key differences between ZEB operations and ICE vehicles.

Key knowledge areas operators should be trained in include:

- ZEB hazards
- On route charging procedures (if applicable)
- Acceleration and Regenerative braking
- Noise level
- Emergency procedures
- High-voltage cabling and batteries
- Fuel cell and hydrogen components
- High-pressure gas storage
- Hydrogen properties

Agencies may also wish to support drivers in addressing concerns regarding range and understanding the state of charge (SOC) and fuel level indicators to alleviate range anxiety and prevent buses from getting stranded due to insufficient fuel or SOC. Additionally, agencies may want to give drivers training on best practices for maximizing fuel efficiency in ZEB operations.

Bus Maintenance Technicians

Bus maintenance technicians will require in-depth initial training and periodic refreshers, as well as additional training as new vehicles or models are incorporated into the fleet. Training is a necessary step in preparing bus maintenance technicians to transition from maintaining ICE vehicles to ZEBs.

Key knowledge areas maintenance technicians may be trained in include:

- General familiarization necessary for maintaining any new bus model
- High-voltage safety procedures, including lockout/tagout (LOTO), PPE and emergency response
- Charging system operation
- Electric drivetrain
- Hydrogen properties and safety procedures, including PPE and emergency response
- High-pressure gas lines
- ZEB-specific diagnostic training

Infrastructure Maintenance Technicians

Infrastructure maintenance technicians will require in-depth initial training, and ongoing training should be provided regularly to address any system upgrades or system expansions. Knowledge of electrical systems is especially important for infrastructure maintenance technicians, as they will be required to maintain charging stations, charging monitoring systems, and communication systems. According to the *FTA Research Guidebook for Deploying Battery Electric Buses*, key knowledge areas for BEB deployments include battery chargers, high-voltage cables, potential thermal events, and locations of emergency cutoff switches and fire response equipment.[13]

For FCEB deployments, high-pressure gas safety and hydrogen safety are both important training topics. While transit agencies do not typically perform hydrogen station maintenance themselves, there are times when they may need to complete visual inspections or turn off specific valves, so appropriate training is still important. Knowledge and awareness of gas detection and alarm systems are also important, even if maintenance of these systems is outsourced.

First Responder Training

Agencies should contact their local first responders before procuring buses to understand their existing knowledge and comfort levels regarding ZEB safety,

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[13] U.S. Department of Transportation, Federal Transit Administration. *TCRP Report 254.* Aug. 2023, https://www.transit.dot.gov/sites/fta.dot.gov/files/2023-08/FTA-Report-No-0254.pdf.

including responding to BEB and FCEB vehicle and related infrastructure fires. Agencies should also procure OEM-supplied first responder training, as necessary, to address knowledge gaps. It is also advisable to schedule periodic drills to evaluate the readiness and effectiveness of all parties in response to an emergency.

Safety Considerations

BEB and FCEB technology present new safety considerations for staff accustomed to ICE vehicles. Vehicle safety plans and training should be incorporated into workforce development plans. Agencies should align vehicle safety planning with established codes, standards, and emergency response guidance. Coordination with internal safety teams and external emergency responders supports safe operations and incident readiness.

Emergency Preparedness

When preparing for a transition to new vehicle technologies, it is important to update existing Emergency Response Plans to be prepared for unexpected incidents. Bus OEMs should provide documentation regarding new vehicles so that first responders can respond appropriately to events both on-road and at the facility. Agencies should establish site-specific procedures for responding to gas leaks or fires on buses from any point in the facility.

Facility Emergency Response Plans (ERPs) will also need to be updated to include the new fueling infrastructure. This will include developing response protocols for emergency events like fires and gas leaks at hydrogen fueling stations. It may also involve more general updates to existing plans, such as adjusting rallying points in the event of an incident. A key component of an ERP is a comprehensive communication plan to ensure that all relevant parties (e.g., transit agency, fire department, station maintenance operator, and fuel provider) and their respective incident commanders are not only contacted in the case of an emergency, but in continuous communication with one another during an emergency.

Additional Support

If completing the requirements of validation testing or workforce development needs is not feasible for an agency given existing staff capacity, the agency should consider hiring additional staff or contracting with consultants to support this effort. Agencies can also join virtual transit working groups like the Zero Emission Bus Resource Alliance (ZEBRA), the Hydrogen Fuel Cell Bus Council (HFCBC), the American Public Transportation Association (APTA) Zero Emission Fleet Committee, or California Transit Training Consortium (CTTC) to access and share peer agency lessons learned and research findings.

Key Questions to Consider:

Commissioning

- Has the agency received a commissioning plan or checklist that will outline all required commissioning activities?
- What is the timeline for commissioning activities?
- What is the plan for handing the station off to the operations and maintenance team?
- Has the agency received equipment maintenance and operating manuals to assist with a possible transition to a new O&M contractor in the future?

Acceptance and Validation Testing

- What were the contractual requirements for vehicle and infrastructure performance that need to be tested?
- How does the agency plan to complete acceptance and validation testing for vehicles and equipment?
- Does the agency have the necessary support from staff for acceptance and validation testing?

Workforce Development, Safety, and Emergency Preparedness

- What is the staff's current level of knowledge regarding ZEBs and supporting infrastructure?
- What are the skills gaps within the workforce that need to be addressed prior to deployment?
- What current training is available?
- When will recurring training take place?
- Does the agency have training programs that can be provided in-house?
- What are the relevant safety rules and regulations pertaining to the applicable technology and fuel type (high-voltage systems and/or hydrogen fuel cell)?

Checklist Before Moving to the Next Step:

Commissioning

- ☐ Commissioning plans have been documented
- ☐ All contractual requirements for vehicle and infrastructure operations have been met
- ☐ Operation of the charging or fueling infrastructure has been adequately tested and compatibility with the buses has been confirmed

Acceptance and Validation Testing

- ☐ Acceptance testing requirements are clearly defined and successfully completed to verify that vehicles and infrastructure meet all contractual performance specifications
- ☐ Validation testing has been conducted and confirms that vehicles and infrastructure perform as expected under real-world operating conditions and are aligned with planned service deployment. If results are not in line with expectations, service plans have been adjusted
- ☐ Potential deployment risks have been identified

Workforce Development, Safety, and Emergency Preparedness

- ☐ Current skills, existing certifications, and remaining skill gaps have been documented
- ☐ Staff and workforce impacts and training needs are understood
    - Identify the staff that will need training
    - Identify who will deliver training (prioritize securing qualified trainers)
- ☐ Available training modules from vehicle and component OEMs have been reviewed
- ☐ Local first responders have been trained and prepared for emergency events
- ☐ Familiarity with industry organizations that provide workforce development training:
    - Automotive Service Excellence (ASE)
    - California Transit Training Consortium (CTTC)
    - National Transit Institute (NTI)
- ☐ A list of specialized training providers has been compiled
- ☐ Training requirements for operators, maintenance staff, supervisors, and emergency responders have been defined
- ☐ Facilities, equipment, and personal protective equipment (PPE) needed to operate and maintain ZEBs have been acquired
- ☐ OEM-provided training for vehicles and infrastructure has been scheduled or completed

- ☐ Emergency list of key individuals to contact in response to an incident has been updated
- ☐ A communication plan has been created to ensure all key individuals are in touch with one another during an emergency
- ☐ A plan to periodically reassess workforce training needs has been defined
- ☐ Periodic first-responder drills to evaluate readiness and effectiveness of ERP have been scheduled
- ☐ Staff can safely operate and maintain ZEB vehicles and infrastructure

Suggested Resources to Reference:

General Resources

- ZEB Training and Technical Assistance (CTTC)
- ZEB 101 & ZEB 201 Courses (CTE)
- Workforce Training Resources (APTA)
    - Zero-Emission Bus Maintenance Training Recommend Practices Report (APTA)
        - FCEB specific - section 1.3.10 Hydrogen fuel cell bus Overview
        - FCEB specific - section 2.2.1 General Safety item 8
        - FCEB specific - section 2.2.2 Onboard safety equipment - item 5
- Bus Transit Systems Standards (APTA)
- Battery Electric Bus Familiarization Course (TWC)
- Electric Drive Vehicle Automotive Technician Training (NAFTC)
- An Overview of Alternative Fuel and Advanced Technology Vehicles (NAFTC)
- Specialized Training Courses on Charging Infrastructure, Energy Storage, and Vehicle Diagnostics (SAE International)
- Technology Maintenance Readiness Guide for Zero-Emission Buses (NREL)
- Transit Training for Safe Transition to Zero-Emissions Bus Technology (FAAC)
- Workforce Development Trainings Courses (NTI)
- Guidebook for Deploying Zero-Emission Transit Buses (TCRP/CTE)
- Zero Emission Fleet Workforce Evaluation Tool (FTA)
- Training Materials for First Responders (H2Tools)
- Zero Emission Bus Resource Alliance (ZEBRA)
- Hydrogen Fuel Cell Bus Council (HFCBC)

Safety Resources

- Safety and Security Certification of Electric Bus Fleets – Industry Best Practices (FTA)
- Emergency Preparedness and Response Plans (FTA)
- Hydrogen Safety Resources (DOE)
- Emergency Response Guides: Standardized Emergency Response Information for Electric-Powered Vehicles (NHTSA)
- Example Safety Plan for Hydrogen and Fuel Cell Projects (H2Tools)
- Emergency Response Training (NFPA)
- Hydrogen Safety Training Courses (Center for Hydrogen Safety)
- Guidance to Hydrogen Permitting (California Hydrogen Business Council)
- Hydrogen Fuel Cell Codes and Standards (H2Tools)
- Welcome to the Hydrogen and Fuel Cell Safety Report (FCHEA)
- Safety Resources (H2Tools)
- Battery Electric Bus Fire Safety White Paper (CTE)

Step 6:

Deployment KPIs and Fine-Tuning

Following station construction, performance and acceptance testing, and workforce preparation, ZEBs can enter revenue service where performance metrics and operational data are used to evaluate outcomes and refine operations. Key performance indicators (KPIs) are quantifiable measures used to evaluate performance. In defining KPIs, agency stakeholders should be mindful of both their deployment goals and data capabilities.

If tracking KPI metrics is not feasible for an agency given existing staff capacity, the agency should consider hiring additional staff or contracting with consultants to support this effort. Agencies can also join virtual transit working groups like the Zero Emission Bus Resource Alliance (ZEBRA) or the Hydrogen Fuel Cell Bus Council (HFCBC) to access and share peer agency lessons learned and research findings.

Goal setting ensures that agencies get value out of their data analysis. Common goals of KPI reporting include comparing the performance of different vehicle propulsion types (such as diesel buses vs. FCEBs), visualizing the impact of charging optimization on utility costs, evaluating fleetwide availability, quantifying estimated emissions reductions, and identifying opportunities to increase vehicle utilization.

Data Capabilities

When defining KPIs, agency staff should consider what existing systems and processes they have in place to collect operational data. Common sources of automatically collected data include onboard vehicle telematics systems, fleet management systems to track fuel consumption, utility bills, and charge management system (CMS) data. Some agencies may use manual logs to collect maintenance data, state of fill, and fueling information. If there is a gap between an agency's goals for KPI reporting and their current data availability, agencies can consider investing in new tools or training staff to collect some information on a temporary basis.

Common KPI Metrics

KPIs help agencies monitor performance, evaluate benefits, and support decision-making for ZEB deployments. Common metrics include energy or fuel use, energy consumption per mile, daily miles per vehicle, depth of discharge for BEBs, charging or fueling efficiency, vehicle availability, idle hours. fuel and maintenance costs per mile, total cost of ownership, and emissions reductions compared across the different vehicle types. Together, these metrics can help agencies validate vehicle and station expectations, track progress toward their goals, and identify areas for improvement.

Application

KPIs are most useful when they inform real-world operational decisions. By evaluating vehicle efficiency and SOC on specific blocks, agencies can identify opportunities for training and route optimization and empower their operators to utilize the full range of their vehicles. KPIs can assist maintenance staff with information alerting them to maintenance issues that need to be addressed in advance of failures. Agencies can also use KPIs to tailor hydrogen deliveries to actual fuel consumption, inform future infrastructure investments, and align charging schedules with off-peak hours to reduce utility costs.

Addressing Challenges

As with any technology, challenges may arise after vehicles and equipment have been commissioned and accepted. Long-term KPI monitoring serves as an opportunity to identify performance concerns early on, including changes to fuel economy. For example, fuel cell degradation is something that can be monitored through KPIs in order to prevent impacts to vehicle range and operations. If performance fails to meet warranty terms and other contractual expectations, agencies should seek resolution from their OEM partners.

Key Questions to Consider:

Operations

- What are the agency's operational priorities?
- How might the agency reduce its operating expenses?
    - How might the agency optimize charging and/or fueling schedules to reduce utility or hydrogen costs?
    - Would higher vehicle utilization reduce fuel costs? Are there opportunities to increase vehicle utilization?

KPI Metrics

- What KPI metrics are most critical to achieving the agency's operational goals?
- Which stakeholders need to be engaged to ensure KPI metrics support operational goals?
- What data sources are available, and what is their accuracy and reliability?

Checklist Before Moving to the Next Step:

☐ Organizational deployment goals and objectives are understood
☐ KPI tracking metrics have been defined
☐ Plans to collect necessary data to support KPIs are finalized
☐ Potential challenges (internal conflict, data access, too much data, data integrity, data interpretation issues) have been defined
☐ Plans to periodically review the KPIs and performance of the vehicles and equipment are defined
☐ Lessons learned from KPIs and early deployments have been documented and addressed
☐ Transition plan and future bus procurements have been updated based on KPI outcomes

Suggested Resources to Reference:

- KPI Development and Tracking Support (CTE)
- ZEB 101/201 Courses (CTE)
- Zero-Emission Transit Bus Technology Analysis (AC Transit)
- Battery Electric Bus Charging Infrastructure: Key Performance Indicators (APTA)

Tool 3:

Funding Sources

The following table contains a non-exhaustive list of government funding programs relevant to ZEB deployments. As of February 2026, several federal programs have funding authorized under the Infrastructure Investment and Jobs Act (IIJA) through FY2026. Some authorized funding is currently paused. It is unclear whether these programs will be included in a new transportation infrastructure bill or will continue to be funded until new legislation is enacted.

Agency stakeholders should confirm current funding availability with internal grants staff and grantor representatives in planning for ZEB-related investments.

Discretionary Programs

Table 4 – Low or No Emission Vehicle Program (5339(c)

Opportunity: Low or No Emission Vehicle Program 5339(c)	
Eligibility Requirements	Provides funding for the purchase or lease of zero- and low-emission transit buses as well as supporting equipment. Eligible applicants include designated recipients, states, local governmental authorities, and Indian Tribes.
Funding Amounts	$1.128 M (FY26)
Application Timeline	FTA typically issues NOFO within 30 days of the funding obligation for a full fiscal year; recent years have included a joint NOFO with Buses and Bus Facilities Program.
Application Considerations & Priorities	• Replacing buses that have met useful life • Gives consideration to applications proposing to use funding only for incremental costs of technology • Availability of other funds to cover base cost of bus • Documented availability of cost share • Low-No applicants are able to name partners in their applications • 2025 awards prioritized low-emission projects

Table 5 – Low or No Emission Vehicle Program 5339(c)

Opportunity: Low or No Emission Vehicle Program 5339(c)	
Eligibility Requirements	Provides funding for the purchase or lease of zero- and low-emission transit buses as well as supporting equipment. Eligible applicants include designated recipients, states, local governmental authorities, and Indian Tribes.
Funding Amounts	$1.128 M (FY26)
Application Timeline	FTA typically issues NOFO within 30 days of the funding obligation for a full fiscal year; recent years have included a joint NOFO with Buses and Bus Facilities Program.
Application Considerations & Priorities	• Replacing buses that have met useful life • Considers applications proposing to use funding only for incremental costs of technology • Availability of other funds to cover base cost of bus • Documented availability of cost share • Low-No applicants are able to name partners in their applications • 2025 awards prioritized low-emission projects

Table 6 – Buses and Bus Facilities Program 5339(b)

Opportunity: Buses and Bus Facilities Program 5339(b)	
Eligibility Requirements	Assists in the financing of buses and bus facilities capital projects, including replacing, rehabilitating, purchasing or leasing buses or related equipment, and rehabilitating, purchasing, constructing or leasing bus-related facilities. Applicants must demonstrate how the project will address an unmet need for capital investment in bus vehicles and/or supporting facilities. Designated recipients that allocate funds to fixed route bus operators, states, or local governmental authorities that operate fixed route bus service, and Indian tribes are eligible recipients.
Funding Amounts	FTA announced additional awards on 2/20/26 of approximately $390 M for FY26 selected from applications submitted in response to the FY25 NOFO. The amount of funding that will be included in the 2026 NOFO release is uncertain as of April 2026.
Application Timeline	FTA typically issues NOFO within 30 days of the funding obligation for a full fiscal year; recent years have included a joint NOFO with the Low-No program.
Application Considerations & Priorities	• Applicants submitting the same application to the Low-No program may also name partners in their Buses and Bus Facilities application

Table 7 – Better Utilizing Investments to Leverage Development (BUILD) Grant Program

Opportunity: Better Utilizing Investments to Leverage Development (BUILD) Grant Program	
Eligibility Requirements	Provides funding for planning or constructing surface transportation infrastructure projects that will improve safety; environmental sustainability; quality of life; mobility and community connectivity; economic competitiveness and opportunity including tourism; state of good repair; partnership and collaboration; and innovation. Eligible applicants are States and the District of Columbia; any territory or possession of the United States; a unit of local government; a public agency or publicly chartered authority established by one or more States; a special purpose district or public authority with a transportation function, including a port authority; a Federally recognized Indian Tribe or consortium; a transit agency; and a multi-State or multijurisdictional group of separately-eligible entities.
Funding Amounts	$1.5 B (FY26)
Application Timeline	2026 NOFO closed 02/04/26
Application Considerations & Priorities	• BUILD is an IIJA-authorized program and may not be included in future infrastructure bills • Awards ranged from $239,000 to $25 million in FY25 • Some awards support ZEBs, but are generally in the context of a larger project

Table 8 – FHWA Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation (PROTECT)

Opportunity: FHWA Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation (PROTECT)	
Eligibility Requirements	Helps make surface transportation more resilient to natural hazards. Eligible activities fall under four categories: 1) Planning; 2) Resilience Improvement; 3) Community Resilience and Evacuation Routes; and 4) At-Risk Coastal Infrastructure.
Funding Amounts	$300 M (FY26)
Application Considerations & Priorities	• 2025 NOFO is under review and has been removed from grants.gov

Table 9 – FTA Metropolitan, Statewide & Non-Metropolitan Planning

Opportunity: FTA Metropolitan, Statewide & Non-Metropolitan Planning	
Eligibility Requirements	Supports planning programs that provide funding and set procedural requirements for multimodal transportation planning in metropolitan areas and states that result in long-range plans and short-range programs of transportation investment priorities. The planning programs are jointly administered by FTA and FHWA. Eligible recipients are states and Metropolitan Planning Organizations (MPOs).
Funding Amounts	$202 M (FY26)

Table 10 – FTA Capital Investment Grants Program – Small Starts

Opportunity: FTA Capital Investment Grants Program – Small Starts	
Eligibility Requirements	Supports design and construction of fixed guideway systems and corridor-based bus rapid transit projects. Eligible recipients are State and local government agencies, including transit agencies.
Funding Amounts	Authorized up to $4.6 billion per year, subject to Congressional appropriations (total encompasses Small Starts, New Starts, and Core Capacity)
Application Considerations & Priorities	• Total project cost is less than $400 million and total Small Starts funding sought is less than $150 million • New fixed guideway systems (light rail, commuter rail, etc.) • Extension to existing fixed guideway system • Corridor-based BRT system

Formula Programs

Table 11 – Congestion Mitigation and Air Quality Improvement (CMAQ) Program

Opportunity: Congestion Mitigation and Air Quality Improvement (CMAQ) Program	
Eligibility Requirements	Funds transportation projects designed to reduce congestion and improve air quality, particularly in areas designated by the U.S. EPA to be in nonattainment of national ambient air quality standards for ozone, carbon monoxide, and particulate matter.
Funding Amounts	Annual apportionment

Table 12 – Urbanized Area Formula Grants 5307

Opportunity: Urbanized Area Formula Grants 5307	
Eligibility Requirements	Makes federal resources available to urbanized areas and governors for transit capital and operating assistance in urbanized areas and for transportation-related planning.
Funding Amounts	FY26 apportionment does not appear to have been released as of February 2026
Application Considerations & Priorities	• Administered to recipients with a population between 50,000–199,999 by Caltrans within California. • Large urban recipients (population 200,000 or greater) apply for their apportionment directly from FTA

Table 13 – Formula Grants for Rural Areas 5311

Opportunity: Formula Grants for Rural Areas 5311	
Eligibility Requirements	Provides capital, planning, and operating assistance to states to support public transportation in rural areas with populations of less than 50,000.
Funding Amounts	FY26 apportionment does not appear to have been released as of February 2026

Table 14 – Carbon Reduction Opportunity

Opportunity: Carbon Reduction	
Eligibility Requirements	Provides funding for projects supporting either zero-emission vehicles and infrastructure, active transportation and micromobility, or rail and transit.
Funding Amounts	California receives about $110 million annually
Application Considerations & Priorities	• Often programmed regionally • This is an IIJA-authorized program and may not be included in future infrastructure bills.

Table 15 – State of Good Repair

Opportunity: State of Good Repair (5337)	
Eligibility Requirements	Provides capital assistance for maintenance, replacement, and rehabilitation projects of high-intensity fixed guideway and motorbus systems to help transit agencies maintain assets in a state of good repair in urbanized areas.
Funding Amounts	California receives about $105 million annually FY26 apportionment does not appear to have been released as of February 2026
Application Considerations & Priorities	• Funding for urbanized areas with a population of 200,000 or more

State Programs

Table 17 – California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)

Opportunity: California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)	
Eligibility Requirements	Transit Set-Aside funds transit buses purchased by a city or county government, a transportation or transit district, or a public agency, including paratransit and microtransit services. Transit agencies may also compete for Standard HVIP funding once set-asides have been exhausted.
Funding Amounts	Catalog provides incentive amounts for each vehicle
Application Considerations & Priorities	• Agencies must be compliant with the ICT regulation, including reporting, to receive funding • HVIP can be used for local match in federal Bus Competitive Program funds, such as FTA's Low and No Emission Vehicle Program

Table 16 – Air District Funding

Opportunity: Air District Funding	
Eligibility Requirements	Many air districts offer funding to public agencies for transit buses and supporting infrastructure. Eligible project types include vehicle replacement – replacing heavy-duty transit buses with zero-emission vehicles, and infrastructure projects – installing new, converting, or expanding existing battery-charging or hydrogen-fueling stations
Funding Amounts	Variable
Application Considerations & Priorities	• Funding is sometimes limited to projects above and beyond regulatory requirements and subject to cost-effectiveness requirements • Applicants often do not need to apply for a particular funding source. Staff match projects with appropriate funding

Table 18 – Air District Funding

Opportunity: VW Mitigation Trust	
Eligibility Requirements	Funds to replace older, high-polluting transit, school, and shuttle buses with new battery electric or fuel cell electric buses. Eligible costs include purchase price and taxes for new buses
Funding Amounts	• $2M remaining for bus projects as of February 2026 • $216,000 per BEB • $480,000 per FCEB
Application Timeline	First come, first served
Application Considerations & Priorities	• Types of buses eligible for replacement include class 4 to 9 school, transit, and shuttle buses • Replacement buses must be new and use commercially available zero-emission technologies

Table 19 – Transit and Intercity Rail Capital Program (TIRCP)

Opportunity: Transit and Intercity Rail Capital Program (TIRCP)	
Eligibility Requirements	In order to be eligible for TIRCP capital project funding under this program, a capital project must demonstrate that it will achieve a reduction in greenhouse gas emissions using the CARB quantification methodology and must also demonstrate an increase in ridership.
Funding Amounts	Cycle 8 TIRCP Funding: $950 million
Application Timeline	Cycle 8 opened February 2026

Table 20 - EnergIIZE Commercial Vehicles

Opportunity: EnergIIZE Commercial Vehicles	
Eligibility Requirements	Includes multiple funding lanes such as the Transit Set-Aside, which provides funding for electric vehicle charging and/or hydrogen fueling infrastructure equipment.
Funding Amounts	Variable
Application Timeline	Check EnergIIZE website to see when applications open for funding lanes

Table 21 – California Air Resources Board (CARB) and California Energy Commission (CEC) Programs

Opportunity: California Air Resources Board (CARB) and California Energy Commission (CEC) Programs	
Eligibility Requirements	CARB and CEC routinely release funding opportunities that advance the state's transition to clean energy and transportation through innovation, efficiency, and the development and deployment of advanced technologies.
Funding Amounts	Variable
Application Considerations & Priorities	Past Program Examples: • Electric Vehicle Charging Infrastructure • Implementation of Medium- and Heavy-Duty Zero-Emission Vehicle Infrastructure Blueprints

Tool 4:

California Hydrogen Market Forecast

An important way to increase the success of hydrogen adoption in California is to create a connected hydrogen fueling network within the state. The first step to achieving this is understanding the status of the hydrogen market in California. In order to do this, CTE began by identifying local hydrogen hubs and corridors within California. CTE developed a baseline of information by reviewing various resources including Innovative Clean Transit (ICT) rollout plans created by agencies throughout the state. CTE also reached out to transit agencies whose rollout plans mentioned a planned transition to hydrogen technology with a list of questions related to their buses and infrastructure. This analysis helped identify existing hydrogen fueling stations serving transit buses and potential locations of future stations. CTE adjusted the initial forecasts in early 2026 to reflect industry adjustments as a result of federal funding changes in late 2025/early 2026 that resulted in the pausing or cancellation of many hydrogen hub programs. Therefore, CTE uses a conservative predictive model through 2028 and then assumes that agencies will resume initial ICT rollout plan predictions. Market conditions are constantly evolving, and so too will supply and demand for hydrogen in the United States.

CTE worked with GreenInfo Network to create an interactive geospatial map based on the market information collected that illustrates hydrogen refueling site locations, key attributes for each site such as delivery type, site status and on-site storage, synchronized map views, comprehensive filtering, and site status overview. Visualizing the data reveals potential hubs and corridor locations that would benefit from expansion or construction of new fueling infrastructure. Mapping of the results also helped to identify where potential public-private partnership opportunities could be formed and where hubs could be connected to each other.

The geospatial mapping tool created by CTE and GreenInfo Network can be accessed via a link to the interactive tool.

Figure 22 – Depiction of the California Hydrogen Refueling Infrastructure Dashboard

Tool 5:

Stakeholder Interviews and CTE Recommendations: Hydrogen Market

This section covers the results of CTE's analysis of barriers to hydrogen adoption. Based on CTE's review of ICT rollout plans and discussions with California transit agencies planning to adopt hydrogen technology, CTE compiled a list of reported FCEB-related challenges as well as recommendations to address them. CTE then created a list of 24 stakeholders interested in hydrogen adoption, which included OEMs, fuel/station providers, transit agencies, and state government agencies. CTE shared initial findings with stakeholders to facilitate discussions and solicit feedback. These conversations allowed CTE to identify barriers and challenges from a local, regional, and state refueling perspective, and refine recommendations to accelerate the adoption of hydrogen fuels for public transit that align with the needs of various industry stakeholders. Below is a summarized list of the key challenges found and discussion questions:

The most frequently cited FCEB-related challenges include:

1. Funding Constraints
2. Technology Limitations
3. FCEB and Hydrogen Availability
4. Workforce Development
5. Space Constraints
6. Transition Timing

Key questions for stakeholders:

- Do these findings reflect the challenges you or your organization are experiencing or anticipating?
- Are there additional barriers or opportunities you believe we should consider?
- Which proposed recommendations do you believe would have the greatest impact?
- Are there any recommendations you disagree with?

Informed by stakeholder feedback, the following section details CTE's findings on barriers to FCEB adoption and recommendations to support hydrogen transitions.

Key Challenges to ZEB Adoption

Analysis of ICT Rollout Plans revealed recurring concerns about adopting zero-emission technology (inclusive of both BEB and FCEB technology) into transit operations. Key challenges identified include:

- Funding Constraints/ High cost of vehicles and hydrogen fuel supply
- Limited FCEB Models
- FCEB and Hydrogen Availability
- Workforce Development
- Space Constraints
- Transition Timing
- BEB- related Grid Capacity Constraints
- Emergency Response
- Facility Ownership
- Maintenance Delays (including availability of spare parts)
- Lack of FCEB Data
- Procurement Alignment
- Resiliency
- Ridership
- Utility Relationships

The most frequently cited FCEB specific challenges include:

Funding Constraints and Affordability

High capital costs for FCEBs, related infrastructure, land acquisition needs, and elevated operating costs (hydrogen fuel and maintenance) are major concerns. The impact of these costs on operating budgets is a significant burden for fleets planning to operate fuel cell buses. These high capital and operating expenditures associated with FCEBs lead to constrained budgets. It is essential to provide gap funding for early adoption of advanced technology until volume production and competition improve the affordability compared to incumbent technologies.

Limited FCEB Models

While FCEBs offer better range than BEBs, the lack of available models (including fuel cell commuter coaches and fuel cell cutaways and vans serving paratransit and rural service needs), as well as weather-related performance issues (extreme temperatures are a challenge for FCEBs due to excessive utilization of AC and electric resistance heaters), are a deployment concern for many.[14]

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[14] Fuel Cell Bus Manufacturer Availability. Technical note, n.d. At the time of the publication, only one manufacturer produces 40' and 60' fuel cell buses that meet FTA) Buy America requirements, and there are no OEMs manufacturing commuter coaches or smaller fuel cell vehicles for paratransit or rural service.

FCEB and Hydrogen Availability

Transit agencies report long lead times for FCEB procurement, sometimes in excess of 18 months, and limited hydrogen fueling infrastructure, especially in rural areas. Delivery logistics for hydrogen fuel and cost volatility of fuel heighten the problem. Compounding the availability of the fuel supply is the policy directive by many agency boards to source renewable hydrogen with a zero or near-zero carbon intensity. While overall hydrogen availability may present challenges in the short term, cost constraints are the primary challenge to sourcing renewable and low-carbon-intensity supplies.

Workforce Development

Agencies are struggling to recruit and train new and existing staff to support ZEB deployment, especially for planning, operations, and maintenance roles. There is a lack of broader workforce partnerships and outreach related to FCEBs.

Space Constraints

Over one-fifth of the transit agencies whose ICT Rollout Plans were reviewed cited space constraints as a concern for on-site hydrogen fueling or new infrastructure. Construction activity during station build-out can create additional space constraints.

Transition Timing

The 2040 zero-emission deadline presents logistical challenges. Infrastructure must be ready before buses arrive, which can be difficult to synchronize, and current procurement and permitting timelines are tight. Agencies can request an extension of requirements if delays arise from factors beyond their control. A true one-to-one replacement of vehicles is critical to make the transition to zero-emission.

Recommendations for Transit Agencies

Building on the key challenges identified, this section outlines recommendations for transit agencies to accelerate the adoption of hydrogen fuel cell technology across California's public transit sector. These strategies aim to reduce deployment risk, strengthen industry capacity, and support timely progress toward the state's goal to transition bus fleets to 100% zero-emission technology by 2040.

Procurement and Supply Chain Development

To address long lead times, limited vehicle availability, and procurement misalignment for purchasing vehicles, transit agencies can:

- Establish in-state regional vehicle procurement consortiums
- Minimize vehicle customizations to take advantage of production economies of scale
- Frame station RFPs around performance needs as opposed to station specifications
- Maintain flexibility in the station design stage to utilize emerging advanced technologies that may better address performance requirements

Hydrogen Infrastructure and Fuel Supply

To improve access to hydrogen fueling and manage delivery risks, transit agencies can:

- Work with California state hydrogen initiatives, the California Air Resources Board (CARB), the California Energy Commission (CEC), Caltrans, and GO-Biz to develop a statewide hydrogen corridor strategy
- Promote shared fueling infrastructure. Agencies, school districts, and municipalities can work in partnership to acquire new land that is more central to all stakeholders, which will aggregate the demand for hydrogen
    - Keep in mind that some transit agencies require their refueling station to be located at their operating division. Deadheading to and from a refueling depot may impact labor costs
- Consider temporary and modular fueling options
- Prioritize proposals that include technology solutions that minimize losses from boil-off, shrink station footprint, and reduce capital and operating costs
- Consider less stringent vendor requirements on fill times so that certain organizations are not precluded from responding to RFPs
    - Determine what will meet pullout requirements

Funding Mechanisms and Financial Risk Mitigation

To help manage the high capital and operating costs of hydrogen transitions, transit agencies can:

- Utilize the Low Carbon Fuel Standard (LCFS) credit program and other incentives to achieve parity or near-parity with the cost of diesel and compressed natural gas (CNG) fuels
- Show support for continuing and expanding California's LCFS credit program and access to capital funds through the state's Clean Truck and Bus Voucher Incentive Project (HVIP), Energy Infrastructure Incentives for Zero-Emission (EnergIIZE), and state sponsored programs like the ARCHES program
- Work with the Department of General Services (DGS) to establish a state-sponsored consortium to act as an aggregator that would commit to long-term offtake agreements with producers, allowing transit agencies to purchase fuel directly from DGS
- Consider longer than five-year term contracts, for fuel and station maintenance. This could be achieved through consortiums of operators with large hydrogen demands
- Consider a revolving loan fund or financing mechanism that provides low-interest capital for hydrogen infrastructure and vehicle procurement, if established by the state
- Advocate in CA for increased federal cost-share for hydrogen-related transit investments, including operational expenses

Workforce Development and Capacity Building

To support readiness and ensure a skilled workforce, transit agencies can:

- Collaborate with high schools, community colleges, universities, trade organizations, and other transit agencies to develop a statewide hydrogen transit training hub to build workforce capacity in hydrogen safety, fueling, operations, and maintenance. AC Transit's Zero Emission Bus University (ZEBU) and SunLine Transit's West Coast Center of Excellence in Zero Emission Technology (WCCOE) could be strong foundations for the hub
- Fund high school and vocational apprenticeships and internships
- Establish standardized hydrogen training certifications
- Create and invest in outreach programs for educating the public on hydrogen best practices

Deployment Planning and Technical Assistance

To address gaps in planning and design capacity, transit agencies can:

- Utilize and invest in ZEB transition technical assistance to ensure a comprehensive understanding of the transition planning process, including bus and service requirements, fleet procurement timelines, infrastructure assessments, redundancy and resilience, bus and facilities capital costs, operating and maintenance cost impacts, and emission benefits
- Check with state and local permitting agencies to determine if there are fast-track review and approval pathways for hydrogen infrastructure projects to streamline the permitting process and allow agencies to take advantage of federal tax credits when available

Recommendations for State Policy and Regulatory Stakeholders

To ensure regulatory flexibility and market transparency, California policy and regulatory entities can:

- Maintain and expand multi-year state-funded incentive programs to assist agencies in bridging the high capital costs of buses and infrastructure compared to incumbent technologies
    - Earmark Cap-and-Invest funds for this purpose to provide predictable, long-term funding that incentivizes new entrants into the FCEB OEM market
- Continue to allow limited deadline extensions for agencies facing delays due to costs, supply chain constraints, or other external barriers
- Mandate Original Equipment Manufacturer (OEM) transparency on expected procurement timelines and vehicle availability via programs such as HVIP
- Relax FTA-mandated spare ratio requirements to allow agencies to retain internal combustion engine vehicles longer to support resiliency requirements and to better prepare for their transition timelines
- Consider a formula allocation of pooled funding from CARB (HVIP and GFOs)/CEC (EnergIIZE and GFOs)/GO-Biz (ARCHES)/Caltrans (TIRCP)/etc. programs to agencies based on ICT rollout plans to decrease competition between agencies for funding
- Support early market commitments through financial incentives and/or state-backed procurement guarantees, particularly in newer models
- Facilitate increased competition by incentivizing additional OEMs to enter the California FCEB market
- Provide state funding to develop prototype fuel cell coaches and fuel cell cutaways and vans to demonstrate performance characteristics that support commuter, paratransit, and rural services
- Offer more technologically- neutral zero-emission infrastructure funding at the state and federal levels
- Relax state sales tax requirements to improve affordability of fuel cell buses and hydrogen fuel
- Release pre-approved, code-compliant, and widely- applicable designs for fueling stations, maintenance bays, and combined ICE/ZEB depots to reduce design costs and shorten project timelines

Tool 6:

H_2 Refueling Station (HRS) Configurations and Layouts

LH_2 – Liquid H_2 Storage**.** **GH_2** – Gaseous H_2 Storage

The station designs in this toolkit are representative of a standard set of layouts and dimensions. Actual equipment specifications, layouts, and dimensions will depend on a number of factors specific to site conditions, access to utilities (connected power requirements expressed in amps or total KVA), space restrictions, tank orientation and size, operating logistics, daily fuel demand, fueling window, and projected growth. Actual setback requirements and barriers will also vary by site and station design.

LH_2 Boiloff and Venting

An LH_2 storage tank (sometimes referred to as a "dewar") is a stainless-steel tank encapsulated within an outer tank. The inner tank is primarily insulated with a high-vacuum, double-walled design, which is required to store liquid hydrogen at 20 Kelvin (-253°C/-423°F). Heat energy from the surrounding environment (radiant heat from the sun) will inevitably propagate through the layers of insulation and gradually increase the temperature of the liquid hydrogen. This results in boil-off at the surface of the stored liquid, increasing the pressure in the tank. As pressure builds inside the storage tank under these conditions, venting occurs to maintain safe pressure levels, resulting in losses of about 1% per day.

There are also hydrogen losses that occur during transfill operations (transferring LH_2 from a delivery trailer to the on-site storage tank), at the startup of a cryopump when hydrogen vaporizes while priming the pump to cool it down, and "blowby" of gaseous hydrogen past the seals during cryopump operation. These losses can amount to 40-50%. Using different offloading technologies and procedures during the transfill process, optimizing storage tank size, employing advanced cryopump systems, and improving vehicle refueling methods can reduce total losses to 5-10%.

High-Capacity LH_2, Small Footprint

Station Footprint: ≈ 50' x 25'

- Cyropump Module: Two-stage LH_2 pump with Off-load transfill capability; integrated with hydraulic pumps and Programable Logic Control System (PLC)
- LH_2 Storage Tanks: Either 18,000 gallons (4,435 kg) or 25,000 gallons (6,273 kg)
- Vaporizers
- No GH_2 Buffer Storage
- Pre-cooling controlled by cryopump module
- Dispensers located adjacent to station platform or at remote location, including existing bus fueling island
- 480V 3-Phase Power

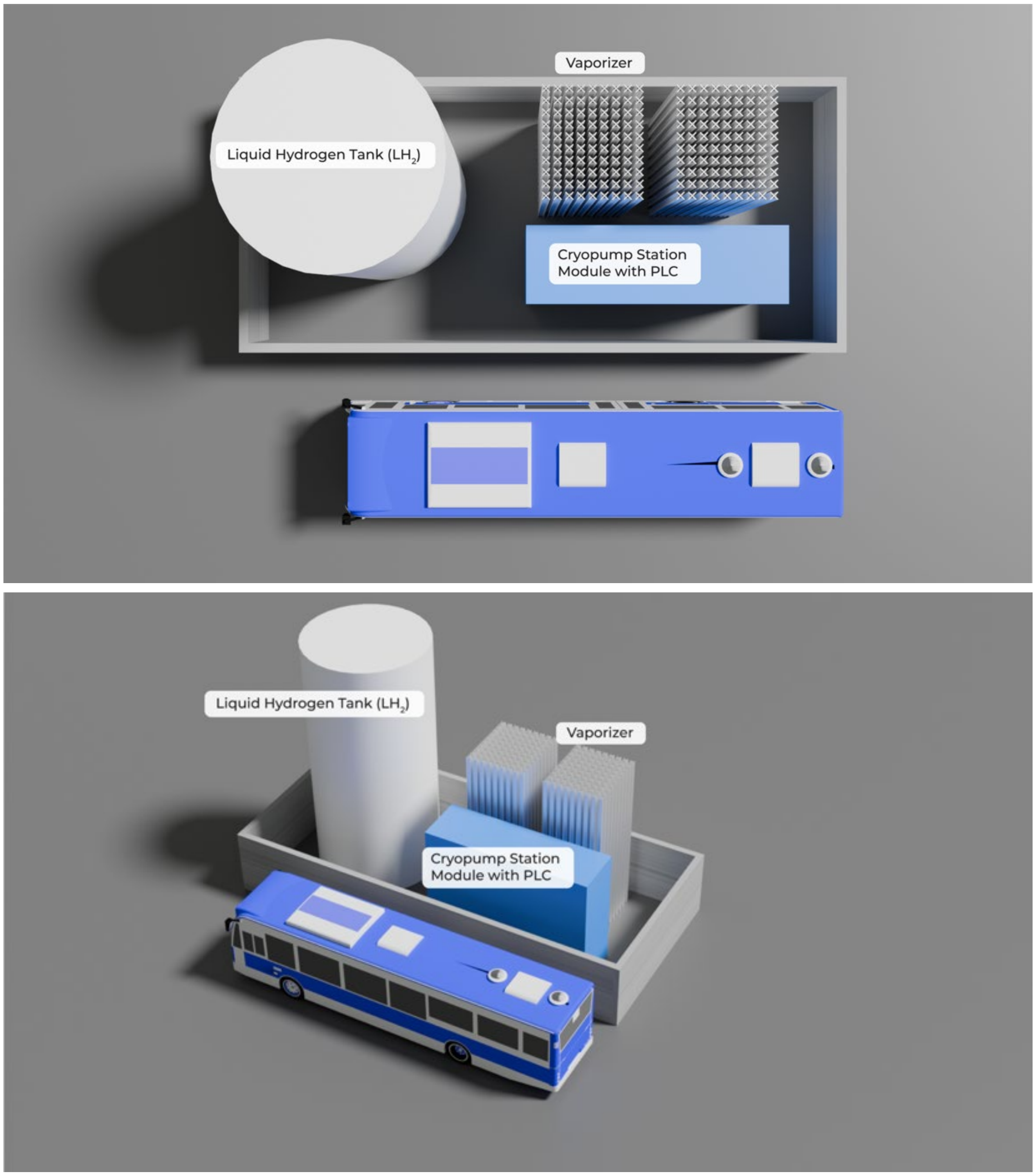

Figure 23 – High-Capacity LH_2, Small Footprint

High-Capacity LH$_2$, Large Footprint

- Station Footprint: ≈ 165’ x 20’; ≈ 100’ x 40’; 120’ x 50’
- Cyropump
- LH$_2$ Storage Tanks: 18,000 gallons (4,435 kg); 25,000 gallons (6,273 kg)
- Vaporizers
- GH$_2$ Buffer Storage
- With or without Boiloff Gas Compressor (BOG)
- With or without Nitrogen
- With or without pre-cooling equipment
- Dispensers located adjacent to station platform or at remote location, including existing bus fueling island
- 480V 3-Phase Power

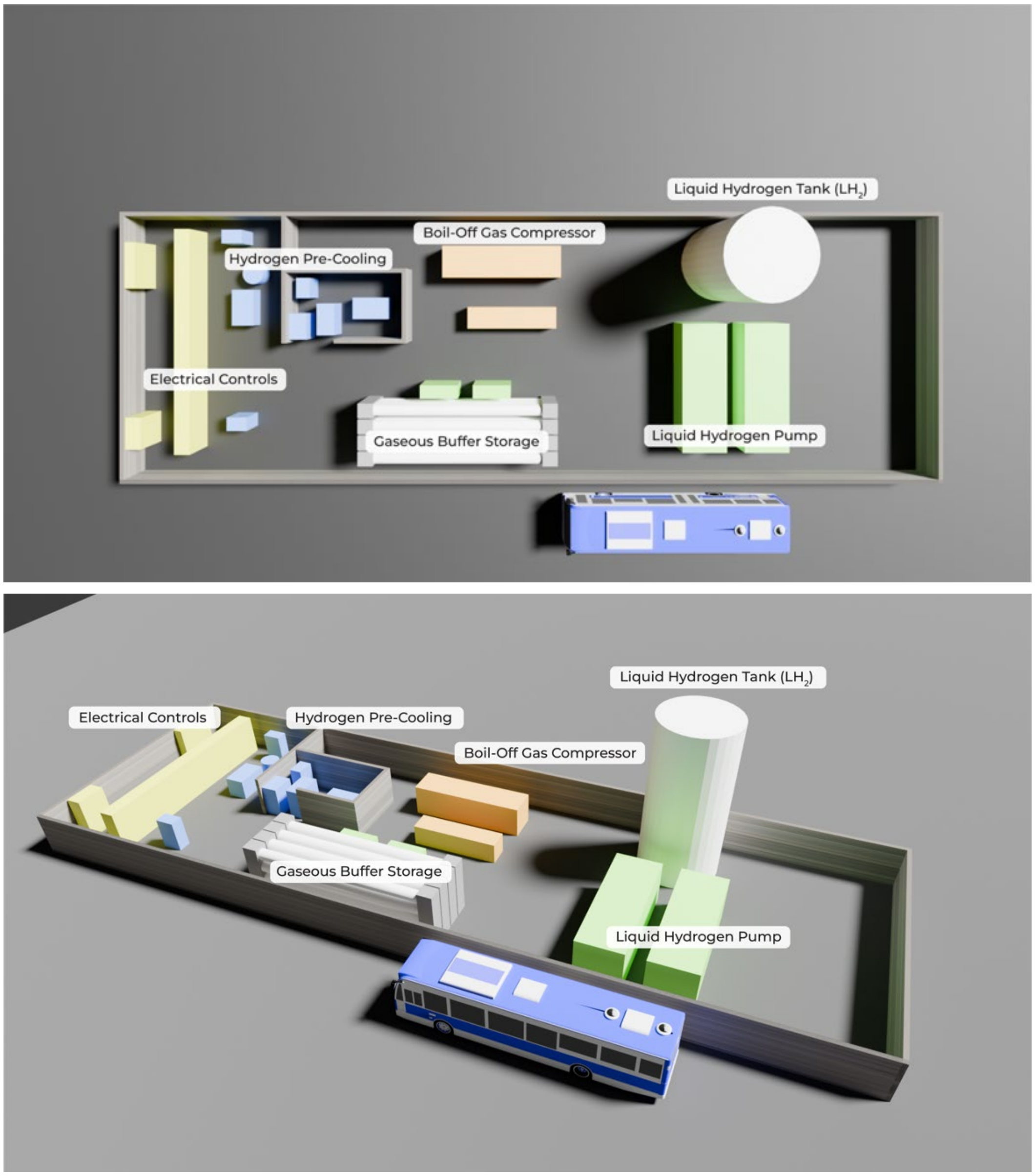

Figure 24 – High-Capacity LH$_2$, Large Footprint

High Capacity LH_2, Square Dimension

- Station Footprint: ≈ 54’ x 44’
- Cryopump
- LH_2 Storage Tank: 15,000 gallons (4,020 kg)
- Vaporizers
- With or without Nitrogen for line purging
- GH_2 Buffer Storage
- Dispensers located adjacent to station platform or at a remote location, including existing bus fueling island
- With or without pre-cooling equipment
- 480V 3-Phase Power

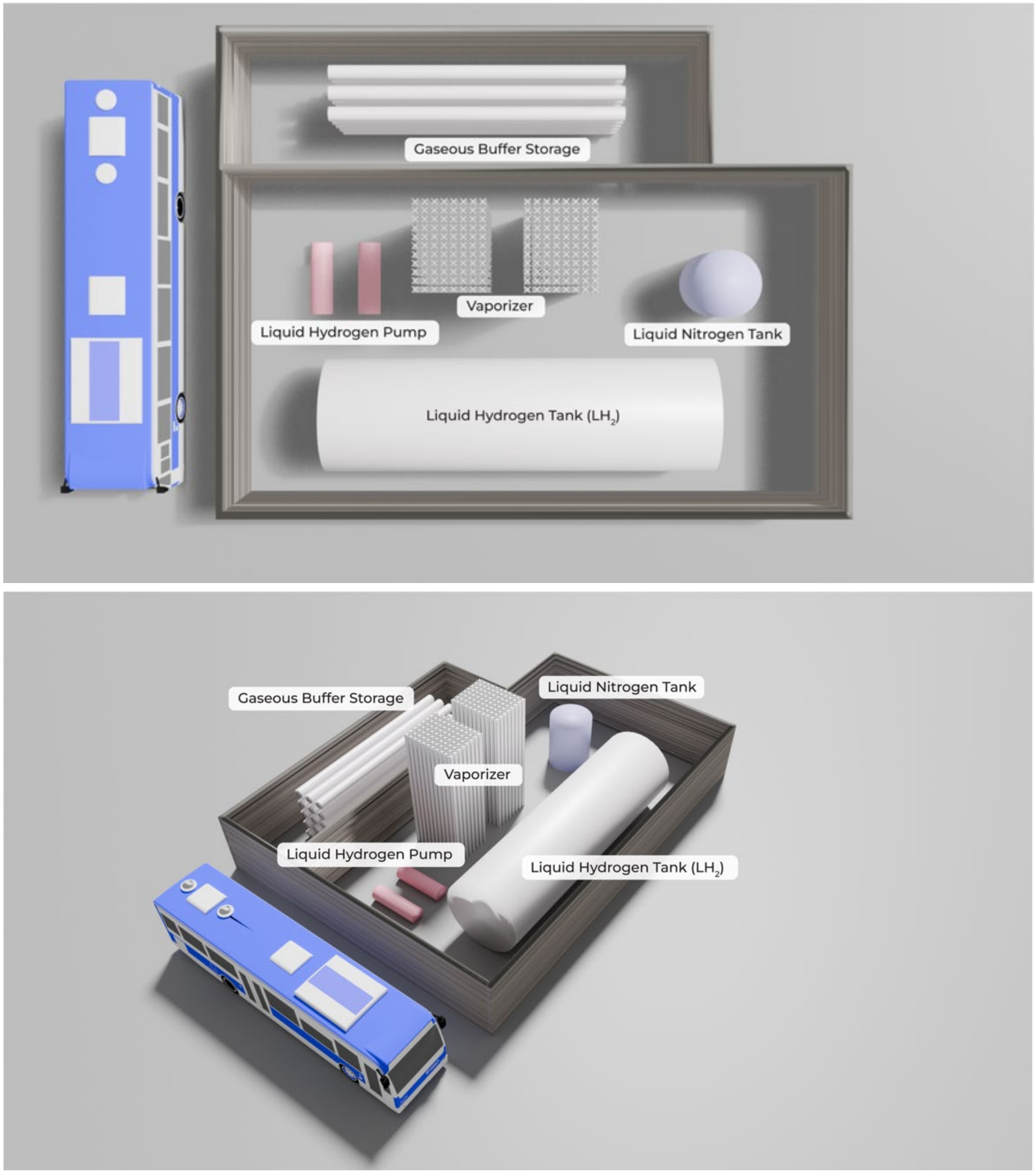

Figure 25 – High Capacity LH_2, Square Dimension

Portable LH_2 (Skid-Mounted)

- Station Footprint: ≈ 70’ x 20’; ≈ 50’ x 20’
- Cryopump
- LH_2 Storage Tank: 3,000 gallons (804 kg); ≈4,000 gallons (1,072 kg); 6,500 gallons (1,742 kg)
- Vaporizers
- No GH_2 Buffer Storage
- Dispenser on trailer or skid-mounted
- Pre-cooling Chiller
- 480V 3-Phase Power or onboard stationary generation

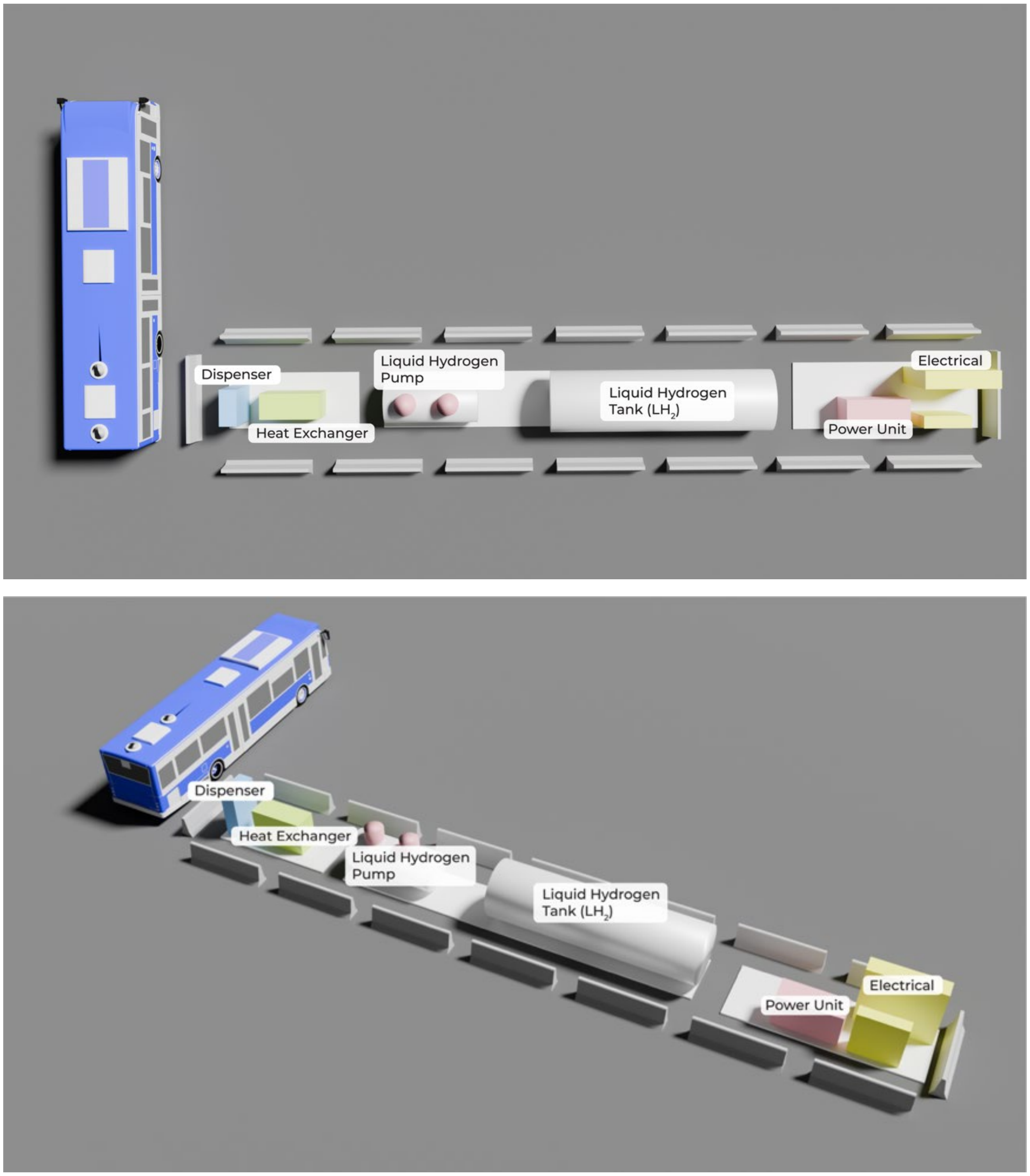

Figure 26 – Portable LH_2 (Skid-Mounted)

Portable LH_2 (Mobile Trailer)

- Station Footprint: ≈ 70’ x 20’; ≈ 50’ x 20’
- Cryopump
- LH_2 Storage Tank: 3,000 gallons (804 kg); ≈4,000 gallons (1,072 kg); 6,500 gallons (1,742 kg)
- Vaporizers
- No GH_2 Buffer Storage
- Dispenser on trailer or skid-mounted
- Pre-cooling
- 480V 3-Phase Power or onboard stationary generation

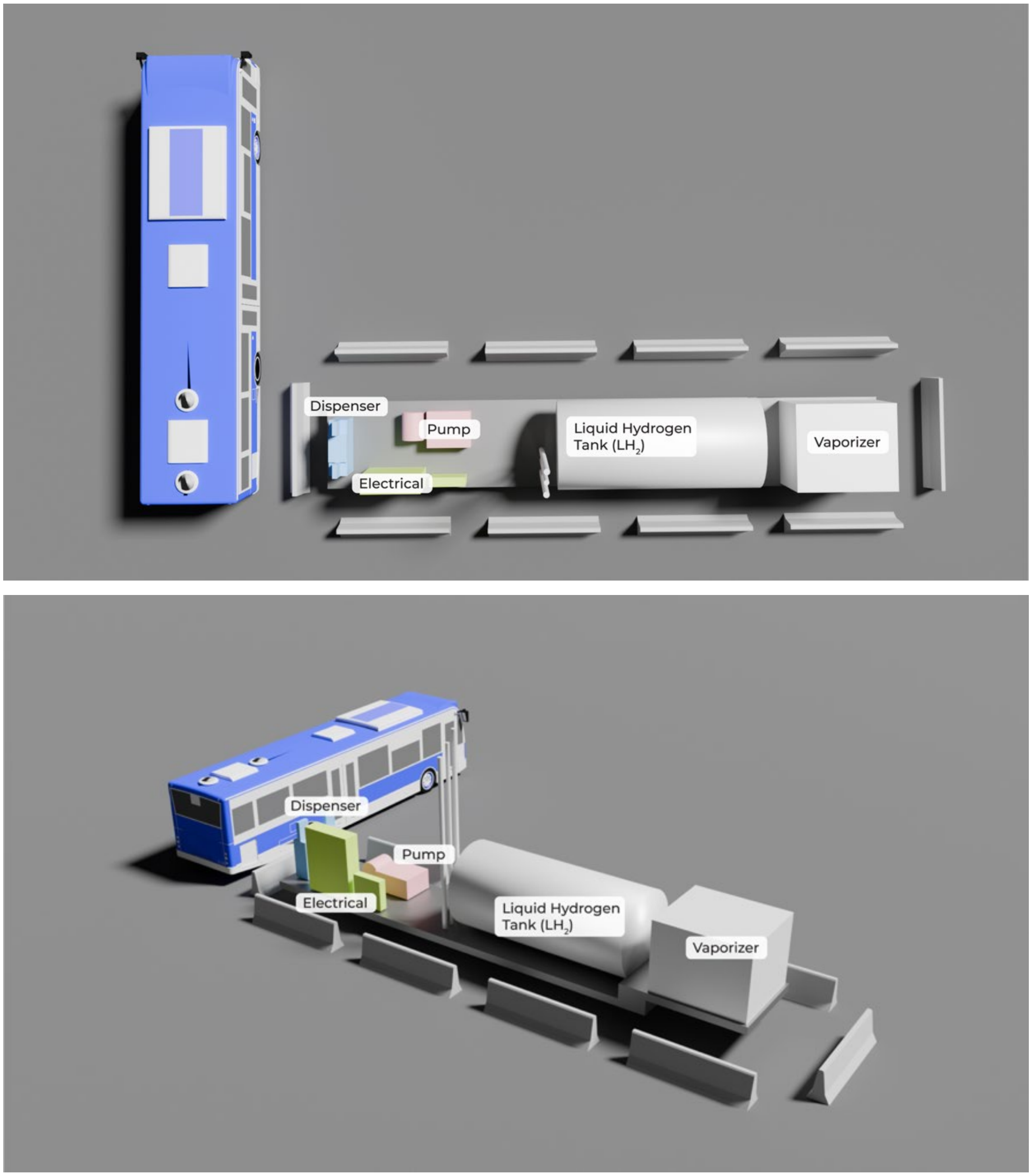

Figure 27 – Portable LH_2 (Mobile Trailer)

Portable GH_2 (Mobile Trailer)

- Station Footprint: ≈ 45’ x 9’
- Gas Compressor
- GH_2 Buffer Storage Tubes: 40 kg @ 500 bar
- Dispenser on trailer or skid-mounted
- Pre-cooling chiller
- GH_2 “Drop and Swap” Tube Trailers (each trailer: 500 kg @ 240 bar pressure)
- 480V 3-Phase Power or onboard stationary generation

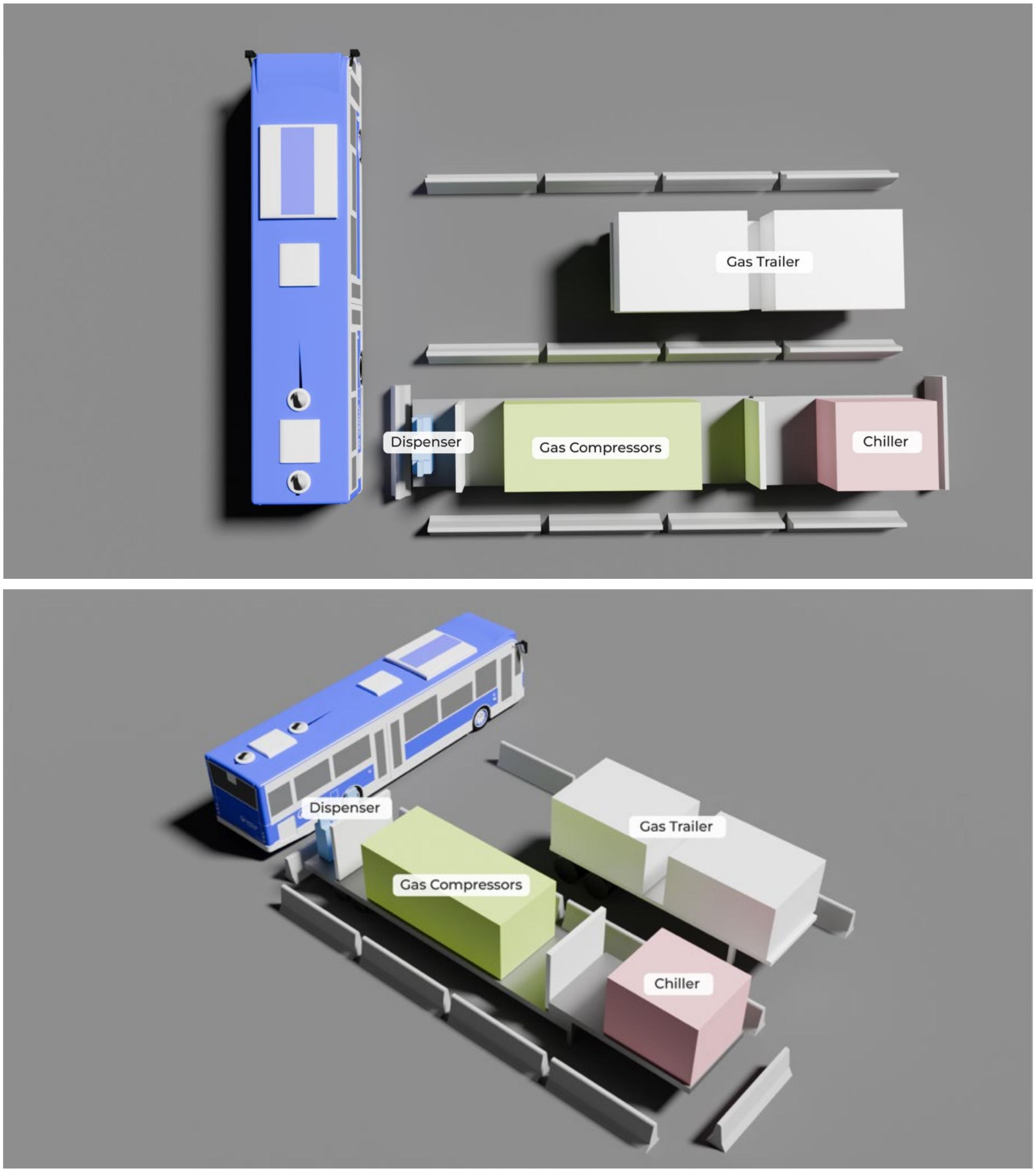

Figure 28 – Portable GH_2 (Mobile Trailer)

GH_2 with Compressor (Skid-Mounted)

- Station Footprint: ≈ 22’ x 12’ for dispenser and compressor module, 40’x50’ for tube trailer storage pad
- Dispenser/Compressor module
- GH_2 Buffer Storage @ 450 to 520 bar pressure
- With or without pre-cooling
- GH_2 “Drop and Swap” Tube Trailers (each trailer: 500 kg @ 240 bar pressure)

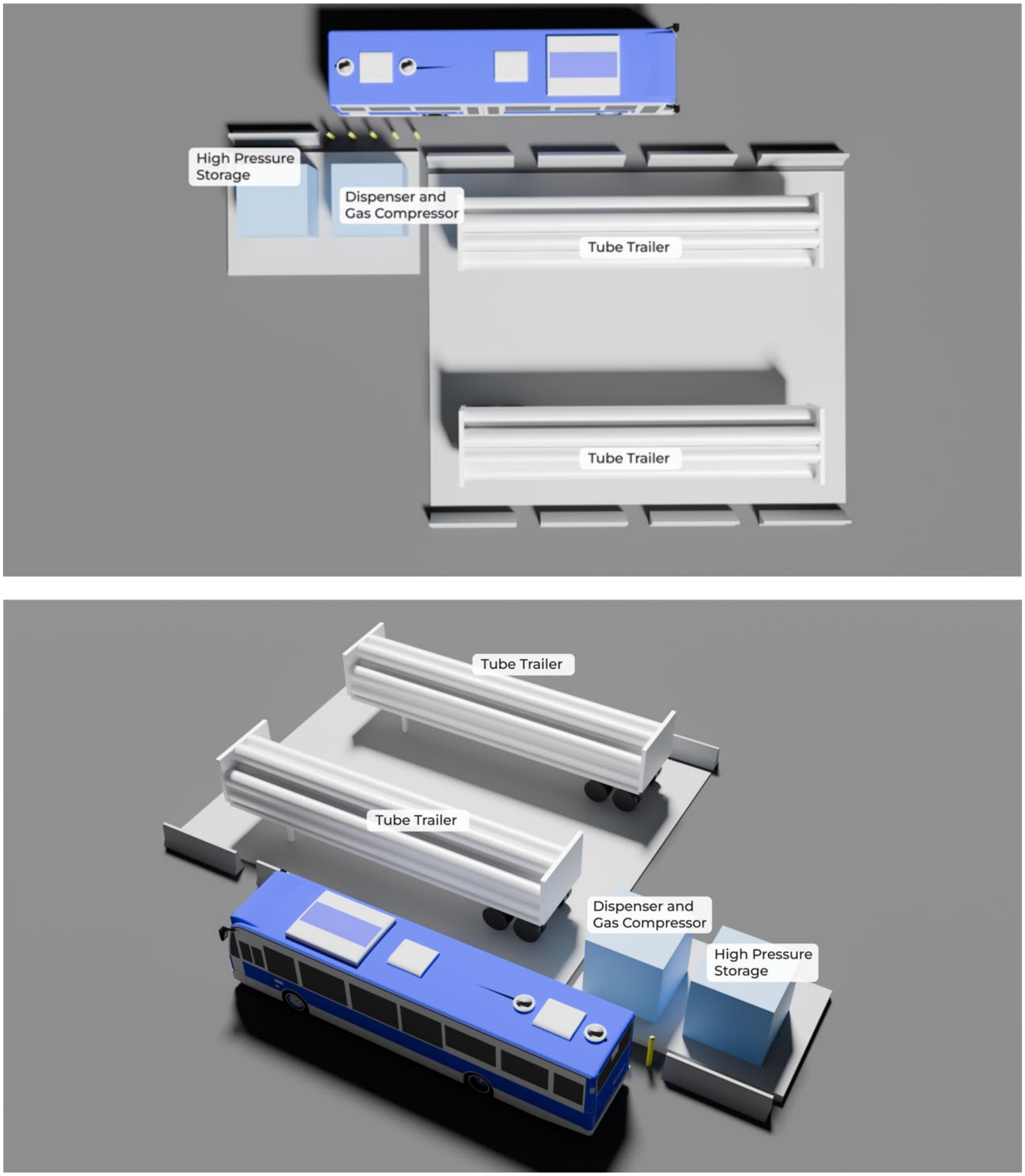

Figure 29 – GH_2 with Compressor (Skid-Mounted)

GH_2 Cascade Refueling (Skid-Mounted or Mobile Trailer)

- Station Footprint: ≈ 22’ x 12’ for dispenser module’
- Dispenser module
- No Gas Buffer Storage
- GH_2 Drop and Swap Tube Trailers (each trailer: 500 kg @ 520 bar pressure)
- Cascade refueling with two to three pressure banks
- No pre-cooling
- 110V Power, solar, or batteries (used for telematics)
- Trailer-only option w/onboard dispenser: ≈ 9’ x 20’ to 50’

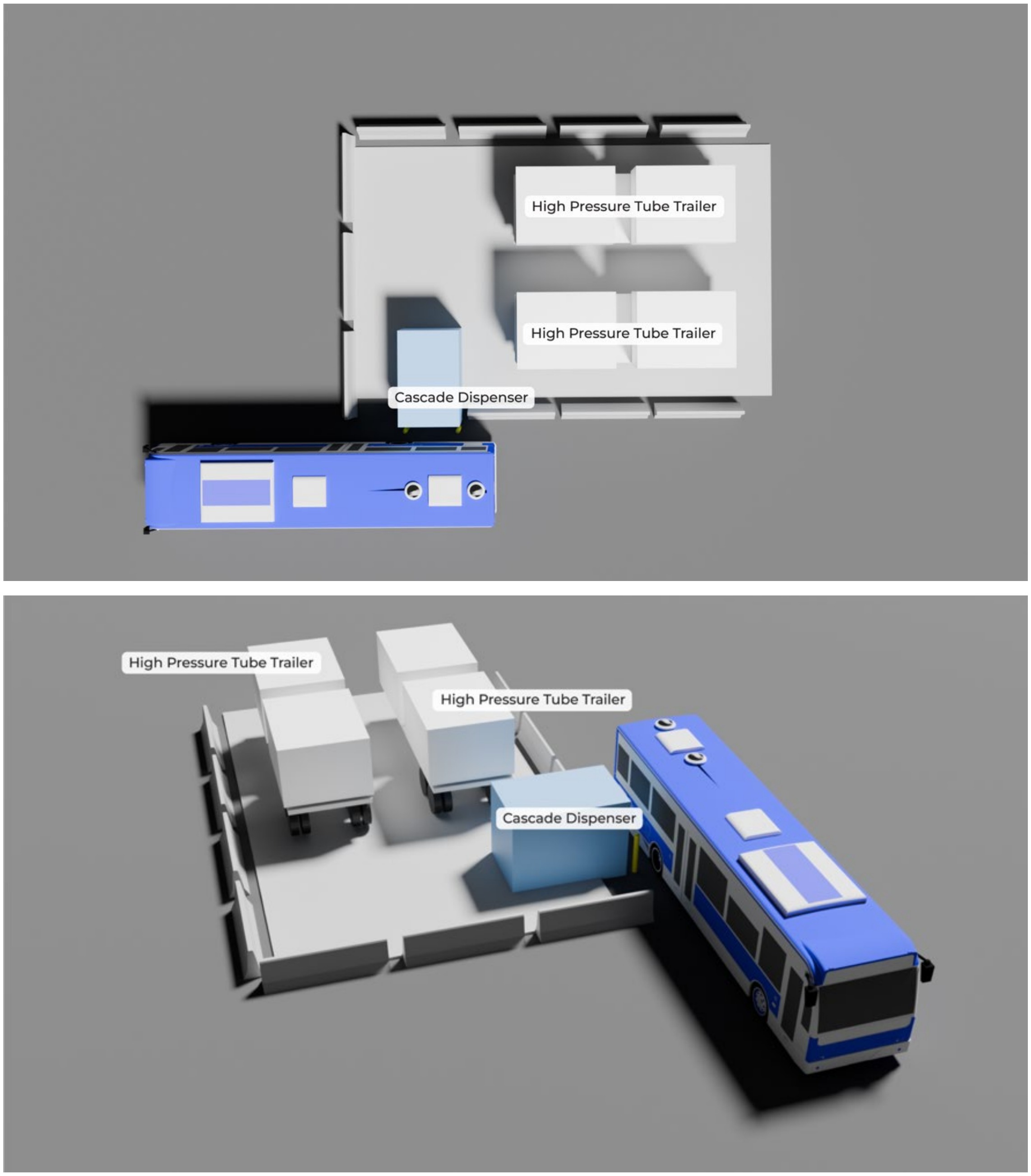

Figure 30 – GH_2 Cascade Refueling (Skid-Mounted or Mobile Trailer)

GH_2 Electrolyzer with Gaseous Storage

- Station Footprint: ≈ 200’ x 70'
- Gas Compressors
- Electrolyzer (1 MW to Produce 420 kg/day) or Steam Methane Reformer
- GH_2 Buffer Storage (≈ 900 kg)
- With pre-cooling equipment
- Dispensers located adjacent to station platform or at remote location, including existing bus fueling island
- 480V 3-Phase Power
- Electrolyzer will require 12 KV Power supply

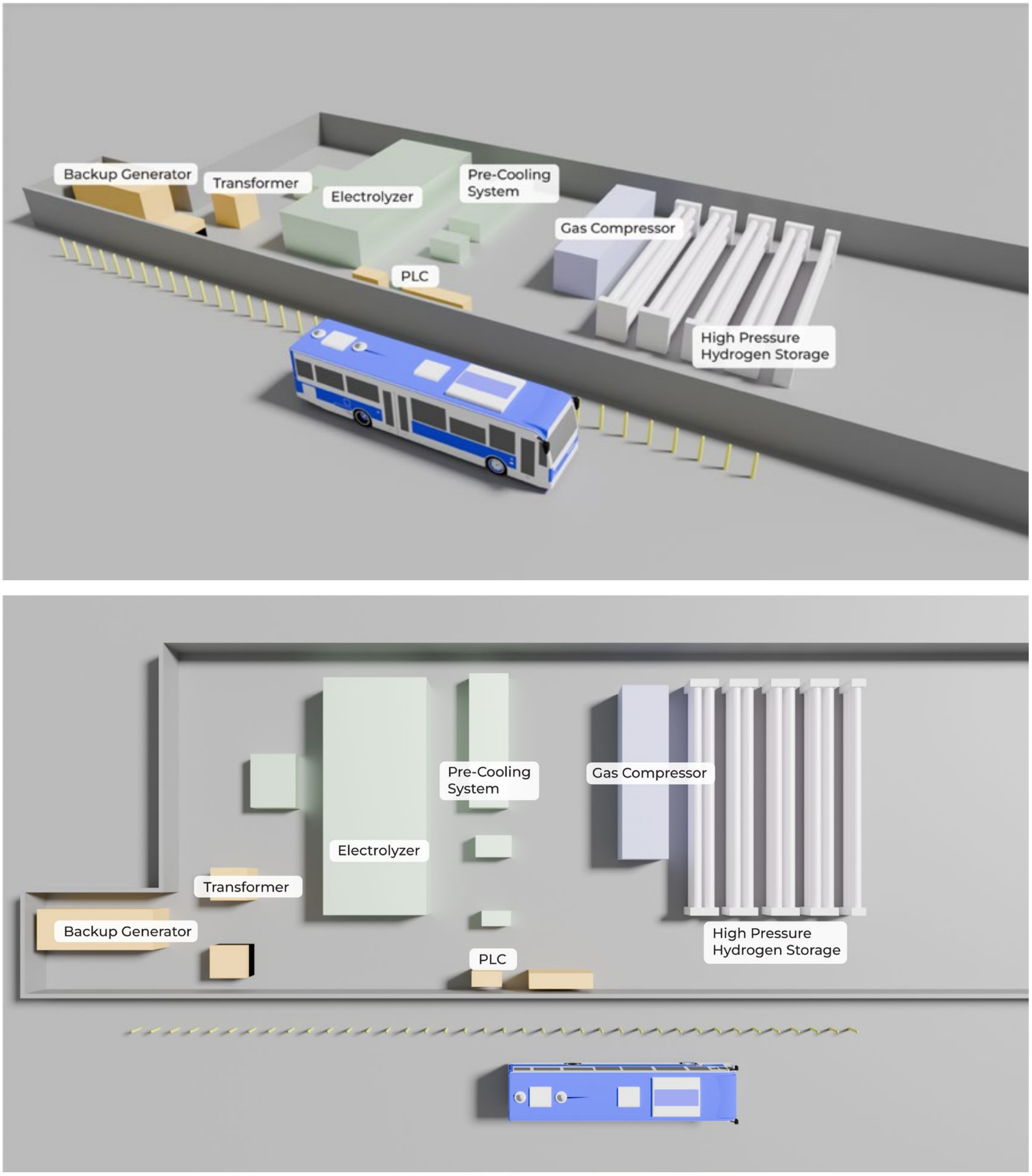

Figure 31 – GH_2 Electrolyzer with Gaseous Storage

Tool 7:

Hydrogen Station Designs

This tool presents examples of hydrogen station layouts and design concepts developed by TAIT (previously the Fiedler Group). These examples reflect the types of designs transit agencies can expect to receive from architecture and engineering (A&E) firms during the design planning process. They are generic plans intended to illustrate possible site plans, but actual configurations, setbacks, and the positioning of station equipment and dispensers will be determined by factors unique to specific site characteristics and agency operating requirements.

Factors affecting design and layouts will be based on equipment specifications, available real estate relative to vehicle parking needs, traffic flows within the maintenance yard and location of pull-in gates to accommodate queuing requirements, access to utilities, a desire to site dispensers in line with existing diesel or CNG dispensers, property lines, adjacent property uses, and required setbacks. By reviewing these concepts, agencies can better understand how site constraints, operational needs, and system requirements influence station design.

Figure 32 is a linear-oriented station with two dispensers located away from the station platform to provide the agency with sufficient space to support the queuing of buses prior to refueling during the pull-in period after evening peak service has concluded.

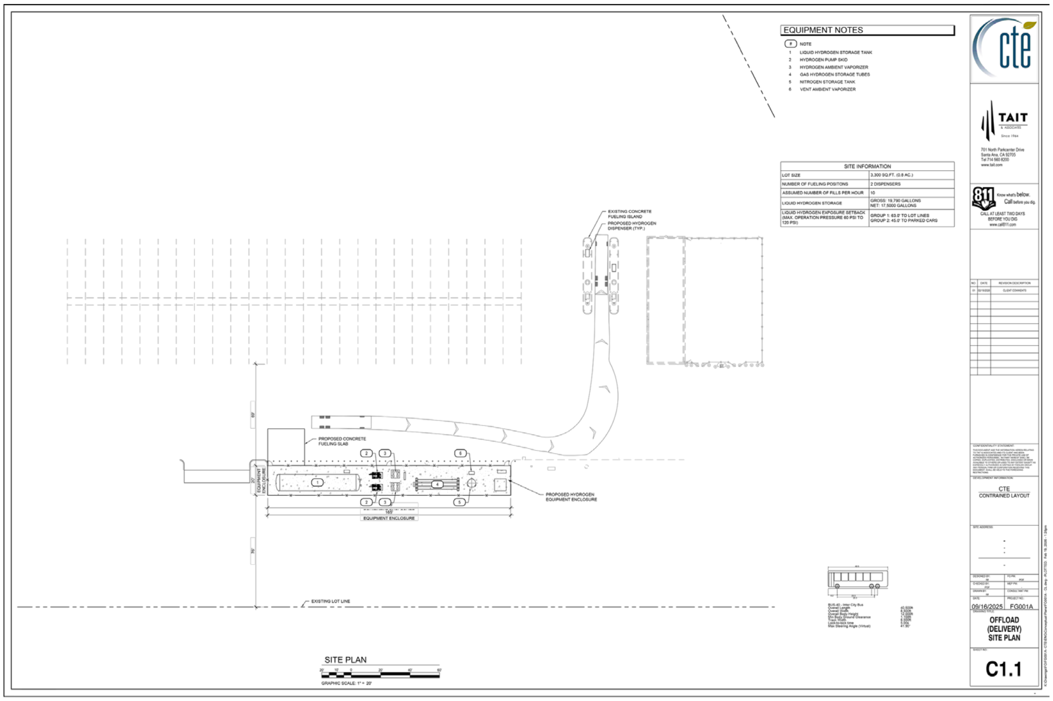

Figure 32 – LH₂ Station with Two Dispensers

Figure 33 is a large refueling station with two LH_2 storage tanks and four dispensers.

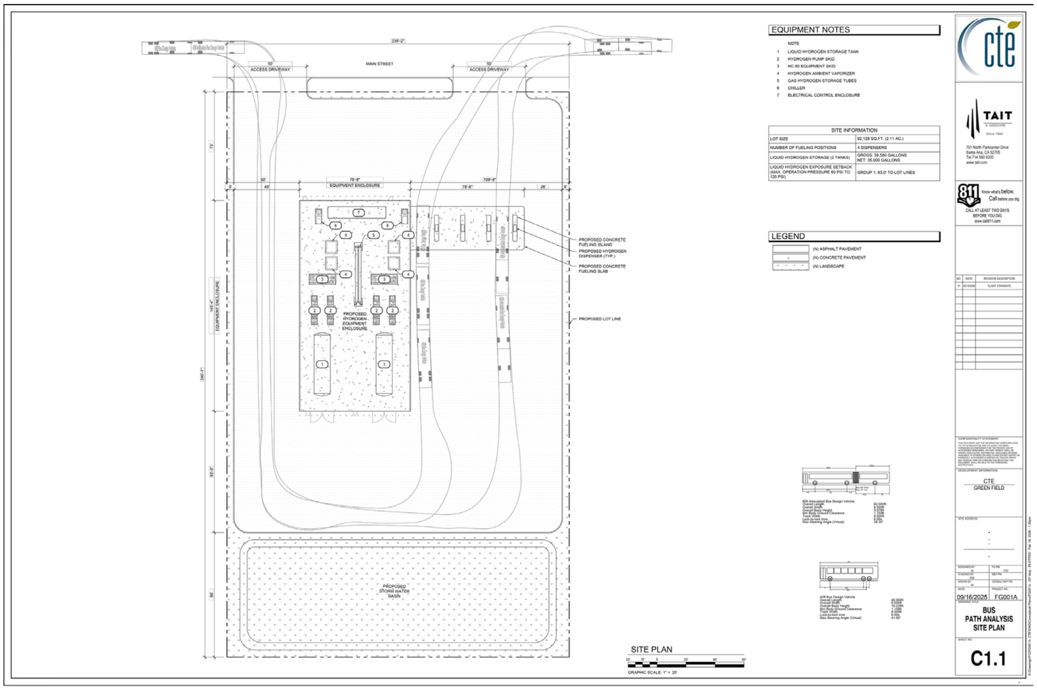

Figure 33 – High-Capacity LH₂ Station with Four Dispensers

Figure 34 is a portable LH_2 refueler with the dispenser located on the station platform.

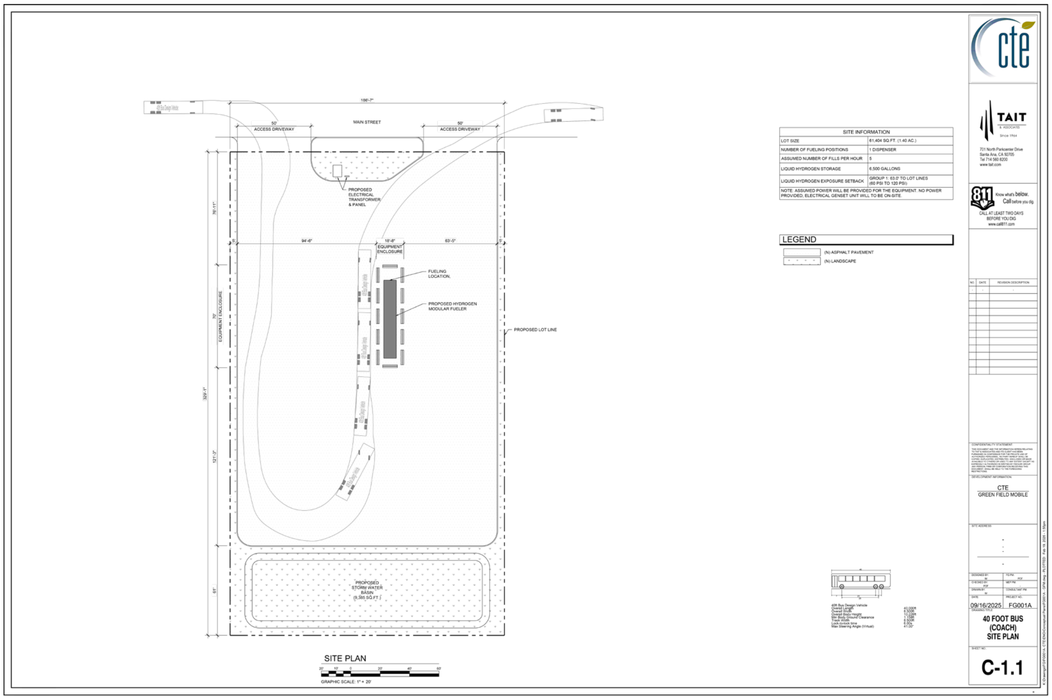

Figure 34 – Portable LH_2 with Dispenser

Figure 35 is a compressed gas station with two “drop and swap” trailer parking slots (one for the trailer in use and the other reserved for the replacement trailer). A gas compressor, high-pressure storage bank of tubes (450 to 520 bar), and a single dispenser are located immediately adjacent to the trailer compound.

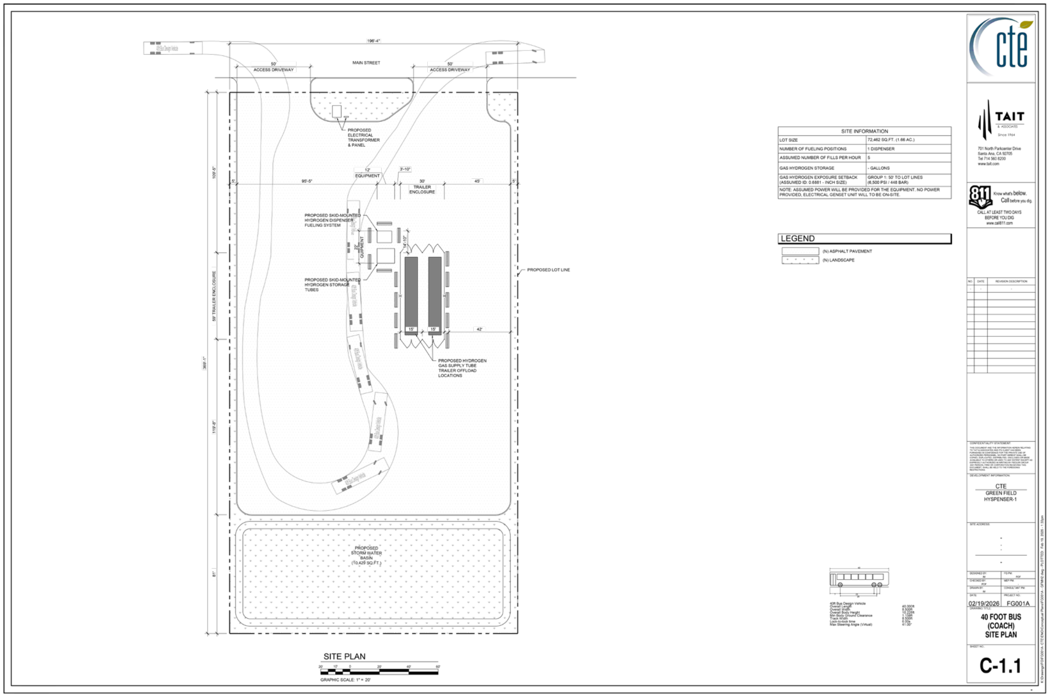

Figure 35 – GH_2 with Dispenser, Compressor, and High-Pressure Gas Storage

Appendix:

Consolidated Readiness Checklist

This appendix compiles all readiness checklist items from each step of **Tool 2: Step-by-Step Framework for ZEB Deployment** into a single, consolidated list. The checklist is intended to provide agencies with key considerations across the full ZEB deployment lifecycle from early planning and procurement through infrastructure development, workforce training, and ongoing operations. The checklist outlines tasks that should be completed by the end of each step before moving on to the next step.

While the framework is presented as a step-by-step process, in practice, ZEB deployment is often iterative. Agencies may revisit earlier steps as agency goals, project scopes, or external conditions change (e.g., funding, policy, or technology advancements). Therefore, this checklist is designed to be flexible, and agencies can begin at Step 1 or focus on specific steps based on their current stage of deployment.

For example, an agency that has already developed a detailed ZEB transition plan and achieved internal alignment on fleet, infrastructure, and funding strategies may be well-positioned to move directly into later stages, such as procurement or deployment. In this case, the agency can use the checklist to validate readiness for those phases while revisiting earlier steps, as needed.

Overall, this consolidated checklist serves as both a quick-reference tool and a gap assessment resource, helping agencies track their progress and ensure a coordinated approach to ZEB implementation.

Step 1: Evaluate Agency Motivations

- ☐ Agency's zero-emission goals are documented
- ☐ Board and executive priorities are understood and aligned
- ☐ Applicable regulations and legislative requirements are defined
- ☐ Key stakeholders have been identified

Step 2: ZEB Education and Agency Stakeholder Engagement

- ☐ Current fleet composition and service information are documented and up to date
- ☐ Knowledge gaps have been identified
- ☐ A plan to address knowledge gaps has been created

- ☐ ZEB basics and the differences between ICE buses, BEBs and FCEBs are understood across staff levels
- ☐ Key questions and concerns from internal stakeholders have been documented
- ☐ Strategies to address key questions and concerns have been identified
- ☐ Vehicle and infrastructure solution options have been reviewed
- ☐ Peer agency sites where ZEBs are operating have been visited
- ☐ Agency's internal capabilities for executing ZEB deployment are understood
- ☐ Agency has developed a plan to hire or contract for additional support as needed

Step 3: Planning Your Transition and Deployment

- ☐ A formal transition plan has been created
- ☐ Regulatory timelines have been included in long-term planning
- ☐ Feasible ZEB technology options have been determined based on operational and facility considerations
- ☐ Initial meetings with the utility provider have been conducted
- ☐ Pilot projects, phased deployments, or mixed fleets have been considered
- ☐ High-level fueling, charging, and facility needs have been evaluated
- ☐ Preliminary maintenance and workforce impacts have been identified
- ☐ Initial cost considerations and funding opportunities have been reviewed
- ☐ Safety and emergency response plans have been identified
- ☐ Board and executive approval to pursue the proposed ZEB transition plan and deployment approach have been received
- ☐ Projected timelines to deploy buses and infrastructure are feasible and coordinated to ensure fuel supply is readily available to operate buses

Step 4a: Bus Procurement and Build

- ☐ Procurement strategy and contracting mechanisms for vehicles have been defined and approved, and carried through to vendor selection and issued purchase order
- ☐ Roles and responsibilities for design, construction, commissioning, and performance testing have been clearly assigned for buses and infrastructure
- ☐ Scope and performance requirements have been clearly defined
    - o Warranties address fuel cell and battery performance guarantees
- ☐ Bus delivery timelines align with planned construction and commissioning of fueling infrastructure
- ☐ Contracts for vehicles have been executed or authorized and define the testing protocols that will be used to verify performance expectations are met prior to acceptance

Step 4b: Infrastructure Procurement, Design, and Build

Infrastructure Procurement

- ☐ Procurement strategy and contracting mechanisms for infrastructure have been defined and approved, and carried through to vendor selection and issued purchase order
- ☐ Vehicle procurement and infrastructure timelines are aligned
- ☐ Fueling process and partners have been determined
- ☐ Utility coordination is on-going and any needed service upgrade timelines have been confirmed
- ☐ Warranties and performance expectations for infrastructure components have been clearly defined
- ☐ Contracts for infrastructure elements have been executed or authorized and define testing protocols that will be used to verify performance expectations are met prior to acceptance

Infrastructure Design

- ☐ Fueling station and facility designs (30%, 60%, 90%, 100% design completion milestones) have been received and reviewed by all stakeholders
- ☐ Facility space limitations have been analyzed
- ☐ Facility modification needs have been documented and planned for
- ☐ Construction timelines have been received

Station Build

- ☐ All required permits have been secured
- ☐ Infrastructure has been installed and commissioned
- ☐ Additional equipment needs for daily operations and maintenance (overhead levers or gantry cranes to remove overhead components, scaffolding, fall protection, defueling equipment, etc.) have been considered

Safety Considerations

- ☐ Safety systems have been installed
- ☐ Emergency response plans have been updated (including establishing who needs to be notified, the type of response expected, and communication protocols)

Step 5: Preparing for Service (Commissioning, Acceptance and Validation Testing, Workforce Development, Safety, and Emergency Preparedness)

Commissioning

- ☐ Commissioning plans have been documented

- ☐ All contractual requirements for vehicle and infrastructure operations have been met
- ☐ Operation of the charging or fueling infrastructure has been adequately tested and compatibility with the buses has been confirmed

Acceptance and Validation Testing

- ☐ Acceptance testing requirements are clearly defined and successfully completed to verify that vehicles and infrastructure meet all contractual performance specifications
- ☐ Validation testing has been conducted and confirms that vehicles and infrastructure perform as expected under real-world operating conditions and are aligned with planned service deployment. If results are not in line with expectations, service plans have been adjusted
- ☐ Potential deployment risks have been identified

Workforce Development, Safety, and Emergency Preparedness

- ☐ Current skills, existing certifications, and remaining skill gaps have been documented
- ☐ Staff and workforce impacts and training needs are understood
  - o Identify the staff that will need training
  - o Identify who will deliver training (prioritize securing qualified trainers)
- ☐ Available training modules from vehicle and component OEMs have been reviewed
- ☐ Local first responders have been trained and prepared for emergency events
- ☐ Familiarity with industry organizations that provide workforce development training:
  - o Automotive Service Excellence (ASE)
  - o California Transit Training Consortium (CTTC)
  - o National Transit Institute (NTI)
- ☐ A list of specialized training providers has been compiled
- ☐ Training requirements for operators, maintenance staff, supervisors, and emergency responders have been defined
- ☐ Facilities, equipment, and personal protective equipment (PPE) needed to operate and maintain ZEBs have been acquired
- ☐ OEM-provided training for vehicles and infrastructure has been scheduled or completed
- ☐ Emergency list of key individuals to contact in response to an incident has been updated
- ☐ A communication plan has been created to ensure all key individuals are in touch with one another during an emergency
- ☐ A plan to periodically reassess workforce training needs has been defined

- ☐ Periodic first-responder drills to evaluate readiness and effectiveness of ERP have been scheduled
- ☐ Staff can safely operate and maintain ZEB vehicles and infrastructure

Step 6: Deployment KPI’s and Fine-Tuning

- ☐ Organizational deployment goals and objectives are understood
- ☐ KPI tracking metrics have been defined
- ☐ Plans to collect necessary data to support KPIs are finalized
- ☐ Potential challenges (internal conflict, data access, too much data, data integrity, data interpretation issues) have been defined
- ☐ Plans to periodically review the KPIs and performance of the vehicles and equipment are defined
- ☐ Lessons learned from KPIs and early deployments have been documented and addressed
- ☐ Transition plan and future bus procurements have been updated based on KPI outcomes