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Zero-Emission Transit Bus and Refueling Technologies and Deployment Status

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16. Abstract

The Massachusetts Global Warming Solutions Act and Executive Order 569 mandate greenhouse gas reductions. In addition, in 2014, Massachusetts joined seven other states in a Multi-State Zero-Emission Vehicle Action Plan to increase those vehicles and establish appropriate refueling infrastructure. One strategy to achieving this mandate is implementation of zero-emission buses (ZEBs) in transit fleets. This report summarizes the characteristics of three ZEB technologies: 1) battery electric buses; 2) fuel cell battery electric buses; and 3) fuel cell plug-in hybrid electric buses, as well as relevant implementations in the U.S., through a comprehensive review of the available literature, an online survey of several transit agencies that have implemented or are planning to implement ZEBs, and interviews with transit agency representatives. The focus is on performance and cost characteristics of these technologies as well as implementation approaches, refueling strategies, and funding mechanisms. Challenges associated with the implementation of such vehicles and lessons learned are also summarized. Finally, the report presents in more detail three case examples of Massachusetts transit agencies that have implemented or are in the planning stages of implementing ZEBs and provides information on funding mechanisms available to Massachusetts agencies for procurement of ZEBs.

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Zero-Emission Transit Bus and Refueling Technologies and Deployment Status

Final Report

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Disclaimer

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Executive Summary

This study of Zero-Emission Transit Bus and Refueling Technologies and Deployment Status was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The Massachusetts Global Warming Solutions Act (GWSA) of 2008 requires greenhouse gas (GHG) emissions reductions from all sectors of the economy to reach a 25% reduction by 2020, and at least 80% by 2050 (using the 1990 emissions level as the baseline). As the Commonwealth's transportation sector emits more GHGs than any other sector (road, rail, air, and marine transportation released 39% of the Commonwealth's GHG pollution in 2014), the Massachusetts Department of Environmental Protection enacted the GWSA for the Transportation Section (310 CMR 60.05) in 2015. This regulation requires MassDOT to track and regulate GHG emissions. Decarbonizing the transportation sector is one approach to achieving the 80% GHG emissions reduction goal and will yield benefits to the environment and public health.

Deploying zero-emission transit buses (ZEBs)[a] is one approach to decarbonize the transportation sector. In an effort to reduce GHG emissions and advance sustainable transportation technology, Massachusetts joined the Zero-Emission Vehicle Program in May 2014. This program, which includes seven other states (California, Connecticut, Maryland, New York, Oregon, Rhode Island, and Vermont), aims to implement a plan that would deploy 3.3 million zero-emission vehicles across the U.S. by 2025. Transit bus systems present an ideal approach for the introduction of zero-emission vehicle technology.

This report presents and compares the characteristics of three ZEB technologies: 1) battery electric buses; 2) fuel cell battery electric buses; and 3) fuel cell plug-in hybrid electric buses. This report presents a discussion of the relevant implementations of these types of technologies across the U.S. through a comprehensive review of the available literature, an online survey of several transit agencies that have implemented or are planning to implement ZEBs, and interviews with transit agency representatives and other relevant stakeholders. This synthesis focuses on in-service performance/cost, infrastructure needs, implementation approaches, fueling strategies, and funding mechanisms of transit ZEBs. In addition, it documents the challenges and lessons learned from agencies that have already implemented or are in the planning stages of implementing ZEBs. Finally, this report highlights four case examples from Massachusetts transit agencies that have implemented or plan to implement ZEBs, to better inform MassDOT of the current ZEB landscape across the state.

[a] Zero-emission vehicles are defined as vehicles that release no tailpipe (tank-to-wheel) emissions; atmospheric pollutants emitted during the production of electricity used to power these vehicles are considered independently.

Battery Electric Buses

Battery electric buses are the most mature technology and currently the most popular zero-emission bus choice by transit agencies. The prevalence of this bus design has been motivated by the excellent fuel economy when compared with the fuel cell technologies and cost. Battery electric buses have an onboard battery system that is operated using solely electric power.

There are more than 70 battery electric bus implementations currently active across the U.S. Battery electric bus manufacturers in the U.S. include *Proterra, Build Your Dreams*, *Complete Coach Works*, and *New Flyer.*

The buses are configured with batteries specific to the chosen charging strategy. The three types of charging for this type of bus are plug-in, conductive, and inductive charging. Plug-in charging usually occurs at the depot and takes a few hours, while high-power conductive and inductive charging are most frequently used on-route and take only a few minutes because of their higher charging power. Driving ranges for battery electric buses have been reported to be 49–350 miles (79–563 km), depending on the charging type and energy storage options. The highest range achieved recently with advancements in battery technology is the highest reported for any ZEB. However, shorter ranges compared to conventional buses that are reality for many battery electric bus implementations need to be taken into account for route assignment and scheduling planning, as well as charging infrastructure decisions. For buses that are to be charged on-route, they can only be deployed on routes that have been electrified and enough chargers must be built to ensure that the distance between chargers does not exceed the range of each charge. Similarly, for buses that are to be charged at the depot, the length of the bus block cannot exceed the range of the bus. In either case, calculations must factor in the use of air conditioner or heater, both of which reduce the effective range.

The fuel economy for a battery electric bus ranges from about 8 to 29 mpdge, making them at least two times more fuel efficient than conventional diesel buses. The procurement cost for battery electric buses ranges considerably ($537,000-$950,000), depending on battery size and charging infrastructure, but is at least twice as high as that of conventional diesel buses. Improvements in battery technology are expected to decrease capital costs of the bus design and further extend driving range. The operating and maintenance costs for battery electric buses are either comparable to or lower than those of conventional diesel buses.

To date, the main challenges reported for this bus are the range and the consequent needs to coordinate charging infrastructure decisions with route assignment and scheduling. However, the limited range that has existed for battery electric buses is being addressed with newer bus models that allow for longer ranges, ranges that are comparable to those of conventional buses.

Fuel Cell Buses

Fuel cell battery electric buses are supplied with a fuel cell that receives hydrogen fuel and produces electricity, which in turn is used to power the vehicle. The most popular design and the one mostly discussed in this report incorporates a storage platform (batteries, super-capacitors, or both) to capture excess energy into the powertrain and is referred to as "fuel cell buses" for the rest of the report. Fuel cell buses offer performance characteristics that are comparable to traditional buses with respect to range, speed, and grades, making them an attractive option for agencies.

There have been a total of 15 hydrogen fuel cell bus implementations in the U.S., with 7 being currently active. Fuel cell buses have been manufactured by *Van Hool*, *New Flyer*, and *ElDorado*; the fuel cells themselves have been manufactured by *Ballard Power Systems* and *United Technology Incorporation Power*; and integrators that have been used are from *ISE Corporation* and *BAE Systems*.

The hydrogen fuel can be produced onsite at the bus depot or offsite and then delivered to a hydrogen storage facility at the bus depot using either electrolysis or steam methane reforming process. Each method has advantages that vary by geographical location of the transit bus fleet and by the relative size of the fueling station or network of stations. Accordingly, the price of hydrogen fuel varies from $4.52/kg to $12.99/kg, which translates to operating costs of $1.10–$2.62/mile, which is higher than that of conventional diesel and compressed natural gas (CNG) buses.

The driving range for this type of bus is between 200 and 325 miles (322 and 523 km), which is comparable to conventional buses and requires them to refuel usually only once a day. However, since this is a relatively new source of fuel that cities or towns may not be fully comfortable with, route assignments for these types of buses are limited by the need for approvals from cities or towns whose routes the bus will be passing through, due to strict safety regulations since hydrogen is highly flammable.

In terms of performance, owing to the battery component, fuel cell buses have almost higher fuel economy compared to conventional diesel and CNG buses (4.53–11.5 mpdge compared to 3.11–4.28 mpg). Regarding procurement costs, recent implementations report that fuel cell buses cost about $1.8 million, almost double that of battery electric buses. Maintenance (scheduled and unscheduled) costs ($0.39–$1.70/mile) are comparable to those of conventional diesel and CNG buses.

The major stumbling blocks in transit agency implementation of this bus design are the bus capital cost, the hydrogen fueling infrastructure requirements, and the hydrogen fuel cost itself. However, capital and hydrogen fuel costs are projected to decrease over the next few years.

Fuel Cell Hybrid Plug-in Buses

Fuel cell hybrid plug-in electric buses are the newest and least common type of zero-emission transit buses. This type of bus couples two different technologies by using power supplied from the grid via a plug-in charger and simultaneously using a fuel cell to maximize efficiency of usage.

There has been a total of seven demonstrations in the U.S., with two being currently active. Infrastructure requirements for fuel cell hybrid plug-in buses are the same as the previous two bus types. Fuel cell hybrid plug-in buses have been manufactured by *Proterra*, *EVAmerica*, and *Ebus*, while the fuel cells themselves have been manufactured by *Ballard Power Systems* and *Hydrogenics*.

Preliminary short-term demonstrations of fuel cell hybrid plug-in buses suggest an improved fuel economy (7.1–7.9 mpdge) as compared to fuel cell buses, but a reduced one compared to that of battery electric buses. Limited information is available on cost of procurement, infrastructure, and maintenance, since these buses have been mainly short-term demonstrations. One implementation reported operating costs of $1.38/mile for a Proterra model, which is similar to fuel cell buses.

Challenges with these buses relate to the high costs required to implement a bus fleet of this type of technology (capital costs of bus, fueling infrastructure, and fuel itself).

Massachusetts Implementations

In Massachusetts, there are currently three active ZEB implementations. Two agencies operate battery electric buses: the Pioneer Valley Transit Authority (three buses) and the Worcester Regional Transit Authority (six buses). The Massachusetts Bay Transit Authority (MBTA) currently operates one fuel cell bus.

The WRTA currently operates 6 battery electric buses among its fleet of 52 buses, which harbors a combination of conventional diesel and diesel electric hybrid buses. This was possible with grants from FTA's Clean Fuel Program and Section 5307 Formula Funds. Five of their six battery electric buses are Proterra's EcoRide BE35, while one is Proterra's Catalyst FC. The buses are charged using an in-depot charger, as well as two overhead chargers.

The PVTA currently operates 3 battery electric buses among its fleet of 186 buses that comprises diesel and diesel electric hybrid buses. The three Proterra Catalyst FC buses were purchased using FTA's Congestion Mitigation and Air Quality Improvement program with matching state funds. Two on-route chargers and one in-depot charger are used to charge the buses.

The MBTA is the only agency in Massachusetts that is operating a fuel cell bus. Other types of buses include conventional diesel, compressed natural gas, and diesel electric hybrid buses. Using a grant from FTA's National Fuel Cell Bus Program, MBTA deployed an

ElDorado National Axess hydrogen fuel cell bus and one hydrogen fueling station. Following an award from FTA's LoNo grant, MBTA purchased five Xcelsior battery electric buses made by the company New Flyer that will be charged using an in-depot charger. MBTA anticipates the delivery of the battery electric buses in 2018.

Martha's Vineyard Transit Authority (VTA) is another transit agency that is adding battery electric buses to its current fleet in the hope to soon fully replace its existing fleet of diesel buses. Using the Capital Investment Plan grant from Massachusetts Department of Transportation (MassDOT), VTA purchased four battery electric buses. The four buses are manufactured by Build Your Dreams (BYD) and are of two models: BYD K7 and BYD K9. Both models will be charged using the in-depot charging method. VTA has also been awarded FTA's LoNo grant to be used for the differential cost between diesel and electric buses, allowing the VTA to purchase two additional electric buses (expected delivery June 2018).

Funding Mechanisms

Several grant programs from U.S. governmental agencies have supported ZEB initiatives by transit agencies. For battery electric buses, most of the implementations have been funded through programs such as Transportation Investment Generating Economic Recovery (TIGER), Transit Investment for Greenhouse Gas and Energy Reduction (TIGGER), and Low or No-Emissions Vehicle (LoNo) programs. Additional funding sources have also been available, such as the Capital Investment Grant, State of Good Repair Grant, Small Starts Grant, Livability Grant, Clean Fuels Grant, and Section 5307 formula funds. The main source of funding for fuel cell buses and fuel cell plug-in buses has been the FTA's National Fuel Cell Bus Program (NFCBP). Funding mechanisms for fuel cell bus implementations and demonstrations also include LoNo and TIGGER. Other funding sources include local funding, tax dollars, and other federal and state funding. Fuel cell hybrid plug-in electric bus demonstrations have primarily been funded by the bus manufacturer Proterra.

Lessons Learned

Across the transit agencies that implemented or demonstrated zero-emission transit buses, most were found to have had a positive experience from the implementation of zero-emission buses. Based on the experiences of these transit agencies, the main takeaways for the success of zero-emission bus implementations relate to: 1) fleet size: starting with a few buses rather than with a large fleet; 2) the choice of technology: understanding the technology and properly choosing the one that matches the needs, conditions, and limitations of a transit agency and service area; 3) staff training: proper training for a suitable amount of time of drivers and maintenance personnel while enabling information exchange between stakeholders for troubleshooting purposes; and 4) stakeholder collaboration: having an effective level of collaboration, cooperation, and support (both monetary and nonmonetary) between stakeholders.

Additional considerations associated with the specific bus technologies include the following.

Battery Electric Buses:

- *Charging* considerations as they pertain to the number of chargers required, as well as their capacity and location in combination with route assignment and scheduling decisions to ensure sufficient range. In addition, demand charged need to be take into consideration when deciding the type of charging method.
- *Costs* related to electricity and the need to establish an active partnership with electrical companies has been reported. In addition, actions to ensure enough capital funding from the beginning of the project and incorporate monitoring systems to maintain batteries and reduce maintenance costs.

Fuel Cell Buses:

- *Route assignment and scheduling* considerations due to the more stringent safety regulations that dictate permits to get the bus "road certified."
- *High cost infrastructure requirements* to accommodate the hydrogen fueling and/or production facilities that often have a large footprint.
- F*ueling and hydrogen storage* need to be carefully designed to ensure enough range for the buses without imposing excess weight (from a bigger battery) that could reduce passenger capacity. In addition, fuel supply should be properly matched with demand.
- *Technology* of fuel cells needs to be improved to allow for longer lifetimes that are comparable to those of the bus itself.
- M*aintenance issues* have led to recommendations on developing guidelines on maintenance practices as well as creating inventories and improving the supply chain of fuel cells across the country.

Fuel Cell Hybrid Plug-In Buses

- *Technological* challenges associated with the battery and fuel cell components have been highlighted as with the other two bus technologies as well as challenges associated with the integration of multiple new technologies.
- *Maintenance* issues have been common given the fact that this technology is still at its early stages of testing and implementation. Therefore, the development of maintenance manuals has been recommended.
- *Costs* are still high for this type of bus technology but there are expectations that standardization and manufacturing processes will reduce them. It is also recommended that spare parts are stored for maintenance when fleets of these buses are big enough to justify the financial investment.

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List of Acronyms

Acronym	Expansion
AC	Alternating current
AC Transit	Alameda-Contra Costa Transit
AT	Advanced Technology
AFCB	American Fuel Cell Bus
BAAQMD	Bay Area Air Quality Management District
BC Transit	British Columbia Transit
BJCTA	Birmingham-Jefferson County Transit Authority
CARB	California Air Resources Board
CapMetro	Capital Metropolitan Transportation Authority
CATbus	Clemson Area Transit
CMAQ	Congestion and Mitigation and Air Quality Improvement
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
COMET	Central Midlands Regional Transit Authority
CTE	Center for Transportation and the Environment
CTTRANSIT	Connecticut Transit
DOE	Department of Energy
DOT	Department of Transportation
FHWA	Federal Highway Administration
Flint MTA	Flint Mass Transportation Authority
FTA	Federal Transit Administration
GHGs	Greenhouse gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWSA	Global Warming Solutions Act
IndyGo	Indianapolis Public Transportation Corporation
kW	Kilowatt
kWh	Kilowatt-hour
LACMTA	Los Angeles County Metropolitan Transportation Authority
LEM	Lifecycle Emissions Model
Lextran	Transit Authority of Lexington, Kentucky
Li-ion	Lithium-ion
LoNo	Low or No-Emissions
MassDEP	Massachusetts Department of Environmental Protection
MassDOT	Massachusetts Department of Transportation
MBRC	Miles between road calls
MBTA	Massachusetts Bay Transportation Authority
mpdge	Miles per diesel gallon equivalent
mpg	Miles per gallon

Acronym	Expansion
MTD	Santa Barbara Metropolitan Transit District
MWh	Megawatt-hour
NO_x	Nitrogen oxides
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
OCTA	Orange County Transportation Authority
OEM	Original equipment manufacturer
PVTA	Pioneer Valley Transit Authority
Santa Clara VTA	Santa Clara Valley Transportation Authority
SARTA	Stark Area Regional Transit Authority
SPR	State Planning and Research
TIGGER	Transit Investment for Greenhouse Gas and Energy Reduction
TIGER	Transportation Investment Generating Economic Recovery
TRL	Technology readiness level
UC Davis	University of California, Davis
UCI	University of California, Irvine
UCLA	University of California, Los Angeles
UMass	University of Massachusetts Amherst
UTC Power	United Technology Corporation Power
VTA	Martha’s Vineyard Transit Authority
WRTA	Worcester Regional Transit Authority
ZEB	Zero-emission bus
ZEBA	Zero-Emission Bay Area
ZERO	Zero-Emission Research Opportunity

1.0 Introduction

This study of Zero-Emission Transit Bus and Refueling Technologies and Deployment Status was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

In 1990, the Environmental Protection Agency made amendments to the Clean Air Act to set National Air Quality Standards (40 CFR part 50)[1] for pollutants that are considered harmful to public health. Most public transit buses emit greenhouse gases (GHGs) and criteria air pollutants, including carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter. Adverse health effects have been found to be associated with increased levels of air pollutants.

Many governmental organizations have recognized the magnitude of the problem of air pollution and have initiated programs to fund efforts for reducing air pollutants, particularly the ones generated by vehicle fleets.

At the state level, the Massachusetts Global Warming Solutions Act (GWSA) and Executive Order 569 mandate GHG reductions in the state and commit the state to expand its efforts to reduce GHGs from the transportation sector, starting with government operations[2]. Directed by Executive Order 569, the Massachusetts Department of Environmental Protection (MassDEP) published the 310 CMR 60.05 Global Warming Solutions Act Requirements for Transportation regulation[3]. This regulation requires the Massachusetts Department of Transportation (MassDOT) to take action to meet enforceable limits on carbon dioxide emissions (CO_2) emitted from MassDOT and Massachusetts Bay Transit Authority (MBTA) vehicles and heating fuels at their facilities. Finally, since May 2014, Massachusetts has joined seven other states (California, Connecticut, Maryland, New York, Oregon, Rhode Island and Vermont) in the Zero-Emission Vehicle Program that aims to implement a plan that would deploy 3.3 million zero-emission vehicles across the U.S. by 2025[4].

The Commonwealth's transportation sector emits more GHGs than any other sector. According to the MassDEP, gasoline and diesel fuel burned for road, rail, air, and marine transportation released 39% of the Commonwealth's GHG pollution in 2014[5].

Deploying zero-emission transit buses (ZEBs) could be one of the important approaches to decarbonizing the transportation sector and reducing conventional air pollution from urban mobile sources. Transit fleets are a big part of the state fleet and can provide an extensive blueprint for testing and refining new technologies while utilizing the benefits of being a large-scale model for fueling and management strategies.

In addition, the U.S. Department of Transportation Federal Transit Administration (FTA), and Department of Energy (DOE) have partnered with transit agencies through funding programs to accomplish goals for reducing GHG emissions. There are currently several transit agencies seeking to implement a full zero-emission fleet whose specifics are reviewed in this report. Since 2009, transit agencies have reported 1,590 fewer tons of CO_2 emissions in part from implementation of federally funded zero-emission buses[6].

Three zero-emission bus technologies are reviewed:

- **Battery electric**
- **Fuel cell**
- **Fuel cell hybrid plug-in**

This report considers three zero-emission bus technologies that have been implemented by transit agencies in the U.S.: battery electric, fuel cell, and fuel cell hybrid plug-in buses. This comprehensive review of transit agency implementations includes information on implementation strategies, funding mechanisms, stakeholders, fueling strategies, in-service performance, maintenance, and cost for transit agencies. The primary focus was placed on the U.S. to enable state comparisons with Massachusetts and to isolate differences that could be present due to differences in policies and legislation applicable to other countries. Finally, more detailed descriptions are presented for three case examples of Massachusetts transit agencies that have implemented or plan to implement zero-emission buses in their fleet. The report concludes with lessons learned and funding mechanisms available to the Commonwealth for procurement and implementation of such bus technologies that are aimed at assisting the Commonwealth with decision making and planning for zero-emission bus implementations.

1.1 Zero-Emission Bus Implementations by Transit Agencies in the U.S.

Currently, more than 70 transit service providers are operating zero-emission buses in their fleet; the majority are battery electric bus implementations.

Motivated by their desire to reduce their carbon emissions and available funding programs, more than 70 transit agencies have introduced zero-emission transit buses into their fleets. In total, three types of zero-emission technologies have been launched in U.S. transit service providers: battery electric buses, fuel cell buses and fuel cell plug-in hybrid buses. All the transit agencies that are currently operating zero-emission buses or are in the process of introducing them in their fleets are presented in Figure 1.1. A complete list of all these transit agencies by state is presented in Appendix A, Table A.1. Across the U.S., more than 70 transit service providers are currently operating zero-emission buses in their fleet[7]. California has been the most active state and also the first one to consider converting its fleets to zero-emission. Moreover, it is the only state where all three technologies have been tested. Since 2010, there have not been any new fuel cell bus implementations, and currently there is only two active fuel cell hybrid plug-in bus implementation.

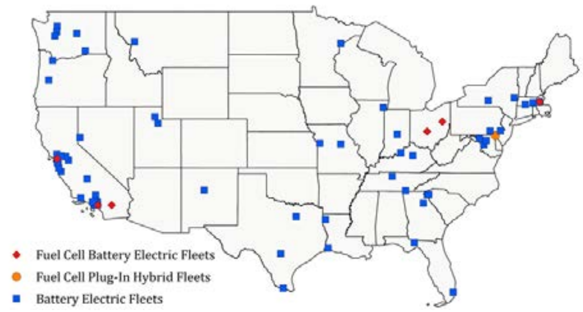

Figure 1.1: Overview of U.S. transit agencies currently operating or having proposed plans to incorporate ZEBs in their fleet

Most past, current, and future (i.e., proposed) implementations are battery electric buses, followed by fuel cell buses. Overall, there have been only seven fuel cell hybrid plug-in demonstrations in the U.S., with only two of them currently active. Other than the total number of implementations, battery electric fleets tend to be higher in number compared to fuel cell bus implementations. Foothill Transit, Stanford University, Santa Barbara Metropolitan Transit District (MTD), and Clemson Transit have the largest battery electric bus fleets. Alameda-Contra Costa County Transit (AC Transit), Stark Area Regional Transit Authority (SARTA), and SunLine Transit operate the highest number of fuel cell buses in their fleet. Fuel cell hybrid plug-in buses have been operated by a limited number of agencies. The University of Delaware and a short demonstration for Mass Transportation Authority in Flint, Michigan, are the only active implementations of this bus type as of December 2016; all the other agencies have demonstrated only one bus for a short period of time. None of these agencies indicated any intention of continuing operations beyond the demonstration period.

Since many of the transit agencies have recently started operating zero-emission buses in their fleet or are still in the planning stages, there are often very limited data for them to report. The transit agency implementations for which information was available and therefore have been studied as part of this project are presented in Appendix A, Tables A.2–A.4. Additionally, their general characteristics in terms of area of service, population, annual ridership, type of area, and its topography are provided in Appendix A, Tables A.5–A.7, for battery electric buses, fuel cell buses, and fuel cell hybrid plug-in buses, respectively. Among current implementations, several universities and transit agencies with different characteristics in terms of size have considered adding zero-emission buses to their fleets.

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2.0 Research Methodology

The research methodology consists of three components: 1) a comprehensive review of published literature to identify characteristics of zero-emission bus technologies and their implementations in the U.S., such as in-service performance and cost, implementation and fueling strategies, and funding mechanisms; 2) an online survey targeted mostly at transit agencies that have already implemented zero-emission buses to collect the specifics of those implementations, such as in-service performance and cost, implementation and fueling strategies, and funding mechanisms; and 3) interviews with transit agency representatives and other stakeholders who have been involved in zero-emission bus implementations to better understand the challenges associated with those implementations, as well as lessons learned.

2.1 Literature Review

An extensive literature review was conducted, aimed at collecting information on zero-emission bus implementations in the U.S. The two main sources utilized were scientific journal papers and published reports from transit agencies and federal organizations.

As for the scientific literature review, the focus was on U.S. cases, since this is the area of interest. Cost-, emissions-, and energy-related information was derived from U.S. studies, while for technology-specific information, studies from other parts of the world were also utilized. For example, the infrastructure and vehicle procurement costs are tightly related with the location of the transit agency and the specific market. On the other hand, technological characteristics such as a battery's efficiency or a fuel cell's operation remain constant and are independent from the location where they operate. Moreover, U.S.-specific research was not always sufficient to provide all the needed information. Scientific literature was the main source of emissions, energy, and noise reduction information.

Publicly available reports published by federal organizations, research institutes, transit agencies, and manufacturing companies provided the main body of information about zero-emission transit buses across the U.S. In this study, the weight of these sources is greater than the scientific literature, since the former concentrates on real-world data. In reports from transit agencies, there have been efforts summarizing the challenges and lessons learned during the implementations. Specifically, FTA and the National Renewable Energy Laboratory (NREL) have been actively monitoring and reporting the results of many zero-emission implementations. These reports make up the basis for acquiring information related to cost and performance measures, funding mechanisms, and involved stakeholders. Furthermore, bus and equipment manufacturing companies (e.g., Proterra, New Flyer, Van Hool, and Ballard Systems) have published reports about their progress and achievements in zero-emission buses. They stand as an important source of technology-related information about the buses and their components.

2.2 Survey Instrument

A concise survey instrument targeting U.S. transit agency representatives was developed following a systematic review of the literature and transit agencies of the zero-emission transit bus technologies. The complete survey is available in Appendix B. Using a survey instrument allowed for the collection of information that may not have been readily available through published reports or peer-reviewed articles. While the funding mechanisms, refueling technologies, energy use, and fuel economy are well documented for most implementations, other information is incomplete. The overall aim of the survey instrument was to obtain details on all the following:

- Drivers/reasons behind the deployments
- Funding mechanisms
- Project implementation partnerships and strategies
- Typical route assignments and driving cycles
- In-service performance such as bus use and availability, road calls, and cold-climate performance (if applicable)
- Refueling technologies, energy use, and fuel economy
- Methods for estimating emission savings
- Cost analysis
- Challenges encountered and lessons learned

The survey instrument was developed and conducted using Qualtrics, a software that enables online data collection and analysis. The survey instrument was divided into three sections (Section A: General Information; Section B: Technology-Related Information; and Section C: Overall Experience) relating to the implementation, demonstration, or proposition of zero-emission buses. Questions from Section A targeted general, monetary, fleet, and operational information. Section B was specific to the type of zero-emission technology used and was divided into three modules (Module I: Battery Electric Buses; Module II: Hydrogen Fuel Cell Buses; and Module III: Fuel Cell Hybrid Plug-In Electric Buses). The transit agencies were shown the module that was relevant to the specific zero-emission technology used in their service area. Section C contained open-ended questions aimed to understand the overall experience of the interviewed individuals with respect to the drivers of the project, the reasoning behind certain technology and other choices, the challenges faced, and other qualitative information. The answers to those questions were collected in phone interviews, as will be described in Section 2.3.

The University of Massachusetts Amherst (UMass) research team reached out to dozens of contacts from transit agencies, of which representatives from eight organizations filled out the survey in its entirety: 1) Worcester Regional Transit Authority (WRTA), 2) Santa Barbara Metropolitan Transit District (MTD), 3) Stanford University, 4) Indianapolis Public Transportation Corporation (IndyGo), 5) Pioneer Valley Transit Authority (PVTA) of Western Massachusetts (Springfield Area Transit), 6) University of California, Irvine (UCI), 7) Los Angeles County Metropolitan Transportation Authority, and 8) Stark Area Regional Transit Authority (SARTA). Partial responses from the University of Delaware, Carnegie

Mellon University, University of Central Florida, Clemson Area Transit (CATbus), and Transit Authority of Lexington, Kentucky (Lextran) were also provided.

2.3 Phone Interviews

22 phone interviews were conducted with transit agencies, university transit service providers, and other stakeholders that have been involved in zero-emission bus implementations.

To collect more data on the personal experiences of organizations and their expertise on the subject matter, short phone interviews were conducted. The organizations were provided with a list of the questions ahead of time. In total, 22 phone interviews were conducted. The names and organizations of the individuals who were interviewed are listed in Appendix B, Table B.1. The list of interviewed organizations included 13 transit agencies, 4 universities, and 5 other organizations. The other organizations were NUVERA (who worked with MBTA on their hydrogen fuel cell bus implementation), the Center for Transportation and the Environment (CTE), the California Air Resources Board (CARB), and NREL.

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3.0 Results

This chapter presents an overview of information collected from the literature review, the online survey, and the interviews. The sections are divided by type of bus technology: 1) battery electric; 2) fuel cell; and 3) fuel cell hybrid plug-in buses. For all three technologies, details regarding the charging or refueling specifications and infrastructure, manufacturers of the buses and of other related supplies, typical route and scheduling assignments, bus performance, overall costs related to the buses, previous funding mechanisms, stakeholders, and the challenges faced with this technology are discussed.

The main drivers for initiating a zero-emission bus implementation, regardless of the type of technology, have overwhelmingly centered on a few key points including: 1) improving the quality of the air and reducing carbon footprints by switching away from diesel engine propulsion technology; 2) stricter state regulatory measures to reduce emissions from state vehicles; 3) long-term economic benefits to transit agencies by decreasing the lifetime ownership costs of the buses and reducing their exposure to fluctuating diesel prices; and 4) the availability of local, state, or federal funding toward zero-emission buses.

3.1 Battery Electric Buses

More than 70 battery electric bus implementations are currently active in the U.S., with two of them in Massachusetts: Worcester Regional Transit Authority and Pioneer Valley Transit Authority. Two more implementations are currently in process for Martha's Vineyard Transit Authority and Massachusetts Bay Transit Authority.

Battery electric buses have an onboard battery system that is operated using solely electric power. While this bus technology generates no tailpipe emissions, generation of the electricity used to charge the onboard battery is associated with atmospheric pollutant releases[8]. Unlike conventional diesel buses, battery electric buses have low energy consumption while idling in traffic and produce less noise. Additionally, they benefit from the regenerative braking energy that they capture due to stop-and-go driving conditions, making them ideal for urban areas[1]. Driving ranges for battery electric buses have been reported by manufacturers to be 49–350 miles (79–563 km), depending on the charging type and energy storage options.[9-10]

Currently, there are 582 battery electric buses being operated through more than 70 active implementations in the United States. In Massachusetts, Worcester Regional Transit Authority (WRTA) has implemented 6 battery electric buses since 2013, and Pioneer Valley

Transit Authority (PVTA) has implemented 3 battery electric buses since 2016 (see Appendix A, Table A.2). Martha's Vineyard Transit Authority (VTA) and the MBTA have plans to purchase and operate 4 and 5 battery electric buses in 2018, respectively. VTA also plans to purchase two additional ones with recent funding from the Low or No Vehicle Emissions (LoNo) Program.

3.1.1. Charging Strategies and Facilities

Battery charging is critical for the implementation of battery electric buses, since it defines the range they can travel and, therefore, their scheduling and charging infrastructure placement and cost. There are three battery-charging options that are used by existing transit agency implementations (Figure 3.1): plug-in slow charging, conductive fast charging, and inductive fast charging. Depending on the choice of the transit system for a charging strategy, the buses are configured with batteries specific to that chosen charging strategy.

Plug-in charging is typically scheduled during extended periods of non-operation time, while the battery electric buses are stationed at their home depot. Charging during the night is referred to as overnight charging. Plug-in charging occurs by physically plugging in the charger to a charging port on the battery electric bus. The charging occurs at a lower voltage (40 to 120 kW), and therefore it requires longer charging times compared to higher-voltage conductive or inductive charging. Overnight charging requires a large battery to be installed on the bus to account for the extended intervals between charge times. Battery electric buses are typically fit with a battery that can operate for a range of up to 200 miles (322 km) and be charged over a two- to four-hour period[11]. In locations with decreased overnight (off-peak) electricity costs compared to daytime usage rates, overnight charging can have cost-saving effects. A potential drawback of plug-in overnight charging is that when battery electric buses are implemented on long routes, there might be a need for buses to return to the depot during the day. As a result, additional buses might need to be purchased to cover part of the schedule while other buses are charging, which could add to the transit agency cost[12].

High-power conductive and inductive charging are most frequently used on-route. In the inductive approach, floor-mounted batteries onboard the bus are charged using a magnetic field passed through two coils. One coil plate is located on the bottom of the vehicle, and the other coil plate is embedded in the pavement at bus stops. The conductive charging method requires a physical connection between the charger and the battery on the bus and tends to be slightly more efficient than inductive charging. Both these charging options use higher power compared to plug-in charging, to allow for short charging times. Therefore, they occur on-route during short layovers at certain stops. As a result, these charging approaches are not suitable for long-distance operations without large-scale retrofits to roads along transit routes. Conductive charging uses a power of, on average, 250 kW across bus manufacturers, allowing for a range of 20 to 30 miles (32 to 48 km) on a 5- to 10-minute charge. Inductive charging uses a higher charging power (400 to 500 kW), such that a 15-second charge can add 12 miles (20 km)[11]. The high charging power offered by both these charging methods enables the size of batteries in battery electric buses to be scaled down compared to the plug-in charging design. Smaller batteries have positive implications on energy consumption and emissions. Facilities for conductive and inductive charging of battery electric buses can be costly because of the need to provide higher power in a short period of time. In addition, they require higher demand for energy during operation as compared to overnight plug-in electric bus charging[8].

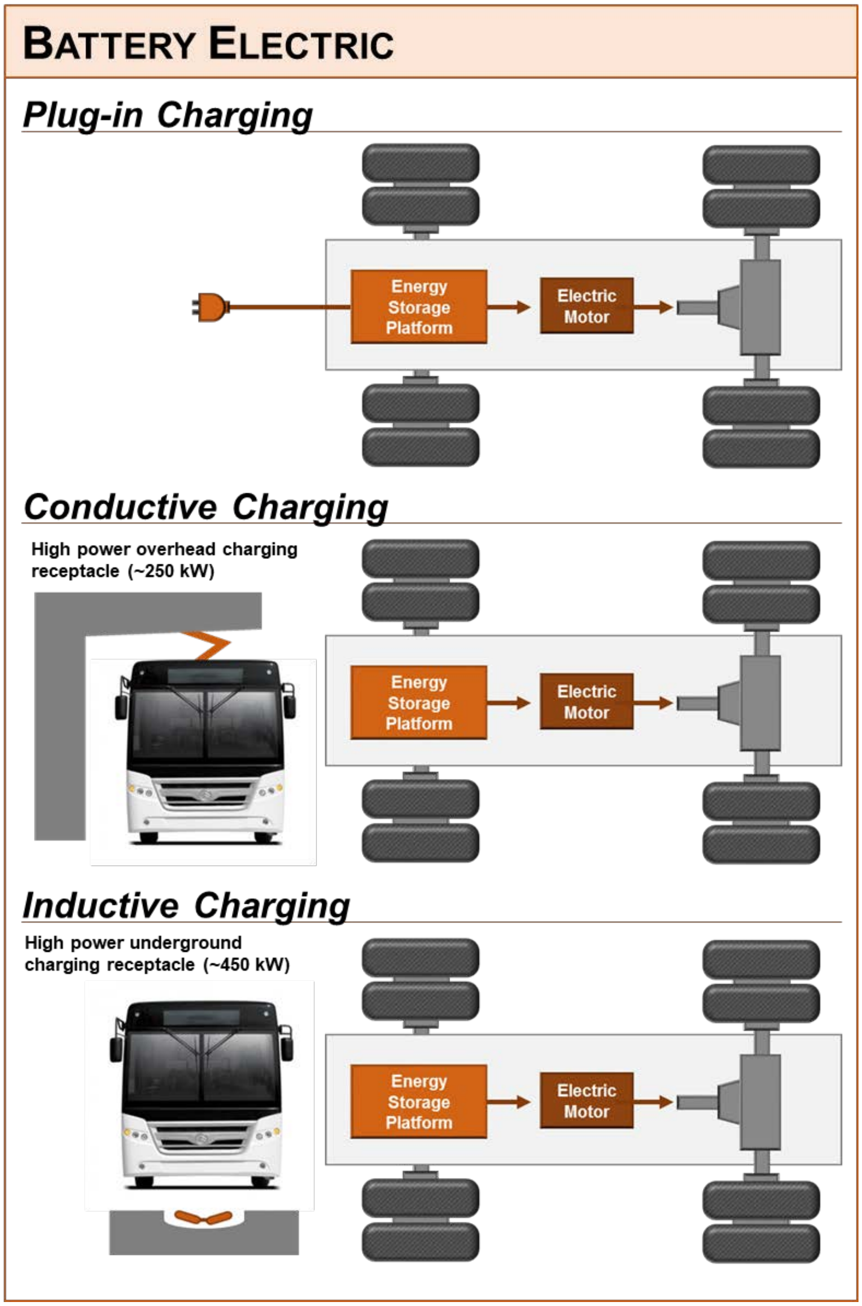

Figure 3.1: Overview of battery electric buses with various charging configurations

Charging strategies for U.S. transit agencies with battery electric technologies are summarized in Appendix C, Table C.1.

3.1.2. Bus Manufacturers and Other Suppliers

Battery electric bus manufacturers in the U.S. include Proterra, Build Your Dreams, Complete Coach Works, and New Flyer. Table C.2 in Appendix C summarizes bus manufacturer characteristics for U.S. transit agency buses for which that information was available, and this section discusses the details of the bus specifications for the various manufacturers.

Proterra is a leading manufacturer of battery electric buses in the U.S. Several agencies have implemented Proterra battery electric buses in their fleet. Proterra currently manufactures six models of battery electric buses with varying driving ranges and dimensions. Buses are available with conductive charge design (<10-minute charge time) and energy storage options ranging between 94 and 660 kWh, enabling a 55 to 350 mile (89 to 563 km) driving range[9].

Build Your Dreams currently manufactures seven models of battery electric buses with varying driving ranges and on-route charging capacities. Build Your Dreams is the only manufacturer to offer on-route inductive charging in the U.S. market. Build Your Dreams battery electric buses have been advertised to drive on a single charge for more than 155 miles (250 km)[13].

Complete Coach Works remanufactures and remodels transit buses to include current applications such as drive train upgrades and geographical information systems installation. The company rehabs diesel buses to operate using electric propulsion systems. The Compete Coach Works retrofitted electric bus has been reported to have a battery capacity of 213 to 242 kWh and a range of 85 to 115 miles on a single charge[14].

New Flyer manufactures conventional diesel as well as compressed natural gas (CNG) buses, in addition to diesel hybrid plug-in buses, trolleys, and, most recently, electric buses. The battery electric vehicles are available in 35-, 40-, and 60-foot lengths and have a lithium-ion battery-based charge range between 105 kWh and 600 kWh[10]. The buses are designed to perform for over 200 miles per single charge and have reported traveling 230 miles with the 480 kWh battery model[15]. New Flyer buses can be charged by using a plug-in or high-power conductive charging approach.

3.1.3 Typical Route Assignment/Scheduling

There are several considerations for deciding on the appropriate routes for battery electric buses, including driving range under one charge, availability of charging infrastructure and space for it, as well as the impact of charging voltage and, therefore, charging time on scheduling. The main consideration for this type of technology is the location of the charging infrastructure. If the buses are to be charged on-route, then the buses can only be deployed where the routes have been electrified and appropriate charging infrastructure is available. Enough chargers should be built on the way so that the range of the bus is not exceeded. Furthermore, charging time must be built into the schedule to prevent delays and range anxiety. Similarly, for buses that are charged at the depot, the length of the route cannot exceed the effective range of the bus, while taking into consideration the terrain and the use of an air conditioner or heater. Moreover, transit agencies tend to prefer to put battery electric buses on routes that have high visibility.

There are modeling and simulation tools available that can determine the effectiveness of buses on certain routes while inputting various terrain, weather, and operational conditions. Transit agencies have validated such models by stating that the real data matched the simulated data very well.

Table C.3 in Appendix C presents some of the available results from the survey instrument and interviews on the features of the trips that battery electric buses make. Most of the participant agencies reported that they operate their battery electric buses five days a week, and some during the whole week. The distance traveled every year by battery electric buses is between 5,300 and 40,000 miles. The routes that the buses are put on vary in length from 3 to 5 miles per trip with stops every 0.1 to 0.2 miles, to 18 miles per trip with stops every 5.3 to 8.3 miles. Overall, the number of stops varies considerably and is dependent on the specific route. There is no consensus on the distances between stops or from the first/last stop to the depot, but the battery electric bus runs (from first stop to last stop) usually take between 30 to 60 minutes.

3.1.4. In-Service Performance

Battery electric buses are at least two times more fuel efficient than conventional diesel buses.

The fuel economy for a battery electric bus ranges from about 8 to 29 mpdge, as compared to a range of 3.8 to 5.4 mpg for conventional diesel buses for the same transit agencies (see Appendix C, Table C.4).

NREL has been working with Foothill Transit in California and King County Metro in Washington to track the service performance of their battery electric implementations and periodically has reported this information (see Appendix C, Table C.5[b]). Based on the provided information, reported average speeds range from 8.4 to 10.6 mph. The monthly average mileage per bus was reported to be about 2,300 miles, and the reported availability (defined as the percentage of days the buses are available out of days that buses are planned for operation) was 84% to 98%. Lower availability was attributed to maintenance needs and issues with the electric motor[16]. Most transit agencies have a target of 85% for their fleets to have enough revenue vehicles providing services. Decreases in availability are attributed to the repair of accident damage and the air conditioning system and not due to any advanced technology component[17].

[b] Note that the types of performance measures and costs summarized in Table C.5 are the ones reported by NREL during its formal assessment of a zero-emission bus implementation.

Another metric of reliability, the miles between road calls, was found to be higher for the propulsion system (between 6,488 and 25,078 miles) and lower for the bus itself, which seemed to have most of its problems ranging from 2,433 to 9,331 miles between road calls[c].

Appropriate accounting for emissions related to the electricity generation process can be done through a lifecycle assessment approach. Lifecycle GHG emission assessment studies have found that battery electric buses are associated with 543 to 1,004 tons of carbon dioxide equivalent (CO_2-eq), as compared to 1,446 to 2,284 tons of CO_2-eq for diesel buses during their 12-year lifetime, depending on the type of model and assumptions used for the lifecycle analysis[18].

Studies on electric vehicles using the Lifecycle Emissions Model (LEM) developed by the University of California, Davis (UC Davis) show fuel cycle GHG emissions that range from 12.4 to 428 g/mile and fuel and vehicle lifecycle GHG emissions that range from 173 to 589 g/mile, depending on the source of electricity production[19]. A recent study by M. J. Bradley & Associates LLC estimated that the well-to-wheel GHG emissions specifically for conventional diesel buses (e.g., Daimler and New Flyer) have an estimated range of 1,700 to 3,900 g CO_2-eq/mile for a 20-year time horizon and 2,200 to 3,750 g CO_2-eq/mile for a 100-year time horizon, depending on the testing cycle used[20]. This study used data from the Altoona Bus Research and Testing Center's tests on those buses.

Finally, Central Contra Costa Transit Authority reported that operation of battery electric technology was expected to decrease total emissions by 154 tons of CO_2 per year and reduce annual diesel fuel purchases by 13,954 gallons[21]. Clemson Area Transit also reported that between September 2014 and March 2016, the agency avoided consumption of 60,000 gallons of diesel due to the addition of battery electric buses. This also resulted to an amount of CO_2 savings equivalent to the amount of carbon sequestered by 304 acres of U.S. forests in one year[22].

Based on the 2014 and most recent e-Grid database, the CO_2-eq emission factor for the New England region is about 577 lbs/MWh[23], and for Massachusetts the CO_2 emission factor for electricity retailers is estimated to be 654 lbs/MWh[24], with an average value for the U.S. of about 1,477 lbs/MWh[25]. These values depend on the energy source for electricity. If the energy source for charging the bus battery originates from renewables such as solar or wind, it is feasible further emission reductions could be achieved for this electric bus design.

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[c] A road call is any problem that causes the bus to stop while it is operating and cannot be resolved within the time between two routes.

3.1.5. Costs

Procurement cost for battery electric buses ranges considerably, depending on battery size and charging infrastructure, but is at least twice as high as that of conventional diesel buses. Operating and maintenance costs for battery electric buses are lower than those of conventional diesel buses.

3.1.5.1 Procurement

Battery electric bus procurement costs ranged between $537,000 and $950,000, depending on bus and battery size that is directly related to the charging infrastructure (Table C.2 in Appendix C). Note that the $350,000 cost reported by Santa Barbara Metropolitan Transit District was the cost in 2000 when it purchased those vehicles. Decreased vehicle procurement costs have been reported for the conductive charged design as compared to the plug-in overnight charged bus design because of the smaller onboard battery package[26]. In contrast, the infrastructure costs for the overnight charged bus types were significantly lower as compared to those of buses using the conductive charging approach. Other costs associated with the implementations were related to charging and retrofitting of batteries.

3.1.5.2 Infrastructure

Battery electric buses commonly have a limited driving range, and new charging infrastructure is necessary for implementation[1]. The cost of infrastructure is dependent on the type of charging mechanism, number of battery electric buses, and the location of the chargers. Overnight charging is commonly placed at a station or in maintenance facilities, but some agencies obtained separate funds specifically for charging infrastructure. None of the service providers offered information on land procurement costs for on-route stations or any bylaws that were required before charging stations were built. In general, limited information on infrastructure costs was available. Only Santa Barbara Metropolitan Transit District reported the cost for a new transformer, switchgear and charging infrastructure was $3 million.

3.1.5.3 Operations

Energy costs for battery electric bus charging vary considerably, and they depend on the utility rate and charging pattern (i.e., charging power, on-route versus depot charging, and number of vehicles charging simultaneously). The reported U.S. battery electric bus implementation electricity charges ranged from $0.07 to $0.30 per kWh and varied widely with the level of demand for the grid. Estimated energy costs for California varied from $0.11 to $0.20/kWh for depot charging and $0.15 to $0.25/kWh for on-route charging[27]. The average industrial energy rate for Massachusetts in 2016 was $0.1338/kWh (transportation sector rate was reported as $0.0594/kWh)[28]. Other studies have reported energy costs for inductive charging to be $0.29/mile ($0.18/km)[12] assuming an electricity cost of transportation of about $0.10/kWh as provided by the Energy Information Administration[29].

Energy costs for overnight charging in the U.S. have been estimated to be $0.20/mile ($0.12/km)[12].

The operating cost (i.e., fuel/energy cost) per mile for battery electric buses ($0.18 to $0.72/mile) is comparable to that of diesel buses ($0.18 to $0.90/mile). Batteries for transit buses have been seen to improve over time within several agencies. In addition, it was found that implementations that accounted for the differences between different routes and are tailored to the specific needs of each route may be less costly.

Regarding training costs, only the Los Angeles County Metropolitan Transportation Authority (LACMTA) provided a value of $100,000, which was spent prior to the implementation of its battery electric buses. In most cases, the cost of training was included in the cost of the battery electric buses reported.

3.1.5.4 Maintenance

The maintenance costs of battery electric buses are dependent on the available parts from the manufacturer and whether the warranty is enacted. Battery electric buses have extended maintenance intervals, fewer fluids, fewer moving parts (about 30% fewer), and decreased emissions[30] as compared to conventional diesel buses. Battery electric buses have regenerative braking systems, which reduce brake wear and extensive and expensive brake repair. For example, the maintenance cost per mile for battery electric buses was reported as 11% lower than that of CNG buses[17] and, on average, 80% lower than that of diesel buses[11]. When comparing between different battery electric buses, maintenance costs are reported to be on average $0.72/mile (range $0.16 to $1.00/mile) in contrast to an average of $1.34/mile for conventional buses (range $0.22 to $3.00/mile) (Appendix C, Table C.6). The range in costs is attributable to the variability in the items included in total maintenance costs across agencies.

In most cases, maintenance was done in-house. For PVTA and WRTA, one maintenance technician from the manufacturing company worked on a full-time basis for the two agencies. Several transit agencies provided maintenance of their fleet through contracts with private firms. Foothill Transit reported its maintenance labor rate as $50 per hour for Proterra technicians to repair buses that were no longer under warranty[31]. In 2015, the Foothill Transit contractor staff took over preventive maintenance inspections and general bus work for the zero-emission vehicles.

The annual cost for maintenance of battery electric buses has been reported by Foothill Transit to average above $9,000 per year, with an average total cost of $0.16/mile. A majority of maintenance costs for battery electric buses can be attributed to preventative maintenance, compared to a majority of costs being propulsion-related for CNG buses[32]. A way to reduce maintenance cost is to ensure increased monitoring of systems that may reduce any malfunctions associated with overheating or voltage levels. Many of the battery electric buses provide data from the vehicle telemetry, and such data can be transmitted to the manufacturer to limit maintenance time.

The operational and maintenance costs for the charging infrastructure were estimated to be $500/year for a depot charger and $13,000/year for an on-route charger[27].

Maintenance costs and explanation of how maintenance is provided for various transit agencies with battery electric bus implementations are summarized in Appendix C, Table C.6.

3.1.5.5. Cost Projections

Table 3.1 reflects the capital cost projections made by the California Air Resources Board for fuel cell buses without accounting for inflation or any decided upon discount from the manufacturer[33]. A decrease in cost of battery electric buses regardless of the charging method over the next 3 years followed by a general increase is expected. The capital cost of the buses will return to their 2016 value for in-depot charging ($770,000) and on-route charging ($750,000) value in about 11 years. At the same time, capital costs for diesel hybrid buses are expected to increase at an annual rate of 2.35%. In terms of the electricity cost across the US and the New England area, prices are projected to have an overall increase following a short period of decrease in prices over the next few years[34].

Table 3.1. Projections of capital battery electric buses, diesel hybrid buses and electricity costs from 2018-2030[33]

Year	Battery Electric Buses (depot charge) ($)[a]	Battery Electric Buses (on-route charge) ($)[b]	Electricity for Transportation in the US (2016 $/MMBtu)[c]	Electricity for Transportation in New England (2016 $/MMBtu)[c]	Diesel Hybrid Buses[d]
2016[4]	770,000	750,000	29.38	40.587	690,000
2017	754,187	733,062	31.36	43.185	706,186
2018	738,374	716,124	31.95	36.38	722,751
2019	722,561	699,186	33.31	39.04	739,705
2020	706,748	682,247	34.52	40.53	757,056
2021	715,099	689,772	35.53	41.97	774,815
2022	723,451	697,297	37.18	44.45	792,990
2023	731,802	704,822	38.28	46.68	811,592
2024	740,153	712,347	38.65	48.21	830,630
2025	748,504	719,872	39.36	49.68	850,114
2026	756,855	727,397	39.89	50.78	870,056
2027	765,207	734,922	40.07	51.22	890,465
2028	773,558	742,447	40.21	51.49	911,353
2029	781,909	749,972	40.30	52.29	932,731
2030	790,260	757,497	40.31	52.48	954,610

[a] Projections are based on: (1) 2016 BYD BEB price (324 kWh), (2) battery cost reduction discussion document regarding battery cost reduction[35], and (3) non-battery cost bus price annual increase of 2.35% based on APTA historical data (2006–2015).

[b] Assumes Proterra on-route and depot charge BEBs have the same price. Price projections are based on: (1) 2016 Proterra BEB price (330 kWh), (2) battery cost reduction discussion document regarding battery cost reduction[35], and (3) non-battery cost bus price annual increase of 2.35% based on APTA historical data (2006–2015).

[c] Reported values from the U.S. Energy Information Admin.[34].

[d] Projections are based on the user consumer price index to adjust the American Public Transportation Association historical data (2006–2015) to 2016 dollars to calculate the annual bus price increase. Annual price increase (in 2016 dollars) is 2.35%.

3.1.6. Funding Mechanisms

Several grant programs have been funded by U.S. governmental agencies to support GHG emission reduction from vehicle fleets. Most of the implementations of battery electric buses have been funded through programs such as Transportation Investment Generating Economic Recovery (TIGER), Transit Investment for Greenhouse Gas and Energy Reduction (TIGGER), and Low or No-Emissions Vehicle (LoNo) programs. The TIGER program, a discretionary grant program, provides federal funds to support innovation in projects that could not be easily funded through traditional federal programs. The program was initiated in 2009. The TIGGER program provides capital funds to transit agencies for projects related to building efficiency improvements, solar installations, wind technology, wayside energy storage for rail, and purchase of technologically innovative, energy-efficient buses. TIGGER started in 2009 and has been implemented in three phases: TIGGER I (Fiscal Year 2009), TIGGER II (Fiscal Year 2010), and TIGGER III (Fiscal Year 2011). The LoNo program provides funding to purchase or lease zero-emission and low emission transit buses and their supporting infrastructure. These funding sources have been primarily used for bus procurement, but in some cases also for charging stations and other facilities. Matching funds were also often provided by state or local sources.

The available information on specific funding mechanisms, year of award, types of purchase, and total amount awarded for all transit agencies with battery electric buses is summarized in Appendix C, Table C.7.

3.1.7. Stakeholders

Stakeholder engagement has been listed as essential for successful implementations and should happen from the early stages of the implementation. Key stakeholders that have been reported include manufacturers, local city officials, and other cities, as well as other transit agencies. Other important stakeholders include utility companies, first responders, the general public, and transit agency employees, particularly drivers.

Manufacturers: Manufacturers are important stakeholders because if they stop participating actively, transit agencies are forced to troubleshoot and repair advanced technology vehicles with existing maintenance staff who are not necessarily trained to address issues specific to battery electric buses. Bus manufacturers in the U.S. primarily manufacture on a built-to-order basis. It is recommended that agencies maintain constant communication with manufacturers to reduce costs. Costs for an implementation may increase if components of the bus or charger are modified or discontinued. Transit agencies have also cautioned against being “wed” to a single bus manufacturer unless bus manufacturers converge on battery technology and charging standards[36]. Many agencies have reported a preference for using a minimum of two vendors, as each vendor uses different technologies[37]. Some agreements between manufacturers and transit agencies include presence of maintenance staff from the bus manufacturer onsite for at least the first few months of the implementation to address maintenance issues.

Cities: Some transit agencies suggested that bringing cities together and collaborating with industry stakeholders facilitates a network to accelerate the implementation of zero-emission bus programs[38].

Other Transit Agencies: Information exchange with other transit agencies that are using the same technology should facilitate successful implementations[22].

3.1.8. Challenges

The major general challenges of battery electric buses are related to: 1) capital costs of the buses and infrastructure; 2) limited driving range; and 3) training skilled maintenance personnel on the technology.

Challenges associated with battery electric buses:

1. **Bus and infrastructure capital cost**
2. **Driving range and charging infrastructure**
3. **Staff training**

Replacing traditional diesel buses with battery electric buses is expected to reduce operating costs and help sustain transit operations long into the future; however, this transition will involve higher capital costs for procuring these more expensive buses.

The charging infrastructure for battery electric buses is dictated by the length of the driving route. For long bus routes that exceed the driving range of the bus, charging stations are required on-route to "fast charge" the onboard battery. This fast-charge infrastructure must be built along the route of the bus, which can be an issue when multiple jurisdictions are involved. Other problems include performance issues, heat distribution within the bus, snow and freezing of overhead chargers, and other equipment and mechanical failures. Slow charging is the alternative charging option, where the major considerations include: the number of buses, number of charging stations, sharing of stations between the buses, and energy demand charges. Therefore, attention to battery size and battery capacity at the time of bus purchase in relation to the available charging infrastructure and transit routes is critical in minimizing driver range anxiety.

Initial challenges experienced by many transit agencies related to staff included training operators and maintenance staff in the differences between battery-powered electric buses and conventional diesel buses. More specifically, during the docking overhead fast-charging procedure, the operator needs to apply the accelerator instead of the brake, which is the opposite of the process for pulling up to a stop with a CNG or traditional diesel bus. In addition, transit agencies found replacement batteries were frequently required because operators failed to shut the bus down at the end of a shift due to the quiet engine. Issues were further observed in the early stages of projects, when workers would push the emergency stop button at charging sites and disable the charger mistakenly. This required someone at the site to physically reset the system.

3.2 Fuel Cell Buses

A fuel cell is an electrochemical reactor, i.e., a device that produces electricity after a chemical reaction. Hydrogen fuel cell vehicles are supplied with a proton exchange membrane fuel cell stack that receives hydrogen fuel and produces electricity, which in turn is used to power the vehicle. The only by-product of this process is water, making a hydrogen fuel cell system a zero-emission technology.

This zero-emission technology can have two power configurations. In the first design, buses use the power directly generated by the fuel cell. The second, and more popular, design incorporates a storage platform to capture excess energy into the powertrain (Figure 3.2). The storage platform on this second design typically includes batteries, super-capacitors, or a combination of these storage options. The need for energy storage was integrated into fuel cell vehicles when high hydrogen costs made operation of this zero-emission technology economically unsustainable[39]. This energy storage device is capable of capturing energy from regenerative braking to buffer peak power loads. In the fuel cell design that includes an energy storage device, either the energy storage device or the fuel cell can be designated as the dominant source of energy. In fuel cell-dominant powertrains, the fuel cell is primarily responsible for power production, with a smaller onboard energy storage platform to provide transient power. Designs with a dominant energy storage system typically include a large battery to act as the prime energy source, with supplemental electricity supplied to the battery from the fuel cell to extend driving range. Only one implementation, which is currently not active, used direct-use fuel cell buses. All other transit agencies used or are using fuel cell buses that also include an energy storage platform. For this reason, the report focuses on this latter zero-emission bus design and refers to this technology as "fuel cell buses." However, information on the one direct-use fuel cell bus implementation is included in relevant tables provided in the Appendix for reference.

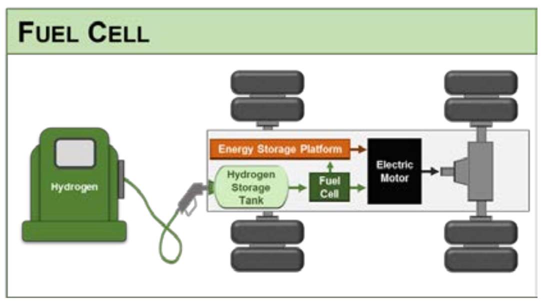

Figure 3.2: Overview of the powertrain in hydrogen fuel cell buses

Transit agencies have reported driving ranges between 210 (322 km) and 325 miles (523 km) [40–42]. These distances are short compared with those of other vehicle technologies such as conventional diesel, which can achieve, on average, 280 miles (450 km) on one tank of fuel, or a range of 217 miles (350 km) on a tank of CNG[43].

15 hydrogen fuel cell bus implementations have been demonstrated in the U.S.; 7 of them are currently active. One of them is at the MBTA.

In total, 15 implementations of hydrogen fuel cell buses have been demonstrated by nine U.S. transit agencies, with the majority being supplied with a battery as the main energy storage system. As of December 2016, 7 of them were active and deployed a total of 21 buses. Santa Clara VTA has been the only agency to demonstrate direct-fuel cell use buses, without the battery component, which was shown to be inefficient; these buses had a fuel economy less than or equal to that of diesel fleets. After this implementation, no other agency has attempted to choose fuel cell-only buses. In Massachusetts, the MBTA has been implementing one fuel cell bus since 2016.

3.2.1. Refueling Strategies and Facilities

Fuel cell buses typically store hydrogen onboard in tanks. Hydrogen can be produced using electrolysis or steam methane reforming processes. Production facilities can either be located onsite at a bus depot location or offsite with hydrogen delivered to a storage site at the bus depot. Each method has advantages that vary by geographical location of the transit bus fleet and by the relative size of the fueling station or network of stations. Onsite hydrogen production facilities primarily use steam methane reforming in the U.S., given the well-developed natural gas infrastructure[44]. Transit agencies with larger fuel cell bus fleets have identified onsite steam reforming facilities to be an economically viable option. However, agencies with smaller fleets being used over short implementations have typically preferred third-party companies to deliver hydrogen to storage facilities to avoid the capital expenditure of production facilities. It should be noted that transport costs significantly increase the price of the hydrogen fuel[44]. Charging strategies for U.S. and Canadian transit agencies using fuel cell technologies are summarized in Appendix D, Table D.1.

3.2.2. Bus Manufacturers and Other Suppliers

Fuel cell buses have been manufactured by three companies: Van Hool, New Flyer, and ElDorado. The fuel cells themselves have been manufactured by Ballard Power Systems and United Technology Corporation, while the manufacturers for the system integrators include ISE Corporation, BAE Systems, and Siemens. Hydrogen fuel supplying companies that have partnered with transit agencies in the U.S. and Canada are Air Liquide, Air Products, HyRadix, Linde, and UTC Power. Appendix D, Table D.2 summarizes the available information about bus manufacturer and other supplier characteristics for implementations of fuel cell buses in the U.S., and this section discusses the details of the bus specifications for the various manufacturers.

3.2.2.1. Bus Manufacturers

Technology maturity (i.e., readiness level of a technology to be fully commercialized) of zero-emission buses is assessed using the Technology Readiness Level (TRL) index[45]. NREL has assigned zero-emission buses a TRL score, and this score will be discussed in this section.

Van Hool is a Belgian company that has been supplying transit agencies with buses since the initial fuel cell bus demonstrations in Europe and North America. Van Hool supplied buses to AC Transit, SunLine Transit, and Connecticut Transit (CTTRANSIT) for their early demonstrations between 2006 and 2010. First-generation buses were used for these early implementations. These buses cost $3.2 to 3.5 million, depending on bus size, and were able to reach a driving range of 250 and 300 miles using a 120 kW fuel cell and a 95 kWh battery. NREL assigned these first-generation buses a TRL score of 6. More recently, the company has collaborated with ClearEdge Power (formerly UTC Power) on a second-generation fuel cell bus that have been operated in California (AC Transit and SunLine Transit), CTTRANSIT, and Flint Mass Transportation Authority in Michigan (Flint MTA). This second-generation bus design has been assigned a TRL of 7, based on changes made to the battery type and bus dimensions. Van Hool replaced the sodium nickel chloride batteries used in the first-generation design with lithium ion (Li-ion) batteries. The bus height was also reduced to match dimensions of traditional diesel buses. The decreased bus height was achieved by decreasing the size of the onboard hydrogen storage tanks. The smaller storage capacity (40 kg) of these second-generation buses has reduced driving range (200–250 miles).

New Flyer is among the largest transit bus and motor coach manufacturers in North America. This company has manufactured several fuel cell buses, which have been assigned a TRL of 7 by NREL. This classification was assigned because of New Flyer's extensive experience with fuel cell bus development and deployment. New Flyer led the successful demonstration of 20 fuel cell buses in Whistler, Canada, from 2009 to 2014. The capital cost per bus was $2.5 million, with a driving range of 210 to 240 miles. Compared to other manufacturers, New Flyer designed buses of lower height (123 in).

ElDorado has an extended history with designing fuel cell buses for U.S. demonstrations. ElDorado was a part of the collaboration with BAE Systems (hybrid manufacturer/integrator) and Ballard Power Systems (fuel cell) that developed the National Fuel Cell Bus Program (NFCBP)-funded fuel cell bus, also known as the American Fuel Cell Bus (AFCB). This bus was designated as a first-generation product in the field-testing stage of development, with a TRL of 6[45]. Since that time, NREL has collected and analyzed more than a year of operational data on the bus, which has shown exceptional performance (270- to 325-mile driving range).

3.2.2.2. Fuel Cell Manufacturers and Integrators

Ballard Power Systems has contributed to a variety of fuel cell demonstrations globally. In particular, North America Ballard Power Systems has cooperated with Santa Clara VTA, BC Transit in British Columbia, and the NFCBP. Ballard was chosen to be the fuel cell supplier for the AFCB project. For this project, Ballard provided its FC Velocity-HD6 fuel cell power system. In 2010, Ballard started to manufacture its fuel cell systems in the U.S. to meet future demand for Buy America-compliant buses. These fuel cells are one of the first systems to be manufactured at a U.S. facility.

United Technology Corporation (UTC) Power has incorporated its PureMotion Model 120 PEM fuel cell in four buses that are operated in commercial transit services: AC Transit in Oakland, California, and one at SunLine in Thousand Palms, California. UTC Power also builds fuel cells that operate with fuels other than hydrogen, such as methanol and CNG.

ISE Corporation is an integrator of fuel cell drive systems into heavy-duty vehicles. The ThunderBus demonstration for SunLine Transit was an ISE prototype fuel cell bus. This was followed in 2003 by contracts to develop and integrate fuel cell drive systems into four Van Hool buses trialed by California's AC Transit and SunLine Transit, and to install a "fuel cell-ready" drive system into a New Flyer Invero bus for Hydrogenics. This bus was demonstrated by SunLine Transit in 2005. ISE has also integrated a fuel cell drive system into a bus deployed in 2007 by CTTRANSIT. Further deployments of ISE involved supplying the electric drive and battery technology for the 20 BC Transit fuel cell buses, with bus manufacturer New Flyer performing the integration.

BAE Systems is a global defense, aerospace, and security company[46]. The company has been manufacturing drive propulsion systems for more than a decade, with approximately 4,000 transit buses operating around the world. The company was chosen by the FTA to be the integrator of the AFCB project. BAE Systems served as the lead vehicle integrator and supplied the propulsion system, power converters, and electric accessories[46].

Since the initial fuel cell bus demonstrations, new U.S.-based fuel cell companies (ElDorado, Ballard, BAE Systems) have gained market share as a result of the AFCB program; this program mandates transit agencies using FTA funds to purchase fuel cell buses and components from U.S.-based companies. While Van Hool was the main bus manufacturer up to 2010, the company is based in Belgium making it ineligible as a fuel cell bus supplier for any transit agency using FTA awards.

3.2.3 Typical Route Assignments/Scheduling

Current fuel cell bus implementations consist of a small number of buses. The main consideration for fuel cell buses in this regard is that route assignments are limited by the need for approvals from routes of cities that the bus will pass through. One desirable aspect in choosing a route is that, like battery electric buses, assigning the buses routes in which there is high visibility by pedestrians promotes the technology. Moreover, since fuel cell buses only need to refuel usually once a day at the hydrogen fueling station, this bus is not limited by driving range. Despite the increased flexibility in driving routes, some agencies have still tested their fuel cell buses on routes with less than ideal conditions, such as a route having a hilly terrain.

Appendix D, Table D.3 presents some of the available information from the survey instrument and interviews on the features of the trips of fuel cell buses for two transit agencies: the University of California, Irvine (UCI) and Stark Area Regional Transit Authority (SARTA). The main difference between these two entities is that UCI has one bus that operates on the university's campus, while SARTA has 11 buses with a wide range of routes. However, the data regarding the average miles traveled per day (150 to 220 miles/day), the average distance between stops (0.6 to 1 mile) and from bus stop to depot (1.5 to 2 miles), and the average trip time (30 to 40 minutes) are comparable. The main difference is the number of stops along the way, with UCI having around a third the number of stops of SARTA, owing to the nature of the route location and service area.

3.2.4. In-service performance

Fuel cell buses have higher fuel economy compared to conventional diesel and CNG buses.

The fuel economy for a fuel cell bus ranges from 4.53 to 11.5 mpdge, compared to a range of 3.8 to 4.28 mpg reported for conventional diesel buses, and 3.11 to 3.33 mpg reported for CNG buses for the same transit agencies (Appendix D, Table D.5).

Average speed varied between 6.1 and 15.6 mph (see Appendix D, Table D.4). The wide range in average speeds is due to the route characteristics, in particular, the number of bus stops, their distance, and the driving conditions in the service area that have a direct impact on average speed. Currently, fuel cell battery electric buses tend to be used in service for longer periods compared with earlier implementations. In the first few years of such implementations (until around 2010), the monthly average mileage per bus ranged between 900 and 1,700, while in more recent ones, the range has been extended to between 1,000 and 3,000 miles. The average mileage for diesel buses ranges between 3,300 and 4,800.

Availability also seemed to range widely from 45% to 90%. The wide range is justified due to improvements in battery and fuel cell technology. First fuel cell buses had an availability of 44% to 75%, with the more recent implementations reporting buses' availability of 70% to 88%. The miles between road calls reported for different transit agencies show that low availability was usually associated with issues related to the bus itself (1,569 to 8,286 miles) and less often with the propulsion (919 to 9,169 miles) or fuel cell system (7,184 to 32,771 miles). It is interesting to note that the availability rate improved over the duration of the implementation and approached 2016 FTA/DOE targets (85% to 90%)[47]. Miles between road calls have also improved with time.

For tank-to-wheel emissions, fuel cell bus designs are zero-emission technologies. Water is the only by-product of the process used to convert hydrogen to electricity in the fuel cell onboard the bus. However, the processes of producing hydrogen offsite and transporting it to the bus depot fueling station are sources of atmospheric pollutants, including CO_2, NO_x, volatile organic compounds, methane, and sulfur dioxide[48]. Like battery electric buses, a lifecycle assessment can be used to estimate the true emission profile of this fuel cell technology. Estimates from existing studies reported lifecycle GHG emissions of 1,500 to 2,000 g/mile for fuel cell buses (using steam reforming of natural gas for hydrogen production)[49], which were much lower than the corresponding value for diesel buses and comparable to the estimate for battery electric buses. Studies using LEM showed fuel cycle GHG emissions that ranged from 77 to 264 g/mile and fuel and vehicle lifecycle GHG emissions that ranged from 155 to 360 g/mile, depending on fuel and fuel feedstock used for hydrogen production[19]. A study that used the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model reported much higher well-to-tank emissions for fuel cell buses compared to battery electric and conventional buses, assuming 100% steam reforming of natural gas from North America[49]. No transit agency has reported estimates of emissions associated with fuel cell bus operations.

3.2.5. Costs

3.2.5.1 Procurement

Most recent implementations report procurement cost of fuel cell buses of $1.8 million, almost double that of battery electric buses. Operating cost is higher than that of conventional diesel and CNG buses.

Fuel cell buses are associated with significantly higher capital costs as compared with conventional diesel buses[27]. Up until 2008, one bus cost about $3 million to $3.5 million. Since about 2010, the per-bus price dropped to $2 million to $2.5 million, with more recent implementations showing a cost per bus of $1.8 million (SARTA) (see Table D.2 in Appendix D). This, however, is still almost two to three times higher than the capital cost of diesel buses[49]. Note that there had been a bus purchase of $1.2 million (SunLine's AT bus), but this was a different case; SunLine purchased a bus that had previously been demonstrated in British Columbia, Canada, so it paid much less for it. SARTA purchased its new buses with a per-bus cost of $1.8 million.

The fuel cell stack has the greatest effect on fuel cell bus cost. The benefits of economies of scale have been studied by the U.S. DOE for the case of fuel cell buses and, in particular, the fuel cell component. It was shown that a five-time increase of fuel cell component production can result in a decrease by almost 50% in their individual cost. Therefore, mass production of these buses in the future is expected to positively affect the prices[49]. The cost of procuring fuel cell buses is also expected to keep decreasing in the next 10 years as fuel cell technology matures and becomes less expensive (see Section 3.2.5.5).

3.2.5.2 Infrastructure

All of the transit agencies needed to build new depot facilities or expand their existing facilities in order to accommodate the fueling and maintenance facilities for fuel cell buses. Available data did not seem to agree on a specific required cost for these modifications. Different bus operators had to build new facilities or expand their current ones, making it hard to make infrastructure cost estimations due to the variability in capacity and types of infrastructure, e.g., whether it is a fueling station or also a hydrogen production facility. Available data existed for AC Transit that showed that a new facility with hydrogen fueling capability of 600 kg of hydrogen per day for both cars and buses cost about $10 million[40]. UCI reported a value of $287,694 per station for a hydrogen refueling station expansion, and SARTA reported a value of $1.8 million as the infrastructure cost of building a new hydrogen production fueling station with capacity of 300 kg per day[50].

3.2.5.3 Operations

Hydrogen fuel has a higher per-unit price ($/kg) than traditional fuels such as diesel and CNG. The price of hydrogen also has a wide range ($4.52–12.99/kg) across different sites (see Table D.1, Appendix D). For transit agencies that filled out the survey instrument, costs were $4.52/kg for SARTA and $12.99/kg for UCI. The range could be attributed to consumption rates related to fleet size: UCI implemented only one bus and SARTA implemented 11 buses. In fact, the price of hydrogen fuel at UCI was a major drawback for this organization and motivated the transition to battery electric, where buses are able to use the university's micro grid. The per-mile cost of operating a fuel cell bus, i.e., fuel cost ($1.10 to $2.62 per mile), is higher than that of conventional bus technologies ($0.44 to $0.69 for diesel and $0.29 to $0.61 for CNG) reported for the same transit agencies (see Appendix D, Table D.5).

3.2.5.4 Maintenance

Maintenance costs are low for scheduled operations, however, unscheduled maintenance results in additional costs. For the different fuel cell bus implementations, scheduled and unscheduled maintenance cost per mile varied between $0.39 and $1.70 per mile per bus compared to a range of $0.22 to $2.55 per mile per bus for conventional buses for the same transit agencies (see Appendix D, Table D.6). It should be noted that unscheduled maintenance mainly contributed to these rates; without it, fuel cell buses had a maintenance cost of about $0.30 per mile. Extensive labor hours can significantly increase these values compared to conventional buses since their labor costs are about 60% higher than those of conventional buses[51]. The 2016 and the ultimate targets set by FTA for per-mile maintenance cost, which includes both scheduled and unscheduled, are $0.75 and $0.40 per mile, respectively[52]. The trend has not stabilized yet, since there are data periods in which transit agencies are close to the targets, but there are also data periods in which they are below the targets.

Maintenance information was provided in-house for the two transit service providers that completed the survey. UCI reported a cost of $0.47/mile per bus for its fuel cell buses as compared with $2.55/mile per bus for conventional buses. UCI also reported its total maintenance cost to be $10,183 per fuel cell bus. Overall, the maintenance cost for fuel cell buses varied considerably due to the variability of problems that might arise and the types of maintenance that are included in the manufacturers' warrantee. No information on training, warranty, research, or salvage value at the end of the buses' usual life was provided by either agency.

3.2.5.5. Cost Projections

Table 3.2 reflects the capital cost projections made by California Air Resources Board for fuel cell buses without accounting for inflation or any decided-upon discount from the manufacturer[33]. A general decrease in the cost of the buses over the next five years followed by a stabilization in price at $750,000 is predicted. The hydrogen prices will decrease over the next couple of years, with a set goal of $4/kg by U.S. DOE in 2020[53].

Table 3.2. Projections of capital cost of fuel cell battery electric buses[33] and hydrogen costs[53].

Year	Fuel cell battery electric bus ($)	Hydrogen price (2016 $/kg)[i]
2018	1,050,000	6.00
2019	1,000,000	5.00
2020	900,000	4.00
2021	850,000	4.00
2022	800,000	4.00
2023	750,000	4.00
2024	750,000	4.00
2025	750,000	4.00
2026	750,000	4.00
2027	750,000	4.00
2028	750,000	4.00
2029	750,000	4.00
2030	750,000	4.00

[i] Projections based on Air Resources Board staff's analysis and assumptions. The target for the U.S. DOE for hydrogen price is $4/kg[53].

3.2.6. Funding Mechanisms

Funding mechanisms that have supported fuel cell bus implementations and demonstrations include NFCBP and the LoNo Program, the U.S. DOT/FTA TIGGER program, and other federal, state, and local support resources (e.g., state commissions and/or taxes, CARB, etc.). The NFCBP has been the most common source of federal funding, while the LoNo has provided funds for the more recent implementations (SunLine Transit, SARTA). The NFCBP was initiated in 2006 as part of the "Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users" by the FTA to support initiatives aimed at developing fuel cell technologies for commercialization[54].

As with battery electric buses, most of the awards have been used to procure buses and, in some cases, to support maintenance and fueling facilities.

The available information on specific funding mechanisms, year of award, types of purchase, and total amount awarded for all transit agencies with fuel cell buses is summarized in Appendix D, Table D.7.

3.2.7. Stakeholders

Fuel cell bus demonstrations have reported involvement of the following stakeholders: transit agencies implementing the demonstration projects, manufacturing companies, the local community, and other transit agencies. Funding mechanisms can trigger the involvement of more stakeholders, as happens with the case of NFCBP. These projects are managed through the following three entities: the clean transportation consortium CALSTART, Pasadena, California; the Center for Transportation and the Environment (CTE), Atlanta, Georgia; and the Northeast Advanced Vehicle Consortium, Boston, Massachusetts. Another stakeholder is NREL, which has been assigned to assess most of the implementations and has worked closely with transit agencies in doing so. More specific information about the involvement of some of the stakeholders follows.

Transit Agencies: Successful projects are characterized by a strong agency commitment and a highly engaged program manager. Drivers and mechanics that are fully committed to the project are also found to be critical for the success of certain projects. Furthermore, transit agency staff must also be well trained, especially when it comes to technical staff. The challenge associated with this is that upon retirement or a change in jobs, highly trained and qualified individuals are lost. At the same time, fewer people are entering the field of technical repair, making new candidates scarce.

Component Manufacturers: While transit agencies are mainly responsible for the smooth operation of the buses, this is tightly related to the manufacturing companies that need to provide solutions when equipment problems emerge. Transit agencies have reported maintaining the cooperation of manufacturers throughout the duration of implementation as a challenge. In some instances, one of the partners dropped out of the team because of resource constraints. In other cases, a company declared bankruptcy. These unforeseen problems are difficult to overcome if other partners cannot step up their level of support. These issues have often caused delays in getting buses ready for service but have also contributed to extended downtime for the buses.

Community: Early and ongoing outreach with the community and local regulators is critical for addressing public safety concerns and facilitating the permitting process.

Practitioners/Other Transit Agencies: As with battery electric buses, there is a need to create a network for information exchange among practitioners to facilitate future implementations by presenting common mistakes and ways of addressing them.

3.2.8. Challenges

Challenges associated with fuel cell buses:

1. **Coordination of multiple stakeholders and manufacturers**
2. **Reliance on third-party hydrogen suppliers**
3. **Need to retrofit existing/build new infrastructure**
4. **High cost of infrastructure and buses**
5. **Staff training**

A common challenge reported by many transit agencies that have implemented fuel cell buses has been related to supporting equipment and fuel cell components. These issues have often been reported as obstacles in operating those buses in full-time service[40]. The involvement of multiple suppliers has also been cited by transit agencies as a reason for many of their problems in operating their fuel cell fleet efficiently. In particular, challenges are associated with lack of communication and overall efficient cooperation between component suppliers, which are often worsened by the involvement of sensitive data and their unwillingness to share them, as well as the inability to attribute a malfunction to a specific component.

Furthermore, in terms of the hydrogen fuel itself, the drawbacks were related to the heavy reliance on third-party suppliers of the hydrogen fuel, its high price tag, and access to the fueling station. For fleets in the U.S., access to hydrogen fuel has been presented as a difficult task, and several planned projects have been delayed because of this issue. Since there is no standardized international price for hydrogen, the price per kilogram is often determined by a contract, and that can vary significantly depending on the location and the supplier.

Challenges related to infrastructure are often caused by the different dimensions of fuel cell buses. More specifically, fuel cell buses are typically taller than conventional diesel or CNG buses[55] and present safety concerns from potential leakages to bus wash[56], creating problems with utilizing existing infrastructure.

More general challenges are similar to those of battery electric buses, including the charging infrastructure, having and training skilled drivers and maintenance labor who are comfortable with the technology, and the capital costs of the buses and the infrastructure.

3.3 Fuel Cell Hybrid Plug-In Buses

The need for hybridized fuel cell buses emerged when it was realized that increasing hydrogen costs were decreasing the economic viability of this electric vehicle design[57]. As with the fuel cell buses, the power train in this bus system consists of a battery and a proton exchange membrane fuel cell stack as sources of energy for the electric motor (Figure 3.3). The main difference with the fuel cell bus is that its battery can be charged by plugging it into an overnight charger in addition to the continuous charging of the battery that occurs onboard from the fuel cell stack. In addition, in this bus design, the batteries are used as the primary source of electric power for the drive motor, while the fuel cell stack is used to recharge the batteries when the level of charge falls below a certain threshold[58].

7 demonstrations of fuel cell hybrid plug-in buses have existed, with only 2 of them currently active: University of Delaware, and Flint MTA in Michigan.

Fuel cell hybrid plug-in buses are the least common type of zero-emission transit bus. In total, fuel cell hybrid plug-in buses have been implemented or demonstrated by seven transit agencies in the United States. As of December 2016, one implementation (University of Delaware) and one short-term demonstration (Flint MTA in Michigan) were active, with a total of three fuel cell hybrid plug-in buses in operation.

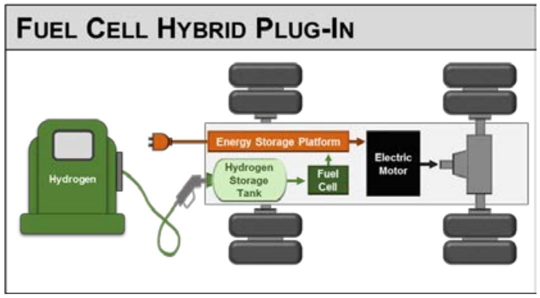

Figure 3.3: Overview of the powertrain in fuel cell hybrid plug-in buses

3.3.1. Fueling Strategies and Facilities

The most common charging method for fuel cell hybrid plug-in buses is overnight through a plug-in connection to the electrical grid. Differing approaches, however, have been taken to fuel hydrogen tanks. The strategy selected for hydrogen fueling has been guided by the access to an existing hydrogen fuel station.

The pressure of the supply line can be varied to modulate the fueling rate. A “slow fill” can be expected to take between two and four hours to fill a 13-kg onboard hydrogen tank at 350 bar (180 miles, 290 km driving range). In contrast, a “fast fill” for this tank size can be completed at 414 bar, on average, in 15 minutes[59]. In general, information on hydrogen refueling and battery charging for fuel cell hybrid plug-in bus implementations in the U.S. besides the hydrogen fuel supplier and hydrogen source is limited. Appendix E, Table E.1 provides a summary of the fueling companies and specifics of fueling and charging per transit agency demonstration/implementation.

Specific infrastructure requirements for fuel cell hybrid plug-in buses, beyond those previously described for battery electric and fuel cell buses, have not been reported. Combining the location of battery-charging and hydrogen supply facilities into one increases space requirements.

3.3.2. Bus Manufacturers and Other Suppliers

Many of the companies involved with the production of these hybrid buses have been previously discussed regarding battery electric buses and other fuel cell-based buses. Appendix E, Table E.2 summarizes available information on the bus manufacturer and other technology suppliers and the specifications of fuel cell hybrid plug-in buses implemented in the U.S., and this section discusses the details of the bus specifications for the various manufacturers.

Proterra is a leader in lightweight, composite body hybrid plug-in technology. The fuel cell hybrid plug-in bus offered by Proterra use NanoSafe lithium-titanate batteries from Altairnano and Hydrogenics hydrogen fuel cells[54]. Proterra selected the NanoSafe Altairnano for its hybrid buses, given its long cycle life (16,000 cycles) and low internal resistance to minimize the risk of overheating and capacity for fast charging (<10 minutes)[60]. The

NanoSafe battery modules may be charged in combination by the onboard fuel cells, regenerative brakes, or external electricity sources through plug-in charging. On-route charging by the fuel cell and braking can extend the range of the bus to about 125 miles (200 km).

EVAmerica[d] is a manufacturer of electric and hybrid-electric medium- and heavy-duty vehicles. The company is based in Chattanooga, Tennessee, and supplied the fuel cell hybrid plug-in bus used in the demonstration by the Birmingham-Jefferson County Transit Authority in 2014. The design of this hybrid bus was supported through an FTA-funded research project and an NFCBP grant[61]. This fuel cell hybrid plug-in bus includes a Ballard hydrogen fuel cell and Altairnano lithium-titanate batteries. EVAmerica partnered with Embedded Power Controls on the propulsion system integration and Fab Industries for the onboard hydrogen storage tanks.

Ebus supplied fuel cell hybrid plug-in buses to the University of Delaware and the University of Texas in 2007. Two buses were built with Saft nickel-cadmium batteries with a Ballard hydrogen fuel cell as an auxiliary power unit. Onboard batteries could additionally be plugged into the electric grid for overnight charging. Since delivery of these hybrid buses 10 years ago, Ebus has transitioned to manufacturing battery electric buses.

Fuel Cell Manufacturer and Integrator Companies

Ballard Power Systems fuel cells were discussed in the previous section and have been used in the demonstrations for Birmingham-Jefferson County Transit Authority and the Universities of Delaware and Texas.

Hydrogenics is an international leader in hydrogen fuel cell products as well as hydrogen generation systems. The HyPM platform has been widely used in a number of fuel cell hybrid plug-in buses manufactured by Proterra, including the demonstrations in BurbankBus, CapMetro, COMET, and Flint MTA.

3.3.3 Typical Route Assignments/Scheduling

Considerations similar to the previous two technologies (e.g., range, visibility, and location of fueling or charging stations) apply to this bus technology as well.

3.3.4. In-service Performance

Given the limited implementations of fuel cell hybrid plug-in buses, very little in-service performance information is available for specific transit agency implementations. This information is limited to fuel economy values. The fuel economy achieved for fuel cell hybrid plug-in bus operations by transit agencies is summarized in Appendix E, Table E.3. Similar results have been reported across the various fuel cell hybrid plug-in bus models: 7.1 (EVAmerica), 7.9 (Ebus), and 7.7 (Proterra average) mpdge. The best fuel economy (12.0 mpdge) was from the Ebus operated by the University of Delaware; however, this value was

[d] It should be noted that EVAmerica is currently insolvent[61]

reported by the bus manufacturer and not measured based on real-world operations. In comparison to traditional diesel buses (average[e] 4.1 mpdge, per Appendix C, Table C.4) and fuel cell buses (average 6.41 mpdge, per Appendix D, Table D.5), fuel cell hybrid plug-in buses have a better fuel economy. However, battery electric buses outperform fuel cell hybrid plug-in buses (average 16.5 mpdge, per Appendix C, Table C.4).

Transit agencies have consistently reported significant downtime for fuel cell hybrid plug-in buses, related to a variety of issues with the batteries, fuel cell system, and hybrid integrator. Extended repair times have been attributed to challenges in diagnosing faults[47].

Tank-to-wheel atmospheric pollutant emissions associated with fuel cell hybrid plug-in buses are zero. However, it is important to note that hydrogen production and distribution processes are responsible for emissions. The only comparison of emissions between fuel cell hybrid plug-in buses and traditional diesel buses found has been performed in Brazil. Fuel cell hybrid plug-in buses were associated with decreased emissions of CO_2 (151.5 g/mile), particulate matter sized below 10 µm in diameter (159.8 g/mile), NO_x (156.5 g/mile), and hydrocarbons (136 g/mile), when compared with engine exhaust released from conventional diesel buses[57].

3.3.5. Costs

3.3.5.1 Procurement

Limited information is currently available regarding bus costs, as fuel cell hybrid plug-in buses are still in an early prototype phase. Proterra reported that the fuel cell hybrid plug-in bus model developed for its round-robin demonstrations with BurbankBus, COMET, CapMetro, and Flint MTA cost $1.2 million. Proterra fuel cell hybrid plug-in buses were given on loan to each of these transit agencies for their respective demonstrations.

3.3.5.2 Infrastructure

Specific infrastructure requirements for fuel cell hybrid plug-in buses, beyond those previously described for battery electric and fuel cell buses, have not been discussed in the literature. Co-locating battery-charging and hydrogen supply facilities increases space requirements at these sites.

3.3.5.3 Operations

Only one transit agency has reported the costs of hydrogen fuel and electricity to calculate the overall mileage costs for fuel cell hybrid plug-in bus operation. COMET noted operation of the Proterra fuel cell hybrid plug-in bus cost at $1.38 per mile in fuel expenditures[54]. This cost is similar to that of other fuel cell bus technologies (see Appendix D, Table D.5).

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[e]These average values have been calculated assuming the lowest fuel economy from the range reported for certain transit agencies.

3.3.5.4 Maintenance

No information is available at this time regarding maintenance costs. A mechanic from the bus manufacturer has typically been staffed at the transit agency for the duration of the demonstration.

3.3.6. Funding Mechanisms

The design and evaluation of fuel cell hybrid plug-in buses in the U.S. have primarily been supported by the FTA through the NFCBP. A number of transit agencies have received support for their fuel cell hybrid plug-in bus demonstrations and implementations, including the Birmingham-Jefferson County Transit Authority (BJCTA), CapMetro, and COMET. The specific amounts and year funds were received have not been reported in published reports by the FTA or the transit agencies. The available information on specific funding mechanisms, year of award, and total amount awarded (when available) for all transit agencies with fuel cell hybrid plug-in buses is summarized in Table E.4 in Appendix E.

3.3.7. Stakeholders

While no particular information is available on specific stakeholders or their involvement in the implementation of fuel cell hybrid plug-in buses, similar stakeholders as those found in other zero-emission bus technology implementations are expected, such as transit agency and city officials, as well as funding source stakeholders.

3.3.8. Challenges

Fuel cell hybrid plug-in bus technology is still in its infancy. Funds through the NFCBP have enabled new designs to be developed by bus manufacturers. Over the past 10 years, these prototype hybrid buses have been deployed for short-term demonstrations with various transit agencies across the United States. These deployments in real-world environments have highlighted technical challenges related to the integration of multiple new technologies.

Challenges are primarily related to the high capital costs required to implement a transit bus fleet with this type of zero-emission vehicle technology. However, the cost of buses and the associated infrastructure are expected to decline over the next 15 to 20 years as larger fleets are implemented across the United States[57].

Challenges associated with fuel cell hybrid plug-in buses:

- **Integration of multiple new technologies**
- **Infrastructure and bus capital costs**
- **Maintenance challenges and staff training**

Difficulties in repairing these buses in the field have also been raised as a major issue by transit agencies. Extended repair times have been attributed to challenges in diagnosing the fault, as well as specific mechanical challenges. As the demonstration period progressed, service staff were reported to have gained familiarity with the hybrid bus, increasing their proficiency in troubleshooting and decreasing repair times. Efficient maintenance of this zero-emission bus requires that transit agencies develop maintenance manuals to facilitate diagnostics, train service staff on the various technologies used in the hybrid plug-in system, and stock all required repair tools and a range of replacement parts onsite.

Other challenges are similar to those from the previous two technologies (e.g., infrastructure, capital costs for bus procurement, and infrastructure needs).

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4.0 Overview of Zero-Emission Bus Implementations

The chapter begins with a comparison of the three zero-emission bus technologies and other conventional bus types (diesel and CNG) and presents the lessons learned from their implementations. Next, an overview of the current and future zero-emission bus technologies in Massachusetts is presented, as well as the possible funding options for MassDOT with regards to zero-emission technologies.

4.1 Comparison of Zero-Emission Bus Technologies

Available information from literature, online surveys, and interviews has been used for performing the comparison of the three zero-emission technologies. The three technologies are compared in terms of monetary cost, efficiency, energy and emissions savings, and performance. Table 4.1 summarizes the ranges that have been reported for each metric used. All the information presented is based on the information available as of June 2017 for the various technologies.

Battery electric buses, the most mature of the three technologies, are associated with lower procurement, operating, and maintenance costs when compared with fuel cell and fuel cell hybrid plug-in bus technologies. Battery electric buses also maintain the highest fuel economy under a wide range of loads, and the latest models present the longest ranges of all zero-emission bus technologies.

The initial cost of a battery electric bus is higher than that of a conventional diesel bus, but the lifecycle cost has been estimated as lower[1]. Typically, the cost to purchase a battery electric bus is about $300,000 more than that of diesel buses[36], but the bus manufacturers claim that these buses as a whole have a 40% longer lifetime[62], and annual savings are estimated at $39,000 per year over the 12-year lifetime of the bus[36]. The capital cost of battery electric buses is lower than that of the fuel cell-based buses, mostly due to the reduced battery costs over time[49]. Battery electric buses are being implemented on a larger scale and for a greater number of years than fuel cell buses.

Overall, battery electric buses outperform in terms of efficiency, reporting a fuel economy five to six times higher than those of diesel and CNG buses and three to four times higher than that of fuel cell-based vehicles. Additionally, battery electric buses have lower fuel and maintenance costs compared to those of all other bus technologies. The battery electric bus technology also appears to be the most reliable, reaching high levels of miles between road calls and availability. The range of battery electric and fuel cell-based buses varies depending on the energy storage unit onboard, but it can be at levels comparable to those of diesel and CNG buses. With recent advances in battery technology, battery electric buses can reach a range of 350 miles, which is currently higher than any other zero-emission bus technology.

In terms of emission and energy savings, all the technologies produce tank-to-wheel zero tailpipe emissions, and, therefore, a well-to-wheel approach makes more sense in revealing the total benefits, since that accounts for the emissions associated with the production of the fuel used. However, even in this case, it is difficult to extract results from existing studies that can be compared against all the technologies, because different studies base their findings on different assumptions. For the emission and energy savings or measurements, available information was derived mostly from published literature, since only a few transit agencies have conducted relative studies. WRTA reported that as of 2017, it has reduced its emissions by 780 tons of CO_2 over the course of about four years, and Clemson Area Transit reported that it has eliminated 850 tons of CO_2 in less than three years (October 2014 to May 2017).

Table 4.1: Summary of typical bus characteristics across all zero-emission bus technologies

	Battery Electric Bus[b]	Fuel Cell Bus[b]	Fuel Cell Hybrid Plug-In Bus	Diesel	CNG[48]
Capital cost ($)	Depot charging: 733,000–919,000 On-route charging: 800,000–1,200,000	FTA target: 1.0 million Active fleets: 1.8–2.5 million	Loan from Proterra: 1.2 million	445,000	400,000–495,000
Fuel economy (mpdge or mpg)	8–29.0	4.53–11.5 (6.06–7.83)[f] [41,45,47,61,63–65]	7.1–7.9[47]	3.8–5.4	2.79–3.33
Fuel cost per mile ($/mile)	0.18–0.72	1.1–2.62 (1.30–1.58)[f] [40,41,47,64]	1.38[54]	0.18–0.90	0.29–0.61
Electricity cost ($/kW)	0.17	NA	0.05[54]	NA	NA
Hydrogen cost ($/kg)	NA	4.52–23.46[40,41,47,64]	9.93[54]	NA	NA
Maintenance cost per mile[a] ($/mile)	0.16–1	0.39–1.70 (0.39–1.31)[f] [40,41,45,47,64,66]	0.55[57]	0.25–3	0.22–0.61
Max. speed (mph)	NR	37–55	44.7–58[54,67,59]	45–50[68]	NR
Max acceleration (m/s^2)	NR	NR	0.73[59]	NR	NR
Availability (%)	84–98	45–88	35–58[67]	>85	78–94
Miles between road calls (MBRC)[a]	6,000–9,000	3,830–6,335	NR	3,400[1]	10,511[1]
Average monthly miles (miles)	2,500	~2,500[40–42,47,64]	491–547[54,67]	4,500	3,900
Range (miles)	50–350 Fast Charge: 49–62 Slow Charge: 136–193	210–325[40–42]	Only-battery: 30–40[61] Fuel Cell & Battery: 280–300[61]	280–690	217
Charging/ fueling time	Fast charge: 6–15 min Slow charge: 4–6 hrs	6–24 min[40,47,61,69]	Fast fill: 15 min Slow Fill: 2–4 hrs	NR	NR
Energy savings	NR	up to 36%	2.58 (kWh/mi)	NA	NA
Fuel cycle GHG emissions[c] (g CO_2-eq/mile)[19]	12–428	77–264	NR	535	535
Well-to-tank CO_2 emissions[d] (g CO_2/MJ)[49]	77	117	NR	19	25.9

Table 4.1: Summary of typical bus characteristics across all zero-emission bus technologies (continued)

	Battery Electric Bus[b]	Fuel Cell Bus[b]	Fuel Cell Hybrid Plug-In Bus	Diesel	CNG[48]
Noise[e] (dB(A))[68,70]	Interior-Standing: 44.7–52.6 Accelerating: 68.3–67.1 Exterior: Constant Acceleration: 57.8–67.1 Standstill Acc.:55.9–66.1 Stationary: 36.1–54.2	Interior Standing: 62 Accelerating (0–30 mph): 65 Accelerating (0–55 mph): 71	NR	Interior-Standing: 46.1-61 Accelerating: 68.9-80.1 Exterior: Constant Acceleration: 73.2–79.8 Standstill Acc.:69.7–79.4 Stationary: 57.4–77.7	Interior -Standing: 44.4–59 Accelerating: 69.7–77.9 Exterior: Constant Acceleration: 69.2–75.5 Standstill Acc.: 74.6–76.4 Stationary: 65.7–76.9
Technology Readiness Level (TRL)	7 (2017)[32]	7–8 (2017)[52]	6 (2016)[47]	9[40]	9[47]

NR: Not reported; NA: Not applicable

[a]: Maintenance costs and miles between road calls could vary depending on the bus age.

[b]: The battery electric, fuel cell, and fuel cell hybrid plug-in considered for this table are either 35 or 40 feet long.

[c]: Estimates vary based on the type of power plant fuel (for battery electric buses) or fuel for hydrogen production (for fuel cell buses); estimates made using LEM from UC Davis.

[d]: Assumptions include: Diesel and CNG: GREET model; Hydrogen: CA-GREET 2.0 assuming 100% steam reforming of natural gas from North America; Electricity: 2010 EPA Electricity emission factors.

[e]: Noise studies measure noise level as one would experience it inside the bus (interior) and outside of the bus (exterior).

[f]: For active implementations.

4.2 Lessons Learned

4.2.1 General

This section highlights some of the main takeaways from this study, based on the available literature and the experience of transit agencies that have been operating or have operated a zero-emission bus fleet.

1. Starting with a few buses and then moving to a large fleet
2. Understanding bus technologies and their requirements
3. Proper training of staff
4. Good coordination between transit agency and other stakeholders

Size of Fleet: One of the main lessons that was almost unanimously agreed upon during the phone interviews was that starting with a few buses, rather than with a large fleet, is key to the success of zero-emission bus fleet implementation. By doing so, the buses can be tested out, and some of the major challenges can be identified.

Type of Technology: After the decision to initiate a zero-emission bus fleet, a transit agency needs to decide on the type of technology. Understanding the technologies that are available and the specifics of the fleet under consideration are key in this decision. For example, despite an extended range being seen as an attractive option on any of the buses, in many circumstances an extended range is not needed. Therefore, the cost can be minimized when deciding to go with shorter-range buses, assuming that those can accommodate the needs of the transit agency and the chosen routes.

Staff Training: Regardless of the type of technology chosen, proper training of drivers and maintenance personnel is important to the success of any zero-emission bus fleet. In addition, presence of staff from the bus manufacturing company in the field has been reported as a major advantage when it comes to troubleshooting issues efficiently.

Stakeholder Collaboration: Information exchange with other transit agencies that are using the same technology should facilitate successful implementations[22]. Finally, successful implementations have reported the importance of agency commitment and, in general, stakeholder involvement and effective collaboration among them.

4.2.2 Battery Electric Bus

- ***Route Assignment and Scheduling***: A modeling/simulation software has proved to be highly beneficial for planning operations of battery electric buses. These models allow transit agencies to study the theoretical performance of different types of buses while inputting data related to routes, topography, weather, and schedule, among other things. Clemson Area Transit and Lextran reported the modeling results to be very useful and to follow the actual results closely. In addition, the use of route profiling to match capabilities of the bus was important to the success of battery electric buses. Determining the electric rate structure and using it to plan operations is also recommended.

For battery electric buses, transit agencies need to consider demand charges and how they fluctuate during the day when they decide the type of charging method.

- ***Charging***: Before fast-charging is to be implemented, the transit agency must make sure that it has enough fast-charging stations on-route, to ensure that the buses have enough range for the routes. In these circumstances, transit agencies will need to get approval for constructing these fast-charging stations from the jurisdictions through which the bus will pass, as reported in an interview with an expert from NREL. A main consideration for on-route charging is that charging occurs during the day where demand charges often apply. In case a transit agency decides to utilize slow (in-depot) charging, it must determine the appropriate number of stations required for the number of buses to be used. Due to the high demand for and cost of electricity when implementing battery electric buses, several transit agencies recommended investing in renewable energy sources. When considering use of renewable energy sources, it is essential to work with an energy storage system to moderate peak demands.

- ***Bus Manufacturers and Suppliers***: Bus manufacturers in the U.S. primarily manufacture on a built-to-order basis. It is recommended that agencies maintain constant communication with manufacturers in order to reduce costs. Costs for an implementation may increase if components of the bus or charger are modified or discontinued. Agencies have cautioned against being "wed" to a single bus manufacturer unless bus manufacturers converge on battery technology and charging standards[36]. Many agencies have reported a preference to using a minimum of two vendors, as each vendor uses different technologies[37]. Some agreements between manufacturers and transit agencies include presence of maintenance staff from the bus manufacturer onsite for at least the first few months of the implementation to address maintenance issues onsite.

- ***Costs***: Transit agencies should expect an increase in electricity costs and may need to establish an active partnership with electrical companies. Ensuring adequate capital funding from the start of the conversion to battery electric buses is essential. Additional monitoring systems are also recommended to maintain bus batteries and other components of battery electric buses in a timely manner, therefore reducing maintenance costs.

4.2.3 Fuel Cell Bus

Real-world implementations have shown that hydrogen fuel cells in combination with electric batteries can power buses the same as internal combustion engine technologies, in terms of range, operation time during the day, speed, and performance in grades.

Fuel cell buses need to be "road certified" before they can be placed on routes.

- ***Route Assignment and Scheduling***: Hydrogen is highly flammable, and, therefore, it is subject to more stringent safety regulations. As a result, getting the appropriate permits to get the bus "road certified" is key to initiating this technology. This includes getting the fire department, bus team, and inspectors involved.

- ***Infrastructure***: If a transit agency decides to implement fuel cell buses, a hydrogen fueling station has to be constructed, and enough space on the property has to be allocated for it. In certain cases, having a separate workshop for these buses for maintenance purposes may be required. The need for fueling facilities that can accommodate large fleets and can expand in the future has also been emphasized, since it has been cited as a reason for delays in service by some agencies[40]. Hydrogen fueling stations have a bigger footprint compared to diesel stations and also often face more stringent safety standards[71]. As a result, it is recommended that hydrogen safety procedures in maintenance facilities need to be standardized, and certain infrastructure such as bus washes[56] need to be updated to address issues.

- ***Fueling:*** Fueling and hydrogen storage options need to be carefully assessed to ensure optimal performance. In particular, the tradeoffs between battery size and storage capacity versus on-board fuel should be determined to allow for longer bus range, without having excess weight that could potentially reduce their passenger capacity[72]. Fuel supply also needs to be properly matched with demand.

- ***Technology***: The need for improving the fuel cell design's lifetime was pointed out by several agencies, since they wanted their lifetime to be closer to or the same as the buses' operation time, which is 10 to 15 years[71]. Addressing this could be one of the ways to make fuel cell buses competitive with diesel and CNG buses.

- ***Maintenance***: Regarding maintenance, similar lessons as the ones obtained for battery electric buses were reported, and the need for best practices and guidelines for maintenance facilities has been emphasized. Particular issues with equipment malfunctioning not being easily attributed to a specific component, issues with the propulsion system, lack of communication and collaboration between transit agency and manufacturers, and other issues have been reported. These have led to recommendations for transit agencies that include reviewing information on malfunctioning equipment from previous demonstrations and developing and maintaining an inventory accordingly. This has also emphasized the need for more robust fuel cell components and for a strategic plan to allow for creation of inventories across the country and efficiency in supply chains.

4.2.4 Fuel Cell Hybrid Plug-in Bus Considerations

Given the lower technology readiness level of fuel cell hybrid plug-in buses, many issues associated with their implementations relate to integration of numerous technologies and maintenance. Maintenance issues can be resolved with proper training and maintenance manuals, while high costs are expected to decrease with advancements in technology.

- ***Technology***: As with fuel cell buses, fuel cell hybrid plug-in buses need to address issues related to both batteries and fuel cell stacks. Since fuel cell plug-in hybrid bus technology is in its infancy, the few real-world deployments that have occurred have highlighted technical challenges related to the integration of numerous new technologies.

- ***Maintenance***: Maintenance issues have also been common, given the unfamiliarity of staff with the new bus components that often led to long repair times. It is recommended that maintenance manuals should be developed and spare parts stored—when it makes financial sense, given the number of fuel cell hybrid plug-in buses that an agency is implementing—to facilitate with maintenance.

- ***Costs***: Regarding high costs associated with fuel cell hybrid plug-in buses, standardization and manufacturing processes are expected to assist in reducing them.

4.3 Massachusetts Implementations

There are currently three Massachusetts transit agencies that operate zero-emission buses. These are: Worcester Regional Transit Authority (WRTA), Springfield Area Transit Company for the Pioneer Valley Transit Authority (PVTA), and Massachusetts Bay Transportation Authority (MBTA). WRTA operates six battery electric buses, PVTA operates three battery electric buses, and MBTA operates one fuel cell bus. Martha's Vineyard Transit Authority (VTA) and MBTA are in the process of receiving four and five battery electric buses in 2018, respectively.

4.3.1 Worcester Regional Transit Authority

WRTA provides public transportation to the city of Worcester, Massachusetts, and its surrounding 36 communities. The agency has a total of 52 buses, of which 29 are conventional diesel, 17 are diesel electric hybrid, and 6 are battery electric buses. During 2016 and 2017, the total ridership on all of routes was 4,049,165 and 3,598,964, respectively.

The agency started operating three battery electric buses on its bus routes in 2013 with a 2012 $4.4 million grant from FTA's Clean Fuel Program[73]. Using this grant money, three Proterra EcoRide BE35 buses were purchased at a cost of about $1,000,000 each, in addition to an in-depot charger, an overhead charger, and other equipment. In 2013, $3 million in Section 5307 funds were used to purchase three additional battery electric buses for $1,000,000. The fleet of six battery electric buses were EcoRide BE35, manufactured by Proterra. EcoRide BE35 buses are 34 feet, 9-inches long, 102 inches wide, and 11 feet, 4 inches high. One of the buses was later replaced by a Proterra Catalyst FC after one of the EcoRide BE35 buses caught fire. The Catalyst FC is 42 feet, 6 inches long, 102 inches wide, and 11 feet, 2 inches high. More detailed information on the six buses is presented in Table 4.2.

The buses are stored indoors overnight. The cold winter weather, particularly snow and ice, has been an obstacle to charging these buses via the overhead charger successfully. As a result, Proterra has engineered heater strips for the top of the bus and the charging head. To determine the routes that the electric buses will take, WRTA worked with CTE in Atlanta, Georgia, which provided it with modeling services. Following the results from the modeling software, WRTA decided on eight to nine routes, of which five were eventually used. A full-time Proterra technician splits his time between WRTA and PVTA for the maintenance of the buses. In 46 months of operation of these battery electric buses, the total reduction in CO_2 emissions was 780 tons, while that of diesel consumption was 110,700 gallons.

Table 4.2. Overview of battery electric bus specifications by transit agency in Massachusetts

Bus Characteristics	WRTA	PVTA	MBTA[a]	VTA
Bus Fleet Size	6	3	Plans for 5	Plans for 4
Bus Manufacturer	Proterra	Proterra	New Flyer	BYD
Model	5 EcoRide BE35 and 1 Catalyst FC	Catalyst FC	Xcelsior XC60	eBus K7 and K9s
Year	2013 (2015 when Catalyst added)	2016	2018	2018
Length (ft.)	34.75 (EcoRide), 42.5 (Catalyst)	42.5	60.83	30.7 (K7) 35.8 (K9s)
Width (in.)	102 (EcoRide), 102 (Catalyst)	102	102	95.7 (K7) 102 (K9s)
Height (in.)	136 (EcoRide), 134 (Catalyst)	134	126	126.9 (K7) 140 (K9s)
Gross Vehicle Weight (lbs.)	38,000 (EcoRide), 39,050 (Catalyst)	39,050	45,500	31,957 (K7), 41,877 (K9s)
Battery OEM	NR (EcoRide), Toshiba (Catalyst)	Toshiba	NR	NR
Battery Type	NR (EcoRide) Lithium titanate (Catalyst)	Lithium titanate	Lithium-ion	Iron phosphate
Battery Model	NR	NR	NR	NR
Battery Power (kW)	E150 peak, 100 continuous (EcoRide), 100 continuous (Catalyst)	120	NR	80 (K7), 80 (K9s)
Capacity (kWh)	NR (EcoRide) 79–105 (Catalyst)	79–105	450[74]	180 (K7) 370 (K9s)[75]
Capital Cost per Bus ($)	1,000,000 (EcoRide BE35), 1,000,000 (Catalyst)	749,000	900,000	550,000 (K7), 750,000 (K9s)
Seating Capacity	37 (EcoRide) 40 (Catalyst)	40	61	22 (K7) 32 (K9s)
Availability (%)	NR	NR	NR	NR
Charging Strategy	1 plug-in depot charger, 2 over-head chargers	1 plug-in depot charger, 2 over-head chargers	plug-in chargers at depot (number not reported)	6 plug-in depot chargers, 3 inductive chargers

NR = Not reported; [a]= Some information is based on New Flyer specifications[10]

4.3.2 Pioneer Valley Transit Authority

PVTA is the largest regional transit authority in Massachusetts, with its fleet of 186 transit buses comprising conventional diesel, diesel-hybrid, and, as of 2016, electric buses. In 2016, PVTA generated over 12 million rides throughout the 24 communities it serves in the Pioneer Valley[76]. In 2016, supported by a $1,841,659 grant (48%) under FHWA's Congestion and Mitigation and Air Quality Improvement (CMAQ) Program and a matching grant of $1,995,131 by MassDOT (52%), PVTA purchased three Proterra Catalyst FC buses. The buses are 42 feet, 6 inches long and 102 inches wide and cost about $750,000 each. The detailed bus specifications are presented in Table 4.2.

The buses serve along Route P21E, the I-391 express route between Holyoke and Springfield, which measures 18 miles in one direction. The choice of route for the electric buses was dictated by the charging time that needed to be built into the schedule and the length of the buses, which limits the choice of where to operate them. To charge the buses, PVTA currently uses two fast (on-route) chargers, one in Springfield and one in Holyoke, and one slow (in-depot) charger. The fast chargers are located on each end of the I-391 express route. The Holyoke charger uses Holyoke Gas & Electric, which serves its electric load through renewable energy (hydroelectric dams) and through purchasing of electricity from other providers. The fast chargers require about 6 minutes for the buses to charge during mild weather. The charging time increases to 10 minutes during colder weather. In addition to taking longer to charge, the colder weather increases the startup time of the buses in the morning due to the longer time it takes to heat the bus to a comfortable temperature and reduces their range. For each of PVTA's electric buses that replaces a diesel bus, about 122 tons of CO_2 is displaced every year[76]. As previously mentioned, a full-time Proterra employee works between WRTA and PVTA to maintain the buses. The buses normally undergo maintenance every 6,000 miles of operation.

4.3.3 Massachusetts Bay Transit Authority

MBTA operates 177 bus routes using a fleet of 1,022 buses that serve the Greater Boston area, an area of approximately 3,244 square miles (8,400 km^2) and 4.7 million people[77]. During 2017 (up to October), the average weekday trip was between 1.25 and 1.36 million rides, of which about 30% were made by bus[78]. Most MBTA buses are conventional diesel, CNG, or diesel electric hybrid buses[79].

Using a grant from FTA's National Fuel Cell Bus Program in 2008, MBTA has put into service one ElDorado National Axess hydrogen fuel cell bus and one hydrogen fueling station in its Charlestown facility since 2016. The bus is 41 feet long, 102 inches wide, and 139 inches high. The bus supplier, ElDorado National, integrated a stainless-steel frame in the design to help prevent rust from forming on the frame of the bus. This is especially useful since the Boston climate includes salt air, snowstorms, and road salt, all of which tend to encourage rust formation. BAE Systems is the bus system integrator and the designer of the hybrid propulsion system. The fuel cell supplier is Ballard, and the hydrogen fueling station is designed and operated by Nuvera Fuel Cells. The hydrogen is produced onsite using the steam methane reforming process. Table 4.3 presents detailed bus specification information for the fuel cell bus used by MBTA.

The routes for the hydrogen fuel cell bus were chosen based on the predesignated routes that depart from the Charlestown facility. The bus is operated in typical revenue service, including morning and evening rush hours, and it has been outfitted with informational signs to help familiarize riders with its zero-emission technology. For now, this bus is stored outside and is plugged in to keep it warm on very cold days. This has been a main challenge for MBTA, since the bus sometimes fails to start in the mornings in colder months, particularly when the temperature drops below 15 degrees F. Not being able to store the bus indoors affects its maintenance and wash locations as well, whereby a separate location from conventional buses had to be designated for it. An indoor maintenance bay originally set up for CNG was converted for hydrogen work and is awaiting a final connection to the fire panel to allow overnight indoor storage of the hydrogen fuel cell bus.

In February of 2015, MBTA was awarded FTA's LoNo grant in the amount of $4,139,188 to develop and deploy five New Flyer battery electric buses. The New Flyer Xcelsior XC60 electric buses cost about $900,000 each and are scheduled to enter production in early 2018, with an expected delivery date to MBTA in the middle of 2018. The buses are 60 feet long, 102 inches wide, and 126 inches high, have a 450-kWh energy storage system, and will be charged using a slow-charging method (in-depot). Additional specification information on MBTA's new electric buses is presented in Table 4.2.

Table 4.3. Overview of the specifications of MBTA's fuel cell bus

Bus Characteristics	Fuel Cell Bus[a]
Number of Buses	1
Bus OEM	ElDorado National
Model/Year	Axess
Year	2014
Length (ft) *Width (in)* *Height (in)*	41 102 139
Curb Weight (lb)	35,000
Fuel Cell OEM	Ballard
Fuel Cell Model	FC Velocity HD 6
Fuel Cell Power (kW)	150
Hybrid System Integrator	BAE Systems
Hybrid System	Series hybrid propulsion system, HDS200, 200 kW peak
Design Strategy	Fuel Cell Dominant
Energy Storage OEM	A123
Energy Storage	Nanophosphate Li-ion (200 kW)
Energy Storage Capacity (kWh)	11
Hydrogen Storage Pressure (psi)	5,000
Hydrogen Cylinders	8
Hydrogen Capacity (kg)	50
Technology Readiness Level	7
Range (mile)	270–325
Seating capacity	39
Capital Cost per Bus ($)	2.5 million

[a]*American Fuel Cell Bus Project:* First Analysis Report, *2013*[72]

4.3.4 Martha's Vineyard Transit Authority

Martha's Vineyard Transit Authority (VTA) provides service to the six towns on Martha's Vineyard. The service area is unique in that it is a historic community with narrow roads, rural routes, and rolling hills. It operates 32 fixed-route buses and six paratransit buses. The island faces significant population, traffic, and congestion increases during the summer, which lead to greater demand for transit services resulting in high ridership. Between July 2016 and June 2017, the total yearly ridership was 1,358,915[80]. During this high season, vehicles are deployed for long distances (250–350 miles) during the day. During the winter months, VTA operates reduced levels of service.

VTA is in the process of replacing its entire fleet of diesel buses with battery electric buses. After assessing its needs and comparing the available zero-emission and non-zero-emission technologies, VTA decided to transition to an electric fleet. Using a $2.5 million grant awarded in 2017 from MassDOT's Capital Investment Plan, VTA will acquire four battery electric buses in 2018 (Table 4.2). VTA chose BYD as the bus manufacturer, with several factors in mind. One of the main reasons was that BYD offered 30-foot-long and 95.7-inchwide buses—key specifications, since Martha's Vineyard has a narrow network of roads. The buses will be of two models, with both models running on alternating current (AC) power. The first model is BYD K7, which is 30 feet long and 96 inches wide, and has a passenger capacity (both seated and standing) of 35–40, and a range of 144 miles on a single charge (180 kWh battery). The second model is BYD K9s, which is 35 feet long and 102 inches wide, has a seated passenger capacity of 38–45 (both seated and standing), and a range of 230 miles on a single charge (370 kWh battery). The batteries are manufactured by BYD. Both types of buses will be charged using the slow (in-depot) charging method, which will take two to five hours per charging episode, depending on the state of charge when the bus returns to the VTA's operations center. In addition to one charger that comes with each bus, two additional charges will be installed: one in the maintenance facility and a mobile one on the back of a maintenance truck. As it expands its fleet, VTA will install on-route chargers to increase the bus's range, allowing it to go longer during the day during the in-season and ensuring adequate battery supply during the winter months. The energy supplier to the electric buses will be Eversource. The price of the buses (including one charger for every bus) is about $550,000 for the 30-foot bus and $750,000 for the 35-foot bus.

VTA has also been awarded FTA's LoNo grant for $1.2 million. Half the funds will be used for the differential cost between diesel and electric buses, allowing VTA to purchase two additional electric buses (expected delivery June 2018). Furthermore, the remaining funds will be used for matching funds to purchase an energy storage system, since VTA is planning to switch its power source to renewable solar energy. VTA aims to start a private-public partnership with a private company that will construct, install, and maintain solar panels in canopy fashion over VTA's parking lot and on the roof of its building, with the energy stored onsite. A fixed price for the energy will be agreed upon for the first 5 years, thereby eliminating the need to pay demand charges. Sometime between years 5 to 8, the solar panels will be purchased by VTA, and it will own them for the time of their life expectancy (about 15 to 20 years after the first 5 years).

4.4 Potential Funding Options for MassDOT

The FTA has several opportunities for funding a zero-emission bus fleet deployment (see Table 4.4). A recent webinar presented by the CTE highlighted the best practices for applying for and getting FTA grants, particularly outlining methods for a successful bid through the LoNo Program. Since its deployment in 2016, LoNo has become a popular funding option for transit agencies (e.g., CATbus, Lextran, and SARTA) for procurement of both battery electric and fuel cell buses. Considering that the LoNo Program cannot be a pilot or a demonstration, other programs, such as TIGER, are essential for getting the market started prior to applying for a LoNo grant. For the LoNo grant, it is important to leverage other federal and state sources of funding to reduce the amount of funds requested. This allows the FTA to grant more LoNo funds to other agencies with the same goals. Since this grant meets all third-party procurement requirements, this eliminates the need for the transit agency to conduct separate bids. Therefore, it is important to assemble the best team possible for all aspects of the project, from bus manufacturers to project management services.

Table 4.4: Available FTA grants for zero-emission buses

Name of Grant	Amount Allocated	Type of Grant	Validity	Cost Sharing	Description
Low and No Emission (LoNo) Vehicle Program[81]	$3M/year	FTA	FY 2013–FY 2020	15% on buses and 10% on charging infrastructure	Provides funding through a competitive process to states and transit agencies to purchase or lease low- or no-emission transit buses and related equipment, or to lease, construct, or rehabilitate facilities to support low- or no-emission transit buses. The program provides funding to support the wider deployment of advanced propulsion technologies within the U.S.'s transit fleet.
Transportation Investment Generating Economic Recovery (TIGER)[82]	$500M/year	FTA	FY 2017–FY 2020	80% in urban and 100% in rural areas	Provides funding for innovative, multimodal, and multijurisdictional transportation projects that promise significant economic and environmental benefits to an entire metropolitan area, a region, or the U.S.
Bus & Bus Facilities Infrastructure Investment Program[83]	$226.5M/year	FTA	Ongoing	80%	Provides funding through a competitive allocation process to states and transit agencies to replace, rehabilitate, and purchase buses and related equipment and to construct bus-related facilities. The competitive allocation provides funding for major improvements to bus transit systems that would not be achievable through formula allocations.
Zero-Emission Research Opportunity (ZERO)[84]	$2.75M	FTA	FY 2020	80%	FTA announced the opportunity for nonprofit organizations to apply for funding to conduct research, demonstrations, testing, and evaluation of zero-emission and related technology for public transportation applications.
Congestion Mitigation and Air Quality Improvement Program (CMAQ)[85]	$2.3B–2.5B (MA Allotment: $329M for the whole period.)	FHWA	FY 2016–FY 2020	80%	Provides funding to areas in nonattainment or maintenance for ozone, carbon monoxide, and/or particulate matter. States that have no nonattainment or maintenance areas still receive a minimum apportionment of CMAQ funding for either air quality projects or other elements of flexible spending. Funds may be used for any transit capital expenditures otherwise eligible for FTA funding, as long as they have an air quality benefit.

4.5 Conclusions

This report presents a comprehensive review of zero-emission transit bus implementations by transit agencies across the United States. Transit agencies have used three technologies to reduce their transportation-related GHGs: battery electric, fuel cell, and fuel cell hybrid plug-in buses. The report has presented the technological specifications and expected performance as reported by the scientific literature. Most importantly, this report has focused on the bus specifications, performance characteristics, funding mechanisms, and lessons learned obtained from transit agencies that implemented them in their fleets.

Future work that could benefit MassDOT would include designing and pursuing a comprehensive performance assessment of current and planned implementations (when active) for the Massachusetts-based transit agencies. This could assist with identifying issues particular to the implementation area, e.g., those associated with weather, and developing solutions to improve performance. In that regard, development of algorithms that can be used to optimize scheduling and refueling of zero-emission bus technologies would be essential for addressing the specific needs of Massachusetts transit agencies. Finally, development of appropriate training programs is necessary for ensuring a seamless transition for employees of transit agencies to operating these new zero-emission buses.

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6.0 Appendices

6.1 Appendix A: U.S. Transit Agency Information

Table A.1: U.S. transit agencies that have implemented, demonstrated, or proposed plans to incorporate zero-emission buses in their fleets

California	
• Anaheim Resort Transportation, Antioch Transit (Tri Delta Transit) • Alameda-Contra Costa Transit • Antelope Valley Transit Authority • Central Contra Costa Transit Authority • City of Gardena • Foothill Transit • Modesto Transit • Mountain View Transportation Management Association • Los Angeles County Metropolitan Transportation Authority	• Long Beach Public Transportation Company Orange County Transportation Authority • Porterville Transit • Salinas Transit • Santa Cruz Metropolitan Transit District • Santa Clara Valley Transportation Authority • Solano County Transit • San Joaquin Regional Transit District • Stanford University • SunLine Transit Agency • University of California Los Angeles
Alabama	*Connecticut*
• Birmingham-Jefferson County Transit Authority	• Connecticut Transit
Delaware	*Florida*
• Delaware Transit Corporation • University of Delaware	• Miami-Dade County Transit • StarMetro
Georgia	*Illinois*
• University of Georgia	• Chicago Transit Authority
Kentucky	*Louisiana*
• Transit Authority of River City • Transit Authority of the Lexington Fayette Urban County Government	• City of Shreveport
Maryland	*Massachusetts*
• Regional Transit Agency of Central Maryland • Frederick County	• Martha’s Vineyard Transit Authority • Massachusetts Bay Transportation Authority • Pioneer Valley Transit Authority • Worcester Regional Transit Authority

Table A.1 (continued): U.S. transit agencies that have implemented, demonstrated, or proposed plans to incorporate zero-emission buses in their fleets

Michigan	*Missouri*
• Flint Mass Transportation Authority	• University of Missouri • City of Columbia • Columbia College
Minnesota	*Montana*
• Duluth Transit Authority	• University of Montana
New Mexico	*New York*
• Albuquerque Rapid Transit	• Capital District Transportation Authority • Tompkins Consolidated Area Transit
Ohio	*Oregon*
• Ohio State University • Stark Area Regional Transit Authority	• Tri-County Metropolitan Transportation District of Oregon • Lane Transit District
Pennsylvania	*South Carolina*
• Red Rose Transit Authority • Southeastern Pennsylvania Transportation Authority	• City of Seneca • Clemson Area Transit
Tennessee	*Texas*
• Chattanooga Area Regional Transportation Authority • Nashville Metropolitan Transit Authority	• Dallas Area Rapid Transit • Metro McAllen • Port Arthur Transit • VIA Metropolitan Transit
Utah	*Washington*
• Park City Transit	• Ben Franklin Transit • King County Metro • Link Transit, Chelan Douglas Public Transportation Benefit Area
Wisconsin	
• Everett Transit and Pierce Transit • Pierce County Public Transportation Benefit Area Corporation	

Table A.2: Timeline of transit agency battery electric bus implementations reviewed in this report

Transit Agency	State	No. of Buses	Year																										
			91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
Antelope Valley Transit Authority	CA	2																								■	■	■	■
Capital District Transportation Authority	NY	1																										■	■
Central Contra Costa Transit Authority	CA	4																										■	■
Chicago Transit Authority	IL	2																								■	■	■	■
Clemson Area Transit	SC	6																								■	■	■	■
Dallas Area Rapid Transit	TX	7																									■	■	■
Foothill Transit	CA	30																				■	■	■	■	■	■	■	■
Indianapolis Public Transportation Corporation	IN	21																							■	■	■	■	■
King County Metro	WA	3																											■
Transit Authority of Lexington	KY	5																									■	■	■
Los Angeles County Metropolitan Transportation Authority	CA	5																											■
Regional Transportation Commission Washoe	NV	4																				■	■	■	■	■	■	■	■
Santa Barbara Metropolitan Transit District	CA	30	Stage 1: 2 buses				Stage 2: 9 buses						Stage 3: 5 buses; Stage 4: 14 buses																
Shreveport Area Transit	LA	5																											■
Southern Pennsylvania Transportation Authority	PA	25																									■	■	■
Pioneer Valley Transit Authority	MA	3																										■	■
Star Metro Transit	FL	5																				■	■	■	■	■	■	■	■
Stanford University	CA	13																				■	■	■	■	■	■	■	■
University of California Los Angeles	CA	2																										■	■
Utah Transit Authority	UT	5																									■	■	■
VIA Metropolitan Transit	TX	3																											■
Washington Metropolitan Area Transit Authority	DC	1																									■	■	■
Worcester Regional Transit Authority	MA	6																											■

Table A.3: Timeline of transit agency fuel cell bus implementations reviewed in report

Transit Agency	State	No. of Buses	Year																										
			91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
Santa Clara VTA	CA	3																											
Alameda Contra Costa Transit	CA	3																											
		13																				Stage 1: 12 buses						Stage 2: 1 bus	
Connecticut Transit	CT	1																											
		4																											
Flint Metropolitan Transportation Authority	MI	1																											
		1																											
Massachusetts Bay Transportation Authority	MA	1																											
Orange County Transit Authority	CA	1																											
Stark Area Regional Transit Authority and Ohio State University	OH	11																											
SunLine Transit	CA	1																											
		1																											
		1																											
		9																					Stage 1: 1 bus			Stage 2: 3 buses			Stage 3: 5 buses
University of California Irvine/Anteater Express	CA	1																											

Table A.4: Timeline of transit agency fuel cell hybrid plug-in bus implementations reviewed in this report

Transit Agency	State	No. of Buses	Year																										
			91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
Birmingham-Jefferson County Transit Authority	AL	1																								■	■	■	
City of Burbank	CA	1																				■	■						
Capital Metropolitan Transportation Authority	TX	1																									■		
Central Midlands Regional Transit Authority	SC	1																				■							
Flint Metropolitan Transportation Authority	MI	1																										■	■
University of Delaware	DE	2																	■	■	■	■	■	■	■	■	■	■	■
University of Texas	TX	1																	■	■									

Table A.5: Characteristics of transit agencies with battery electric bus implementations reviewed in this report

Transit Agency	State	Service area population	Total number of routes	Ridership (monthly)	Total fleet size	Battery electric bus fleet size	Area Type	Topography
Antelope Valley Transit Authority	CA	450,000	18	NR	75	2	Suburban	Flat
Capital District Transportation Authority	NY	850,000	59	1,400,000	306	1	Urban/ Suburban	Flat & Hills
Central Contra Costa Transit Authority	CA	1,049,025	62	348,000	131	4	Urban/ Suburban	Flat & Hills
Chicago Transit Authority	IL	2,700,00	140	26,160,000	1,879	2	Urban	Flat
Clemson Area Transit	SC	30,000	10	178,000	NR	15	Urban	Hills
Dallas Area Rapid Transit	TX	1,197,000	113	6,000,000	652	7	Urban	Flat
Foothill Transit	CA	1,500,000	39	1,230,000	330	15	Urban	Flat
Indianapolis Public Transportation Corporation	IN	900,000	32	850,000	165	21	Urban	Flat
King County Metro	WA	2,000,000	NR	11,850,000	1,427	3	Urban	Flat
Transit Authority of the Lexington Fayette Urban County Government	KY	320,000	23	340,000	65	5	Urban/ Suburban	Flat & Hills
Los Angeles County Metropolitan Transportation Authority	CA	10,000,000	170	91,700,000*	2,200	100	Urban	Flat
Regional Transportation Commission Washoe	NV	750,000	26	625,000	57	4	Urban	Flat
Santa Barbara Metropolitan Transit District	CA	200,000	20	583,000	108	14	Urban	Hills
Shreveport Area Transit	LA	200,000	17	233,000	49	5	Urban	Flat
Southern Pennsylvania Transportation Authority	PA	4,000,000	196	27,400,000	2,295	25	Urban	Flat
Pioneer Valley Transit Authority	MA	470,690	25	575,5000	186	3	Urban	Flat
Stanford University	CA	50,000	20	190,000	79	23	Urban	Flat
StarMetro Transit	FL	190,000	12	290,000	NR	5	Urban	Flat
University of California Irvine/Anteater Express	CA	44,700	8	241,000	20	20	Suburban	Flat
University of California Los Angeles	CA	50,000	7	NR	16	2	Urban	Flat & Hills
University of Central Florida	FL	400,000	32	150,000	14	2	Urban	Flat
Utah Transit Authority	UT	2,100,000	120	3,800,00	400	5	Urban	Flat
VIA Metropolitan Transit	TX	2,100,000	90	3,750,000	474	3	Urban	Flat
Washington Metropolitan Area Transit Authority	WA	6,100,000	325	22,500,00	2,280	1	Urban	Hills
Worcester Regional Transit Authority	MA	500,000	26	299,914	52	6	Urban	Hills

*NR=Not reported; *This value was reported in the survey; however, the published monthly ridership is about 25,000,000* [86].

Table A.6: Characteristics of transit agencies with fuel cell bus implementations reviewed in this report

Transit Agency	State	Service area population	Total number of routes	Ridership (monthly)	Total fleet size	Fuel cell bus fleet size	Area Type	Topography
Alameda-Contra Costa Transit	CA	1,500,000	151	4,580,000	630	13	Urban/ Suburban	Hills
Connecticut Transit	CT	1,212,400	53	2,000,000	500	5	Urban/ Suburban	Hills
Flint Mass Transportation Authority	MI	102,400	28	639,000	283	2	Urban/ Suburban	Flat
Massachusetts Bay Transportation Authority	MA	4,700,000	177	39,000,000	1050	1	Urban	Hills
Orange County Transit Authority	CA	3,000,000	77	4,300,000	550	1	Urban/ Suburban	Hills
Santa Clara VTA	CA	1,026,900	82	4,260,000	19	3	Urban	Flat
Stark Area Regional Transit Authority	OH	370,000	32	225,000	80	11	Suburban	Hills
SunLine Transit	CA	440,500	32	400,000	82	9	Urban/ Suburban	Flat
University of California Irvine/Anteater Express	CA	44,700	8	241,000	20	1	Suburban	Flat

Table A.7: Characteristics of transit agencies with fuel cell hybrid plug-in bus implementations reviewed in this report

Transit Agency	State	Service area population	Total number of routes	Ridership (monthly)	Total fleet size	Fuel cell hybrid bus fleet size	Area Type	Topography
Birmingham-Jefferson County Transit Authority	AL	400,000	31	250,000	109	1	Urban	Flat
Burbank Bus	CA	100,000	4	42,000	NR	1	Urban	Flat
Capital Metropolitan Transportation Authority	TX	2,100,00	49	3,900,000	417	1	Urban	Flat
Central Midlands Regional Transit Authority	SC	140,000	27	130,00	39	1	Suburban	Hills
Flint Mass Transportation Authority	MI	102,400	28	639,000	283	1	Urban/ Suburban	Flat
University of Delaware	DE	20,000	16	500	NR	2	Suburban	Flat
University of Texas	TX	50,000	10	430,000	NR	1	Suburban	Hills

NR=Not reported

6.2 Appendix B: Survey Instrument

SECTION A: GENERAL INFORMATION

General Questions

1. Organization name
2. Organization type (*e.g.*, transit or government agency, university, research center)
3. Region/country/city/jurisdiction served (*if applicable*)
4. Name of the person being interviewed
5. Title of the person being interviewed
6. Service area population (*approximate range*)
7. Total number of routes
8. Monthly ridership
9. Type of area (*please circle one*)
    A. Urban
    B. Rural
    C. Suburban
    D. Other (*please name*)
10. Topography of the service area (*please circle all applicable*)
    A. Flat
    B. Hills
    C. Mountains
    D. Other (*please name*)
11. How many projects/programs/demonstrations of zero-emission buses has your agency been involved with? If more than one, then a separate survey should be filled out for each project.
12. Start date of the project (*if applicable*) [mm/dd/yy]
13. End date of the project (*if applicable*) [mm/dd/yy]
14. The project happened in stages (*please circle one*)
    A. Yes. What were the dates of the stages [mm/dd/yy - mm/dd/yy]
        Stage 1:
        Stage 2:
        Stage 3:
        Stage 4:
    B. No.
15. How many buses were implemented/demonstrated?
        Stage 1:
        Stage 2:
        Stage 3:
        Stage 4:

16. What is the current status of the project? (*please circle one*)
    A. In research stage
    B. In planning stage
    C. On-going/Active
    D. Complete
    E. Other (*please specify*)

Finance-Related Questions

1. Who is/are the funding agency/agencies?
2. What was the source of funding for your zero-emission bus implementation? Please note the funding source, amount and year.
    Grant 1:
    Grant 2:
    Grant 3:
3. What was the total cost of the project [$]?
4. Breakdown of the cost of the project.
    A. Procurement
        i. Vehicle [$/bus]
        ii. Entire fleet [$]
        iii. Total fleet size
        iv. Batteries on-board vehicle (*if applicable*, for battery electric, fuel cell electric, or fuel cell hybrid plug-in electric) [$/unit]
        v. Spare batteries (*if applicable*, for battery electric, fuel cell electric, or fuel cell hybrid plug-in electric) [$/unit]
        vi. Other [$] (*please specify*)
    B. Energy cost [cents/mile or cents /kwh]
    C. Charging or refueling
        i. Infrastructure for electric charging stations at bus depot (*if applicable*, for battery electric, fuel cell electric, or fuel cell hybrid plug-in electric) [$/station]
        ii. Infrastructure for electric charging stations on-route (*if applicable*, for battery electric, fuel cell electric, or fuel cell hybrid plug-in electric) [$/station]
        iii. Land for charging stations at bus depot (*if applicable*, for battery electric, fuel cell electric, or fuel cell hybrid plug-in electric) [$/station]
        iv. Land for charging stations en route (*if applicable*, for battery electric, fuel cell electric, or fuel cell hybrid plug-in electric) [$]
        v. Infrastructure for hydrogen refueling (*if applicable*, for hydrogen fuel cell and fuel cell hybrid plug-in electric) [$/station]

vi. Land for hydrogen refueling at bus depot (*if applicable*, for hydrogen fuel cell and fuel cell hybrid plug-in electric) [$]
vii. Hydrogen delivery to bus depot [$]

D. **Maintenance** [$/km]
E. **Annual Maintenance** [$]
F. **Research prior to implementation** [$] (*if applicable*)
G. **Training prior to implementation** [$] (*if applicable*)
H. **Training during implementation** [$] (*if applicable*)
I. **Operational cost** [$/km]
J. **Other** [$] (*please specify*)

5. What is the length of the return-on-investment [years]?

Fleet- and Operation-Related Questions

1. Number of new buses:
2. Number of retrofitted buses:
3. What is the percent of zero-emission buses in your fleet?
4. What is the average service life of a bus?
5. How many bus stops on average does the bus have along the route?
6. What is the average travel distance per trip (from first to last stop) [miles]?
7. What is the average travel distance per day [miles]?
8. What is the average distance between bus stops [miles]?
9. What is the distance from bus depot to first bus stop [miles]?
10. What is the distance from last stop to bus depot [miles]?
11. What is the average travel time per trip (from first stop to last stop) [min]?
12. How many days per week of service do the buses operate?
13. How many hours per day of service do the buses operate?
14. How often do the buses require maintenance?
15. What is the availability of these buses (the percentage of days the buses are available out of days that buses are planned for operation) [%]?
16. How does this availability compare with other conventional fuel buses you have in your fleet [%] (*if applicable*)?
17. What is the maximum grade that the bus can operate at with a full load %]?
18. Was emission savings compared to conventional buses calculated? If yes,
    A. Reduction in CO emissions [%]
    B. Reduction in CO_2 emissions [%]
    C. Reduction in NO emissions [%]
    D. Reduction in PM emissions [%]
    E. Reduction in hydrocarbon emissions [%]
    F. Others [%]
19. What model/method was used to estimate emission savings?

20. Was noise pollution for the buses calculated? (*please circle*)
    A. Yes [Noise Level, dB]
    B. No
21. Which zero-emission bus technology was implemented? (*please circle one*)
    A. **Battery electric**: This bus design includes an onboard battery system that is operated solely with electric power.
    B. **Hydrogen fuel cell:** This bus type has an onboard fuel cell that directly powers the drivetrain. No onboard energy storage, such as a battery or supercapacitor, is available.
    C. **Hydrogen fuel cell battery electric:** This bus design incorporates an energy storage platform (*i.e.* battery, supercapacitor) to capture excess energy generated by the fuel cell or regenerative braking.
    D. **Hydrogen fuel cell hybrid plug-in electric**: This bus type operates entirely in an electric mode. Energy is supplied from the electrical grid via a plug-in charger or generated by the on-board fuel cell.

SECTION B: TECHNOLOGY-RELATED INFORMATION

Module I: Battery Electric Buses

1. What is the driving range [miles]?
2. What is the maximum speed [miles/hr]?
3. What is the average cruising speed [miles/hr]?
4. What is the name of the bus manufacturer? (*please circle one and indicate bus model and year*)
    A. Build Your Dreams (BYD)
    B. Complete Coach Works
    C. Gillig
    D. New Flyer
    E. Proterra
    F. Other (*please specify*)
5. What is the name of the battery manufacturer(s)? (*please circle one)*
    A. Altairnano
    B. Tesla
    C. Other (*please name*)
6. What is the type of batteries on board?
    A. Lithium cobalt
    B. Lithium titanate
    C. Nickel cadmium
    D. Other (please specify)
7. What is the model of the batteries?

A. Terravolt
B. Other (please specify)

8. How many batteries are on board the vehicle?
9. What percent increase does regenerative breaking provide?
10. What is the name of the battery charging company?
11. What is the electricity source? (*please circle*)
    A. Grid
    B. Solar
    C. Wind
    D. Other (*please specify*)
12. What kind of charging method is used? (*please compete all that apply*)
    A. **Overnight plug-in:** *Slow charge (hours) where the battery is connected to the electrical grid.*
        i. How many hours of charging is needed to reach a full charge?
        ii. What is the range of one charge [miles]?
        iii. What is the electricity cost overnight [$/kWh]?
        iv. Where does the overnight charging occur?
        v. How many charging bays are at the station?
    B. **Opportunity charging:** *Fast charge (minutes) that is usually conducted using overhead receptacles.*
        i. Where are buses charged? (*please circle one and specify locations*)
            En route
            Not along the bus route
        ii. How many charging stations?
            En route
            Not along the bus route
        iii. How many chargers in each station?
            A. En route:
            B. Outside the bus route
        iv. How long does every charging episode take [min]?
        v. What is the range of one charge [miles]?
        vi. What is the frequency of charging during the day?
    C. **Flash charging:** *Very fast high-power charge (seconds), typically conducted with two coils located at the top and bottom of the bus.*
        i. Where are buses charged? (*please circle one and specify locations*)
            En route
            Not along the bus route
        ii. How many charging stations?
            En route

Not along the bus route

iii. How many chargers in each station?
    C. En route:
    D. Outside the bus route
iv. How long does every charging episode take [min]?
v. What is the range of one charge [miles]?
vi. What is the frequency of charging during the day?

D. **Other** (*please specify*)

Module II: Hydrogen Fuel Cell Buses

1. What is the driving range [miles]?
2. What is the maximum speed [miles/hr]?
3. What is the average cruising speed [miles/hr]?
4. What percent increase does regenerative breaking provide?
5. Which company manufactured the bus? (*please circle one and indicate bus model and year*)
    A. ElDorado
    B. Gillig
    C. New Flyer
    D. Proterra
    E. Van Hool
    F. Other (*please specify*)
6. What is the type of power configuration? (*please circle one*)
    a. Fuel cell (direct use, no energy storage platform)
    b. Fuel cell battery electric (with onboard energy storage):
7. For fuel cell battery electric buses, what is the dominant energy source? (*please circle one*)
    A. Energy storage device
    B. Fuel cell
8. For fuel cell battery electric buses, which company manufactured the hybrid integration system? (*please circle one*)
    A. BAE systems
    B. Bluways
    C. ISE Corporation
    D. Siemens
    E. Van Hool
    F. Other (*please specify*)

Fuel Cell Buses or Fuel Cell Battery Electric Buses (Fuel Cell Component)

1. Which company manufactured the hydrogen fuel cell? (*please circle one and indicate the model*)
    A. Ballard
    B. Hydrogenics
    C. UTC Power
    D. Other (*please specify*)
2. How is the hydrogen produced? (*please circle one*)
    A. Off-site and delivered
        i. Gas delivery
        ii. Liquid delivery
    B. Produced on-site
        i. Electrolyzer
        ii. Methanol reformer
        iii. Natural gas reformer
3. What is the capacity of the hydrogen storage tank on-board the bus [kg]?
4. How many hydrogen storage tanks are on-board the bus?
5. How many stations are there for hydrogen refueling?
6. Who supplies the hydrogen fuel (if off-site)? (*please circle one*)
    A. Air Liquide
    B. AirGas
    C. Linde
    D. Other (*please specify*)
7. Where does hydrogen refueling occur? (*please circle one*)
    A. At the bus depot
    B. Off-site at a hydrogen fuel station (*specify station*)
8. What is the overall hydrogen dispensing capacity of the station [kg/day]?
9. What is the hydrogen fill rate [kg/min]?
10. What is the hydrogen dispenser pressure [bar]?
11. What is the maximum hydrogen production rate per session [kg]?
12. What is the hydrogen pressurization method (*e.g.*, diaphragm compressor, gas compressor)?
13. What is the hydrogen storage pressure [psi]?
14. What is the hydrogen storage capacity [kWh]?
15. What is the area of the hydrogen refueling station [ft^2]?
16. How many times per day does a bus need to be refueled with hydrogen?
17. How long does hydrogen refueling take [min]?

1. What is the name of the battery manufacturer(s)? (*please circle one)*
    A. A123 Systems
    B. EnerDel
    C. Valence
    D. ZEBRA
    E. Other (*please specify*)
2. What is the type of batteries on board?
    A. Lithium cobalt
    B. Lithium titanate
    C. Nickel cadmium
    D. Other (*please specify*)
3. What is the model of the batteries?
    A. Terravolt
    B. Other (*please specify*)
4. How many batteries are on board the vehicle?
5. What percent increase does regenerative breaking provide?

Module III: Fuel Cell Hybrid Plug-In Electric Buses

1. What is the driving range [miles]?
2. What is the maximum speed [miles/hr]?
3. What is the average cruising speed [miles/hr]?
4. What percent increase does regenerative breaking provide?
5. Is the location for battery charging and hydrogen supply the same?
6. Which company manufactured the bus? (*please circle one and indicate bus model and year*)
    A. Proterra
    B. EVAmerica
    C. Ebus
    D. Other (*please specify*)
7. Which company manufactured the hybrid integration system? (*please circle one*)
    A. BAE systems
    B. Bluways
    C. ISE Corporation
    D. Siemens
    E. Van Hool
    F. Other (*please specify*)

Fuel Cell Hybrid Plug-in Electric Buses (Battery Component)

8. What is the name of the battery manufacturer? (*please circle one*)
    A. Altairnano
    B. SAFT
    C. Other (*please specify*)
9. What is the type of batteries on board? (*please circle one*)
    A. Lithium titanate
    B. Nickel-cadmium
    C. Other (*please specify*)
10. What is the model of the batteries? (*please circle one*)
    A. Terravolt,
    B. Other (*please specify*)
11. How many batteries are on board the vehicle?
12. What is the charging power of each battery [kW]?
13. What is the energy storage capacity of each battery [kWh]?
14. What is the battery charging company?
15. What is the electricity source? (*please circle*)
    A. Grid
    B. Solar
    C. Wind
    D. Other (*please specify*)
16. Where and when does the charging occur?
17. How many hours of charging is needed to reach a full charge?
18. What is the range of one charge [miles]?
19. What is your cost of electricity [$/kWh]?
20. How many stations does charging occur at?

Fuel Cell Hybrid Plug-In Electric Buses (Fuel Cell Component)

1. Which company manufactured the hydrogen fuel cell? (*please circle one and indicate the model*)
    A. Ballard
    B. Hydrogenics
    C. UTC Power
    D. Other (*please specify*)
2. How is the hydrogen produced? (*please circle one*)
    A. Off-site and delivered
        i. Liquid delivery
        ii. Gas delivery
    B. Produced on-site

i. Electrolyzer
ii. Methanol reformer
iii. Natural gas reformer

3. What is the capacity of the hydrogen storage tank on-board the bus [kg]?
4. How many hydrogen storage tanks are on-board the bus?
5. For hydrogen delivery, who supplies the hydrogen fuel? (*please circle one*)
    A. Air Liquide
    B. AirGas
    C. Linde
    D. Other (*please specify*)
6. Where does hydrogen refueling occur? (*please circle one*)
    A. At the bus depot
    B. Off-site at a location other than the bus depot (specify stations name)
7. How many stations are there for hydrogen refueling?
8. What is the overall hydrogen dispensing capacity of each stations [kg/day]?
9. What is the hydrogen fill rate [kg/min]?
10. What is the hydrogen dispenser pressure [bar]?
11. What is the maximum hydrogen production rate per session [kg]?
12. What is the hydrogen pressurization method (*e.g.*, diaphragm compressor, gas compressor)?
13. What is the hydrogen storage pressure [psi]?
14. What is the hydrogen storage capacity [kWh]?
15. What is the area of the hydrogen refueling station(s) [ft^2]?
16. How many times per day does a bus need to be refueled with hydrogen?
17. How long does hydrogen refueling take [min]?

Table B.1: Individuals who were interviewed as part of this report

Transit agencies

No.	Name	Organization	Bus Technology Discussed
1	Steve Hahn	Santa Barbara Metropolitan Transit District	Battery Electric
2	Annette Darrow	Indianapolis Public Transportation Corporation	Battery Electric
3	Brian Jackson	Stanford University	Battery Electric
4	Jonathan Church	Worcester Regional Transit Authority	Battery Electric
5	Cole Pouliot	Pioneer Valley Transit Authority	Battery Electric
6	Angie Grant	Martha's Vineyard Transit Authority	Battery Electric
7	Carrie Butler	Transit Authority of Lexington	Battery Electric
8	Roland Cordero	Foothill Transit	Battery Electric
9	Len Engel	Antelope Valley Transit Authority	Battery Electric
10	Keith Moody	Clemson Area Transit	Battery Electric
11	Kirt Conrad	Stark Area Regional Transit Authority	Fuel Cell
12	Tim Rudek	University of California Irvine	Fuel Cell
13	Jennifer Kritzler	Connecticut Transit Authority	Fuel Cell
14	Ajay Prasad	University of Delaware	Fuel Cell Hybrid Plug-In
15	Jason Bakos	Central Midlands Regional Transit Authority	Fuel Cell Hybrid Plug-In
16	Bryan Ross	Massachusetts Bay Transportation Authority	Fuel Cell

External agencies with experience reviewing ZEB performance

No.	Name	Organization	Bus Technology Discussed
17	Leslie Eudy	National Renewable Energy Laboratory	Battery Electric and Fuel Cell
18	Jaimee Levin	Center for Transportation and the Environment	Battery Electric and Fuel Cell
19	Yachun Chow	California Air Resources Board	Battery Electric and Fuel Cell
20	Steve Clermont	Center for Transportation and the Environment	Battery Electric and Fuel Cell
21	Fan Tong	Carnegie Melon University	Battery Electric

Fuel cell company

No.	Name	Organization	Bus Technology Discussed
22	Brian Bowers	NUVERA	Fuel Cell

6.3 Appendix C: Battery Electric Bus Implementation Characteristics

Table C.1: Charging strategies used by U.S. transit agencies for battery electric buses

Transit Agency	Bus Manufacturer	Fueling Method
Antelope Valley Transit Authority (CA)	Build Your Dreams	*Chargers*: Total of 87 charge stations (15 inductive; 72 conductive) located on-route and at transfer stations. *Charging time*: 10 minutes (inductive); minutes (conductive)
Chicago Transit Authority (IL)	New Flyer	*Chargers*: A slow-charging station is available for the buses. *Charging time*: 3 to 5 hours (plug-in)
Clemson Area Transit (SC)	Proterra	*Chargers*: One fast charger on-route and one slow charger for overnight charging at the bus depot. *Charging time*: 6 minutes (conductive, fast-fill); several hours (plug-in)
Dallas Area Rapid Transit (TX)	Proterra	*Chargers*: Four fast-fill charging stations (two at the depot, two at the central station). Slow plug-in chargers are also available at the bus depot. *Charging time*: minutes (conductive, fast-fill); several hours (plug-in)
Foothill Transit (CA)	Proterra	*Chargers*: On-route fast fill and a slow charger at maintenance facilities to be used as needed. *Charging time*: 5 minutes (conductive, fast-fill); several hours (plug-in)
Indianapolis Public Transportation Corp. (IN)	Complete Coach Works	*Chargers*: Total of 22 slow plug-in chargers available at a solar-powered garage. Range of 130 miles. *Charging time*: 4 to 6 hours (plug-in)
Los Angeles County Metropolitan Transit Authority (CA)	New Flyer	*Chargers*: Total of 5 charging bays at station available at one charging station. Range 80 to 100 miles on one charge. Charging completed on third shift. *Charging time*: 4 hours (plug-in)
Pioneer Valley Transit Authority (MA)	Proterra	Chargers: One overhead charging station available at 2 locations on-route and one slow charger at the garage. Range of 40 miles. *Charging time:* 6 to 9 minutes (conductive)
Regional Transportation Commission Washoe (NV)	Proterra	*Chargers*: Two chargers, one fast and one slow. *Charging time*: minutes (conductive, fast-fill); several hours (plug-in)
Santa Barbara MTD (CA)	Ebus	Chargers: Bus depot has 14+ plug-in chargers. Range of less than 100 miles. *Charging time:* 3+ hours charge time for $LiFePO_4$ batteries, 5+ hours charge time for NiCd batteries (plug-in)
StarMetro Transit (FL)	Proterra	*Chargers*: Fast-fill charging station. *Charging time*: 10 to 15 minutes (conductive, fast-fill)
University of California Los Angeles (CA)	Build Your Dreams	*Chargers*: Slow charge solar-powered charging stations. Number of chargers was not reported. *Charging time*: 4 hours (plug-in)
VIA Metropolitan Transit (TX)	Proterra	*Chargers*: Plug-in charger and fast-fill charger at the bus depot. *Charging time*: minutes (conductive, fast-fill); several hours (plug-in)
Washington Metropolitan Area Transit Authority (DC)	Proterra	*Chargers*: On-route fast-fill available. *Charging time*: 10 minutes (conductive, fast-fill)

Table C.2: Overview of battery electric bus specifications by transit agency in the U.S.

Transit Agency	Antelope Valley Transit Authority* [87]	Capital District Transportation Authority* [10,88]	Central Contra Costa Transit Agency	Chicago Transit Authority*	Clemson Area Transit [22]	Dallas Area Rapid Transit *	Foothill Transit [31]	Indianapolis Public Transportation Corporation [89]	King County Metro* [90]	Los Angeles County Metropolitan Transportation Authority *
Bus Fleet Size	2	1	4	2	6 10	7	30	21	3	5
Bus Manufacturer	Build Your Dreams	New Flyer	Gillig	New Flyer	Proterra Proterra	Proterra	Proterra	Complete Coach Works	Proterra	New Flyer
Model	K11 Electric	Xcelsior XE60	NR	Xcelsior XE40	EcoRide BE35 Catalyst E2	NR	Catalyst	Retrofitted Gillig	Catalyst FC+	Xcelsior XE60
Year	2016	2016	NR	2014	2015 2017	2015	2014	2001	2015	NR
Length (ft)	60.6	60		40	35 & 42.5	35	35	40	42.5	60
Width (in)	101.6	102	NR	102	102 & NR	NR	102	102	NR	102
Height (in)	134.5	133		130	136 & 134	NR	129	NR	135.6	133
Gross Vehicle Weight (lbs)	65,036	45,500	NR	30,500	38,000 43,650	NR	37,320	39,600	39,500	45,500
Battery OEM	NR	Parker Vansco	NR	Parker Vansco	NR	NR	Altairnano	Samsung	NR	Parker Vansco
Battery Type	Iron-Phosphate	Lithium-ion	NR	Lithium-ion	NR	NR	Lithium-titanate	Lithium-cobalt	Lithium-titanate	Lithium-ion
Battery Model	NR	NR	NR	Mitsubishi	NR	Terravolt	Terravolt	NR	NR	NR
Battery Power (kW)	180	NR	NR	NR	NR	NR	220	90	120	NR
Capacity (kWh)	324	250	NR	200	NR 440–660	NR	88	213	126	250
Capital Cost Per Bus ($)	NR	900,000	NR	735,000	NR 700,000	NR	537,000	NR	NR	900,000
Seating Capacity	102	61	NR	32	37 40	NR	55	NR	28	59
Availability (%)	NR	NR	NR	NR	NR	NR	90	66	84–98	62

**For transit agencies that did not provide bus specifications, information was obtained from the bus or battery manufacturer.*
NR: Not Reported

Table C.2 (continued): Overview of battery electric bus specifications by transit agency in the U.S.

Transit Agency	Regional Transportation Commission, Washoe*	Santa Barbara Metropolitan Transit District	Shreveport Area Transit*	Southeastern Pennsylvania Transportation Authority	Stanford University[91]	StarMetro Transit	Transit Authority of the Lexington Fayette Urban County Government *	University of California, Los Angeles *	Utah Transit Authority *
Bus Fleet Size	4	14	5	25	23	5	5	2	5
Bus Manufacturer	Proterra	E-bus	Proterra	Proterra	Build Your Dreams	Proterra	Proterra	Build Your Dreams	New Flyer
Model	NR	NR	Catalyst	Catalyst	NR	EcoRide BE-35	Catalyst E2	K9	Xcelsior Electric XE40
Year	2014	2000	2016	2016	2016: 30 ft. 2014: 40 ft.†	NR	2015	2016	2015
Length (ft)	NR	22	42.5	42.5	40	35	42.5	40	40
Width (in)	NR	99	NR	NR	101.5	102	NR	101.6	102
Height (in)	NR	92	135.6	135.6	133	134	134	134.5	130
Gross Vehicle Weight (lbs)	NR	16,000	39,050	39,050	39,150	35,660	43,650	39,680	30,500
Battery OEM	Tesla	CALB, Thundersky, Winston	NR	NR	NR	Altairnano	NR	NR	Parker Vansco
Battery Type	Lithium-ion	Nickel Cadmium	Lithium-titanate	Lithium-titanate	Lithium	Lithium-titanate	NR	Iron-Phosphate	Lithium-ion
Battery Model	NR	400AH	NR	NR	BYD	TerraVolt	NR	NR	Mitsubishi
Battery Power (kW)	NR	120	120	120	90	150	NR	180	NR
Capacity (kWh)	NR		440–660	440–660	NR	72	440–660	270	200
Capital Cost Per Bus ($)	850,000	350,000	749,000	749,000	NR	825,000	750,000	700,000	735,000
Seating Capacity	NR	22	40	40	36	37	40	NR	32
Availability (%)	NR	90	NR	NR	NR	NR	NR	NR	NR

**For transit agencies that did not provide bus specifications, manufacturer sources were used. Current year model information was provided from manufacturer.*
† All listed bus specifications are for the 40-foot bus model.
NR: Not Reported

Table C.2 (continued): Overview of battery electric bus specifications by transit agency in the U.S.

Transit Agency	VIA Metropolitan Transit*	Washington Metropolitan Area Transit Authority*
Bus Fleet Size	3	1
Bus Manufacturer	Proterra	New Flyer
Model	NR	Xcelsior Electric XE40
Year	2017	2015
Length (ft)	40	40
Width (in)	NR	102
Height (in)	NR	130
Gross Vehicle Weight (lbs)	NR	30,500
Battery OEM	NR	Parker Vansco
Battery Type	NR	Lithium-ion
Battery Model	NR	Mitsubishi
Battery Power (kW)	NR	NR
Capacity (kWh)	NR	200
Capital Cost Per Bus ($)	NR	735,000
Seating Capacity	NR	32
Availability (%)	NR	NR

**For transit agencies that did not provide bus specifications, manufacturer sources were used. Current year model information was provided from manufacturer.*
NR: Not Reported

Table C.3: Route and stop features of battery electric buses obtained from interviews and surveys

Transit Agency	Miles traveled annually per bus	Average # stops per route	Average miles per trip	Average miles per day	Average miles between stops	Travel time per trip (min)	Average speed (mph)	# Days per week	Hours per day operate
Clemson Area Transit	NR	NR	NR	NR	NR	NR	NR	NR	NR
Indianapolis Public Transportation Corporation	40,000	NR	NR	NR	0.2	NR	14.5	5	7
Los Angeles County Metropolitan Transportation Authority	5,371	64	16	49	5.3	60	8	5	8
Pioneer Valley Transit Authority	NR	35	18	255	8.3	60	NR	7	13
Santa Barbara Metropolitan Transit District	20,000	10	5	80	0.1	NR	12	7	13
Stanford University	20,000	20	3	100	0.25	30	25	5	8
Transit Authority of the Lexington Fayette Urban County Government	NR	NR	NR	NR	NR	NR	NR	NR	NR
Worcester Regional Transit Authority	NR	NR	NR	NR	NR	NR	NR	NR	NR

NR: Not Reported.

Table C.4: Fuel economy and fuel cost per mile for battery electric buses implemented by transit agencies in the U.S.

Transit Agency	Fuel Economy		Fuel Cost per Mile	
	Battery Electric (mpdge)	Conventional Diesel (mpg)	Battery Electric ($/mile)	Conventional Diesel ($/mile)
Clemson Area Transit (SC)	17.0	3.9	0.26	0.66
Foothill Transit (CA)	17.5	NR	0.39	NR
Indianapolis Public Transit	NR	5	NR	NR
King County Metro (WA)	16.7	5.4	0.18	0.44
Los Angeles MTA (CA)	12.1	2.7	NR	NR
Regional Transportation Commission Washoe (NV)	17.0–29.0	3.8	NR	NR
Santa Barbara MTD (CA)	27.32	4.0	NR	NR
StarMetro (FL)	NR	NR	0.72[62]	0.90
Worcester Regional Transit Authority (MA)	8*–23	4–5	0.40	0.60

NR: Not Reported; mpg: miles per gallon; mpdge: miles per diesel gallon equivalent
**Low fuel economy is attributed to low temperatures during the winter months.*

Table C.5: Performance measures for battery electric buses implemented by transit agencies in the U.S.

Transit Agency	Operation Period (mm/yy)	Fleet Size	Total Hours	Total Miles	Average Monthly Miles	Average Speed (mph)	Availability	Miles Between Road Calls (miles)	
								Bus	Propulsion
Foothill Transit (CA)	4/14–7/15 8/15–12/16	12 12	47,462 58,497	401,244 501,039	2,333 2,456	8.4 NR	90% 90%	9,331 6,180	25,078 16,405
King County Metro (WA)	4/16–11/16	3	6,688	70,691	2,467	10.6	84–98%	2,433	6,488

Transit Agency	Battery Electric Bus Fuel Economy (mpdge)	Battery Electric Bus Fuel Cost per Mile ($/mile)	Diesel Bus Fuel Economy (mpg)
Foothill Transit (CA)	17.5 17.4	0.35–0.60	4.34
King County Metro (WA)	16.7	0.40–0.60	5.4

NR: Not Reported

Table C.6: Maintenance costs for battery electric buses implemented by transit agencies in the U.S.

Transit Agency	Cost of maintaining a BEB [$/mile/bus]	Cost of maintaining a conventional bus [$/mile/bus]	How maintenance services are provided for buses	Cost of midlife rehabilitation or overhaul of buses [$]	Annual maintenance cost per ZEB [$/bus]
Alameda-Contra Costa Transit	NR	1.15	NR	NR	172,912
Clemson Area Transit	NR	NR	NR	NR	NR
Foothill Transit	0.16-0.21	0.22	Proterra	NR	NR
Indianapolis Public Transportation Corporation	NR	NR	In-house	NR	NR
Los Angeles County Metropolitan Transportation Authority	>1.00	3	In-house	NR	21,000
Santa Barbara Metropolitan Transit District	>1.00	<1.00	In-house	100,000	7,000
Stark Area Regional Transit Authority and Ohio State University	NR	NR	In-house	NR	NR
Pioneer Valley Transit Authority	NR	NR	Proterra	NR	NR
Stanford University	NR	NR	Third party	NR	NR
Transit Authority of the Lexington Fayette Urban County Government	NR	NR	In-house	NR	NR
University of Central Florida	NR	NR	NR	NR	NR
Worcester Regional Transit Authority	NR	NR	Proterra	NR	52,908

NR= Not reported

Table C.7: Funding sources used by transit agencies for battery electric bus projects in the U.S.

Transit Agency	Funding Source	Year Use	Purchases	Total Awarded Amount
Clemson Area Transit (SC)	TIGGER III grant	2010	Buses, charging station, and maintenance storage facility	NR
	LoNo Grant	2016	Buses	$3.9 million
Dallas Area Rapid Transit (TX)	LoNo Grant	2015	Buses, infrastructure, maintenance	$7.6 million
Foothill Transit (CA)	American Recovery and Reinvestment grant; TIGGER grant	2014	Charging stations, transit centers, and maintenance facility	$10.2 million
Indianapolis Public Transportation Corp.	TIGER grant	2014	Buses	$10 million
	State of Good Repair grant	2014	Solar panels for garage	$3 million
King County Metro (WA)	TIGGER grant	2010	Buses	NR
Los Angeles County MTA (CA)	MeasureR local funds	2017	NR	$4.5 million
Martha's Vineyard Transit Authority (MA)	MassDOT's Regional Authority Capital Asset Program	2017	Buses	$1.4 million
	LoNo Grant		Buses and cost share for energy storage system	$1.2 million
Massachusetts Bay Transportation Authority (MA)	LoNo Grant	2015	Buses	$4.1 million
Pioneer Valley Transit Authority (MA)	FTA MassDOT	2016	NR	$1.8 million $1.9 million
Regional Transportation Commission Washoe (NV)	TIGER grant Local Sales Tax	2010	Charging stations, transit centers, and maintenance facility	$12.5 million

Transit Agency	Funding Source	Year Use	Purchases	Total Awarded Amount
Santa Barbara MTD (CA)	FTA, City of Santa Barbara, City of Carpinteria	1990–2000	NR	NR
StarMetro (FL)	TIGGER II grant	2011	Infrastructure, vehicle introduction promotion, program management	$6.47 million
Transit Authority of the Lexington Fayette Urban County Government (KY)	LoNo Grant	2015–2017	Buses, equipment and facilities	$6.4 million $683,400 $1 million
VIA Metropolitan Transit (TX)	TIGGER grant	2011	Buses	$5.0 million
Worcester Regional Transit Authority (MA)	Clean Fuels Grant	2012	Buses, shop charger, overhead fast charger, and other equipment	$4.4 million
	Section 5307 formula funds	2012–2013	Buses	NR

NR: Not Reported

6.4 Appendix D: Fuel Cell Bus Implementation Characteristics

Table D.1: Fueling strategies and facilities used by transit agencies for fuel cell buses in the U.S. and Canada

	Transit Agency						
	AC Transit[40,69]	**BC Transit**[66,69]	**CTTRANSIT**[92]	**Santa Clara VTA**[56]	**SARTA**[5050]	**SunLine**[70]	**UC Irvine**[69]
Fuel Supplier	Linde	Air Liquide	UTC Power	Air Products	Air Products	HyRadix	Air Products
Hydrogen Source	Liquid Delivery	Liquid Delivery	Liquid Delivery	Liquid Delivery	Liquid Delivery	Natural Gas Reformer	Liquid Delivery
Station Dispensing Capacity (kg/day)	600	800	NR	NR	300	216	100
Max Production Rate (kg/day)	65 (electrolyzer only)	No Production	NR	No Production	No Production	216	NR
Pressurization Method	Gaseous Compressor	Liquid Hydrogen Pumps	NR	Liquid Compression System	Liquid Compression System	Gaseous Compressor	Gaseous Compressor
Dispenser Pressure (bar)	350–700	350	NR	350	350	350	350
Fill Rate (kg/min)	Fast (1.93)	Fast	NR	Fast (1.35)	Fast	Fast (1)	Fast
Fueling Time (min)	6	15–20	10	16	NR	18	24
Active Communications	NR	NR	NR	Yes	NR	NR	Yes
Fleet Size	13	20	5	3	11	5	1
Fueling on Bus Depot	Yes	Yes	No	Yes	Yes	Yes	Yes
Station Capital Cost (million $)	10	4.7	NR	0.64	1.8	0.75 for reformer only	0.28
Hydrogen Cost ($/kg)	9.10	10.55	NR	9.06	4.52	7.66–23.46	12.99
Maintenance Cost ($/year)	142,000	NR	NR	Included in monthly fee to Air Products	NR	NR	NR

NR: Not reported

Table D.2: Fuel cell bus specifications by transit agency in the U.S. and Canada

	AC Transit[40]	BC Transit[93]	AC Transit[94,92] CTTRANSIT[92] SunLine[92]	CTTRANSIT [55]	Santa Clara VTA*[94]	SunLine[46]	SunLine[45]	UC Irvine[47]
Number of Buses	13	20	5	4	3	4	1	1
Bus OEM	Van Hool	New Flyer	Van Hool	Van Hool	Gillig low floor	ElDorado	New Flyer	ElDorado
Model/Year	A300L/2010	H40LFR 2010	A330 low-floor	A300L/2010	2004 model	Axcess 2011, 2014	H40LFR 2011	Axcess 2011, 2015
Bus Length, Height, Width (ft/in/in)	40/136/102	40/123/102	40/137/102	40/136/106	40/144/102	40/NR/NR	40/123/102	40/NR/NR
Gross Vehicle Weight (lbs)	39,350	44,530	43,420	39,350	40,600	43,420	44,530	43,420
Fuel Cell OEM	UTC Power	Ballard	UTC Power	UTC Power	Ballard	Ballard	Ballard	Ballard
Fuel Cell Model	Puremotion 120	FC Velocity HD6	Puremotion 120	Puremotion 120	P5-2	FC Velocity HD 6	FC Velocity HD 7	FC Velocity HD 7
Fuel Cell Power (kW)	120	150	60 (x2)	120	150 (x2)	150	150	150
Hybrid System Integrator	Van Hool	Bluways	Siemens ELFA	Van Hool	non-hybrid	BAE Systems	Bluways	BAE Systems
Design Strategy	Fuel Cell Dominant	Fuel Cell Dominant	Fuel Cell Dominant	Fuel Cell Dominant	NA	Fuel Cell Dominant	Fuel Cell Dominant	Fuel Cell Dominant
Battery OEM	EnerDel	Valence	ZEBRA	EnerDel	NA	A123	Valence	A124
Energy Storage Type	Li-ion	Li-ion	Sodium Nickel Chloride	Li-ion	NA	Li-ion	Li-ion	Li-ion
Energy Storage Capacity (kWh)	21	47	95	21	NA	11	48	12
Hydrogen Storage Pressure (psi)	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Hydrogen Cylinders	8	8	8	8	11	8	6	8
Hydrogen Capacity (kg)	40	56	50	40	55	50	43	60
Technology Readiness Level (TRL)	7–8	7	6	7	NA	7	7	7
Range (miles)	220–240	210–240	250–300	240	NR	270–325	210–230	244
Capital Cost per Bus	2.5	2.1	3.2–3.5	3.2	NR	2.5	1.2	2.1

*NR=Not reported; NA: Not applicable; * The Santa Clara VTA implementation was a direct-use fuel cell bus, and, therefore, no battery was present.*

Table D.3: Route and stop features of fuel cell buses obtained from interviews and surveys

Transit Agency	Miles traveled annually per bus	Average # stops per route	Average miles per trip	Average miles per day	Average miles between stops	Travel time per trip (min)	Average Speed (mph)	# Days per week	Hours per day operate
SARTA	NR	30	NR	220	1	40	NR	7	NR
UC Irvine/ Anteater Express	NR	10	NR	150	0.6	30	NR	5	NR

NR: Not reported

Table D.4: Performance measures for fuel cell buses implemented by transit agencies in the U.S. and Canada

Transit Agency (Program)	State	Demo. Period*	Fleet Size	Total Hours	Total Miles	Average Monthly Mileage (miles per bus)	Average Speed (mph)	Availability (%)	Miles Between Road Calls (MBRC) (miles)	Fuel Economy (mpdge)
AC Transit (NFCBP prototype)[72, 92, 94]	CA	Apr.2006–Oct.2007	3	5,499	60,198	1,056	10.9	80–90 (69 after 5 months)	1,230**	7.03
		Aug.2008–Jul.2009	3	8.636	83,156	2,310	9.6	69	Much lower than diesel buses	6.69
		Aug.2009–Jul.2010	3	7,794	76,112	2,114	9.8	68	~1,000**	NR
AC Transit & 4 other Bay Area Transit Agencies (ZEBA)[40, 46, 47, 95]	CA	Sep.2010–Jul.2011	12	8,663	96,209	1,755	11.1	67	NR	6.06
		Aug.2012–Jul.2013	12	18,251	156,789	1,089	8.6	81	Bus: 5,000 Propulsion: 7,500 Fuel Cell: 15,000	7.34
		Aug.2014–Jul.2015	12	40,559	360,587	2,504	8.9	75	Bus: 5,007 Propulsion: 8,011 Fuel Cell: 32,771	6.94
		Aug.2015–Jul.2016	13	48,356	412,610	2,645	8.5	77	Bus: 4,585 Propulsion: 9,169 Fuel Cell: 21,716	6.08
		Jan.2016–Dec.2016	13	NR	447,720	2,780	10	80	Bus: 1,569 Propulsion: 2,775 Fuel Cell: 7,184	6.12
BC Transit[91]	BC	Apr.2011–Mar.2013	20	156,887	1,318,830	2,748	NR	69	Bus: 1,523 Propulsion: 2,013 Fuel Cell: 8,347	4.53
CTTRANSIT (NFCBP prototype)[65, 72, 95]	CT	Aug.2008–Jul.2009	1	2,738	18,900	1,650	6.9	68	Much lower than diesel buses	4.74
		Aug.2009–Jul.2010	1	1,839	11,212	934	6.1	52	~1,000**	6.34
CTTRANSIT (Nutmeg)[64]	CT	Oct.2010–Jul.2011	4	3,756	50,708	1,268	13.5	44	NR	5.25
		Aug.2012–Jul.2013	4	1,914	24,479	510	12.8	51	Bus: 3,000 Propulsion: 6,000 Fuel Cell: 24,000	7.1
Santa Clara VTA[56, 94]	CA	Mar.2005–Jul.2006	3	NR	40,429	793	11.4	58	Propulsion: 919	3.52
		Nov.2004–Jun.2007	3	5,741	65,627	648	11.4	NR	NR	3.52
SunLine Transit (Thunder Power Bus)[70]	CA	Aug.2002–Feb.2003	1	640	8,800	1,257	17	71	NR	11.5
SunLine Transit (NFCBP prototype)[63, 65, 72, 90]	CA	Jan.–Nov.2006	1	NR	19,208	1,749	NR	61	Propulsion: 1,130	8.28
		Aug.2007–Jul.2008	1	1,532	19,306	1,609	12.6	68	Propulsion: 4,000	131% > CNG
		Jan.2006–Mar.2008	1	4,027	52,336	1,938	13	67	Propulsion: 1,130	NR
		Aug.2008–Jul.2009	1	1,559	21,556	1,796	13.8	63	Propulsion: ~3,900	142% > CNG
		Aug.2009–Jul.2010	1	1,965	25,537	2,128	13	69	Propulsion: ~2,000	149% > CNG

NR: Not reported
** For the missing periods in between, no data were recorded;*
***For transit agencies with a single number reported for MRBC, no specific component was provided.*

Table D.4 (continued): Performance measures for fuel cell buses implemented by transit agencies in the U.S. and Canada

Transit Agency (Program)	State	Demo. Period*	Fleet Size	Total Hours	Total Miles	Average Monthly miles	Average Speed (mph)	Availability (%)	Miles Between Road Calls (MBRC) (miles)	Fuel Economy (mpdge)
SunLine Transit (AT) [45,95]	CA	May.2010–Jul.2011	1	1,927	22,841	1,523	11.9	63	NR	6.69
		Feb.–Nov.2012	1	1,520	16,571	1,657	17	62	Bus: 8,286	5.93
		Aug.2013–Jul.2014	1	1,109	16,066	1,339	14.5	45	Bus: 3,213 Propulsion: 3,213	6.40
SunLine Transit (AFCB) [41,45,47,64,67]	CA	Aug.2011–Jul.2012	1	1,510	23,683	1,974	15.7	71	Bus: 1,692 Propulsion: 3,383 Fuel Cell: 7,894	7.83
		Aug.2012–Jul.2013	1	2,380	36,339	3,028	15.3	75	Bus: 4,159 Propulsion: 7,724 Fuel Cell: 28,000	7.20
		Aug.2013–Jul.2014	1	1,486	23,218	1,935	15.6	61	Bus: 2,580 Propulsion: 5,805 Fuel Cell: 11,600	6.99
		Aug.2014–Jul.2015	4	5,869	80,439	1,676	13.7	72	Bus: 3,830 Propulsion: 5,746 Fuel Cell 20,111	6.43
		Aug.2015–Jul.2016	4	8,799	123,374	2,570	13.7	77	Bus: 6,335 Propulsion: 8,025 Fuel Cell: 21,500	6.20
UC Irvine[47]	CA	Jan.–Jul.2016	1	2,379	18,221	2,603	NR	88	Bus: 4,170 Propulsion: 5,213 Fuel Cell: 10,425	5.82

NR: Not reported

** For the missing periods in between, no data were recorded.*

Table D.5: Reported fuel economy and fuel cost per mile for fuel cell buses in the U.S. and Canada

Transit Agency (Program)	Fuel Economy (mpdge)		Fuel Cost per Mile ($/mile)	
	Fuel Cell	Conventional*	Fuel Cell	Conventional*
AC Transit [65,72,92,94] (NFCBP prototype)	6.69–7.03	4	1.23–1.29	0.55
AC Transit [40] (ZEBA)	6.06–7.43	3.85–4.24	1.30–1.58	0.44
BC Transit [66,93]	4.53	4.28	2.62	NR
CTTRANSIT [65,92] (NFCBP prototype)	4.74–6.34	3.89	1.11	0.69
CTTRANSIT [64] (NFCBP Nutmeg)	7.10–7.87	3.9	NR	NR
SunLine (ThunderPower Bus)[70]	11.5	NR (CNG)	NR	NR
SunLine [65,72,92] (NFCBP prototype)	FC bus: 131–149% > CNG		1.1	0.61 (CNG)
SunLine [45,56,95] (AT)	5.93–6.69	3.11–3.33 (CNG)	1.25	0.29 (CNG)
SunLine [41,45,47,64,67] (AFCB)	6.20–7.83	3.11–3.32 (CNG)	1.35	0.34 (CNG)
Santa Clara VTA [56] (Fuel Cell direct use)	3.52	3.98	2.91	0.52
UCI [47] (AFCB)	5–5.82	NR	NR	NR

NR: Not Reported
** Refers to diesel (unless otherwise mentioned)*

Table D.6: Comparison of maintenance costs for fuel cell and conventional buses

Transit Agency	Bus Maintenance Costs ($/mile/bus)	
	Fuel Cell	Conventional**
AC Transit (NFCBP Buses)	0.57–0.70	0.25–0.68
AC Transit (ZEBA)	0.86–1.31	
BC Transit	1.60–1.70	NR
CTTRANSIT (NFCBP Bus)	1.04–8.45*	0.65–0.82
SunLine (NFCBP Bus)	0.42–0.44	0.48–0.54 (CNG)
SunLine (AT Bus)	0.47–0.84	
SunLine (AFCB)	0.39–0.54	
University of California Irvine	0.47	2.55

NR: Not reported
**This is an unusually high cost due to the labor costs associated with CTTRANSIT maintenance staff (not covered by the warrantee) and the fact that both the fuel cell and the hydrogen storage tank on the roof of the bus*[51].
***Refers to diesel (unless otherwise mentioned)*

Table D.7: Funding sources used by transit agencies for fuel cell buses in the U.S. and Canada

Transit Agency	Funding Source	Year of Award	Purchases	Total Awarded Amount
AC Transit (CA)[94]	MTA, BAAQMD, FTA, DOE, State of CA, CARB	2005 & 2010	Buses, maintenance facilities update, new fueling station	$21 million (2005–2010) $68.2 million (2010–2016)
BC Transit (BC Canada)	Federal, province, and private funds	2009	Buses, maintenance and fueling facilities	$89 million[66]
CTTRANSIT (CT)	NFCBP[92], DOE[96] NFCBP-Nutmeg[55]	2005 2007	Buses, maintenance facility	NR
Flint MTA (MI)[41]	NFCBP	2011	Bus	NR
MBTA (MA)[97]	NFCBP	2008	Bus	NR
OCTA (CA)[67]	NFCBP	2015	Bus	NR
Santa Clara VTA (CA)[56]	DOE, FTA, BAAQMD, Local sales tax	2004	Buses, infrastructure, maintenance	$18.5 million
SARTA (OH)	LoNo, OH DOT	2014, 2015 NR	Buses, fueling and maintenance facilities	$10.6 million $2.3 million
SunLine Transit (CA)	NFCBP TIGGER Federal funds	2005–2016	Buses, infrastructure expansion	NR
UC Irvine (CA)[98]	CalStart/Ballard/ BAE/Eldorado/ UC Irvine	2015	Bus, fueling station (update)	NR

NR: Not Reported

6.5 Appendix E: Fuel Cell Hybrid Plug-in Bus Implementation Characteristics

Table E.1: Hydrogen fueling and battery charging strategies used by transit agencies for fuel cell hybrid plug-in buses in the U.S.

	BJCTA	BurbankBus[99]	CapMetro	COMET[54]	Flint MTA	University of Delaware[69]	University of Texas
Battery Charging Power	NR	NR	NR	30 kW	NR	NR	NR
Power Source	Grid	Grid	Grid	Grid	NR	Grid, Wind, Solar	NR
Battery Charging Time	Overnight	Overnight	Overnight	Overnight	Overnight	NR	NR
Hydrogen Fuel Supplier	Air Liquide	AQMD Burbank Station	UT-CEM; AirGas (Backup)	AirGas	Air Products/ Proton	Air Liquide	University of Texas Center for Electromechanics
Hydrogen Source	Gas delivery in tube trailers	Natural gas reformer	Natural gas reformer; Gas delivery in tube trailers (backup)	Gas delivery in tube trailers	Electrolyzer	Liquid delivery	Natural gas reformer
Station Dispensing Capacity (kg/day)	NR	108	NR	66	NR	NR	48
Max Production Rate (kg/session)	NR	NR	29	NR	NR	NR	15
Pressurization Method	NR	Diaphragm compressor	Gas compressor	NR	NR	NR	Gas compressor
Dispenser Pressure (bar)	NR	350–700	310–362	483	NR	NR	310–362
Fill Rate (kg/min)	NR	1.74 (700 bar) 0.25 (350 bar)	NR	NR	NR	Fast	NR
Fueling Time (min)	NR	NR	NR	NR	NR	15	NR
Fueling at Bus Depot	NR	Yes	No	NR	NR	Yes	Yes
Station Capital Cost	NR	NR	NR	NR	NR	NR	NR
Hydrogen Cost ($/kg)	NR	NR	NR	9.93	NR	NR	NR
Maintenance Cost ($/year)	NR	NR	NR	24,000 AirGas rental fees	NR	NR	NR

NR: Not Reported; BJCTA: Birmingham-Jefferson County Transit Authority; CapMetro: Capital Metropolitan Transportation Authority; COMET: Central Midlands Regional Transit Authority; Flint MTA: Flint Mass Transportation Authority; UT-CEM: University of Texas Austin – Center for Electromechanics

Table E.2: Fuel cell hybrid plug-in bus specifications used by transit agencies in the U.S.

	BJCTA[47,100]	BurbankBus[101]	CapMetro[47]	COMET[54]	Flint MTA[47]	University of Delaware[58]	University of Texas[102,103]
Number of Buses	1	1	1	1	1	2	1
*Bus OEM**	EVAmerica	Proterra	Proterra	Proterra	Proterra	Ebus	Ebus
Model/Year	Ecobus	FCEB-35 /2009	HFC-35 /2009	HFC-35 /2009	HFC-35 /2009	NR	NR/2007
Bus Dimensions Length (ft)/ Width (in)	32/ NR	35/102	35/102	35/102	35/102	22/92	22/90
Gross Vehicle Weight (lbs)	25,300	27,000	27,680	27,000	27,680	20,500	19,500
Fuel Cell OEM	Ballard	Hydrogenics	Hydrogenics	Hydrogenics	Hydrogenics	Ballard	Ballard
Fuel Cell Model	FC Velocity HD6	HyPM HD16	HyPM	HyPM HD16	HyPM	Mark 9 SSL	NR
Fuel Cell Power (kW)	75	32 (16 x2)	60 (30 x2)	32 (16 x2)	NR	40	19.1
Hybrid System Integrator	Embedded Power Controls	Proterra	Proterra	Proterra	NR	NR	NR
Energy Storage OEM	Altairnano	Altairnano	Altairnano	Altairnano	Altairnano	SAFT	SAFT
Energy Storage Type	Lithium-titanate	Lithium-titanate	Lithium-titanate	Lithium-titanate	Lithium-titanate	Ni-Cd	Ni-Cd
Energy Storage Capacity (kWh)	54	NR	54	NR	NR	60	60
Hydrogen Storage Pressure (psi)	5,000	5,000	5,000	5,000	NR	5,000	5,000
Hydrogen Cylinders	5	4	4	4	NR	2	2
Hydrogen Capacity (kg)	25	29	29	29	NR	25.6	12
Technology Readiness Level	6	6	6	6	6	6	6
Capital Cost per Bus (million $)	NR	NR	1.2 (Loan from Proterra)*	1.2 (Loan from Proterra)*	1.2 (Loan from Proterra)*	NR	NR

NR: Not Reported
BJCTA: Birmingham-Jefferson County Transit Authority; CapMetro: Capital Metropolitan Transportation Authority; COMET: Central Midlands Regional Transit Authority; Flint MTA: Flint Mass Transportation Authority; OEM: Original Equipment Manufacturer.
**A single bus has been tested in sequence by multiple agencies.*

Table E.3: Reported fuel economy and fuel cost per mile for fuel cell hybrid plug-in buses implemented by transit agencies in the U.S.

Transit Agency	Fuel Economy	
	FCPB (mpdge)	Conventional Diesel (mpg)
Birmingham-Jefferson County Transit Authority (AL)[61]	7.1	NR
BurbankBus (CA)	NR	NR
Capital Metropolitan Transportation Authority (TX)[61]	7.0	NR
Central Midlands Regional Transit Authority (SC)[95]	8.3	NR
Flint Mass Transportation Authority (MI)	NR	NR
University of Delaware (DE)[59]	12.0	5.5
University of Texas (TX)[104]	7.9	NR

FCPB: fuel cell hybrid plug-in bus; mpg: miles per gallon; mpdge: miles per diesel gallon equivalent; NR: Not Reported

Table E.4: Funding sources used by transit agencies for fuel cell hybrid plug-in bus projects in the U.S.

Transit Agency	Funding Source	Year	Total Awarded Amount
Birmingham-Jefferson County Transit Authority (AL)	FTA, NFCBP (FTA)	2010	NR
BurbankBus (CA)	California Air Resources Board, California Energy Commission	2010	$1.37 million
Capital Metropolitan Transportation Authority (TX)	NFCBP (FTA)	2011	NR
Central Midlands Regional Transit Authority (SC)	NFCBP (FTA), South Carolina Research Authority	2014	NR
Flint Mass Transportation Authority (MI)	NFCBP (FTA)	NR	NR
University of Delaware (DE)	FTA	2005	NR
University of Texas (TX)	DOT/ FTA	2006	NR

NR: Not Reported
DOT: Department of Transportation; FTA: Federal Transit Administration; NFCBP: National Fuel Cell Bus Program