Fuel Cell Buses in U.S. Transit Fleets: Current Status 2011

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Technical Report
NREL/TP-5600-52927
November 2011

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Acronyms and Abbreviations

AC Transit	Alameda Contra-Costa Transit District
CARB	California Air Resources Board
CNG	compressed natural gas
CTE	Center for Transportation and the Environment
CTTRANSIT	Connecticut Transit
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
FCEB	fuel cell electric bus
ft	feet
FTA	Federal Transit Administration
GNHTD	Greater New Haven Transit District
kg	kilograms
MBRC	miles between roadcalls
mpdge	miles per diesel gallon equivalent
mph	miles per hour
NAVC	Northeast Advanced Vehicle Consortium
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
SFMTA	San Francisco Municipal Transportation Agency
UT	University of Texas
ZEBA	Zero Emission Bay Area

Executive Summary

This report is the fifth in a series of annual status reports that summarize the progress resulting from fuel cell transit bus demonstrations in the United States and provide a discussion of the achievements and challenges of fuel cell propulsion in transit. Progress this year includes an increase in the number of fuel cell electric buses (FCEBs), from 15 to 25, operating at eight transit agencies. The operating FCEBs include 16 new buses from Van Hool and UTC Power that use a Siemens hybrid electric propulsion system and Ener1 lithium-based batteries for energy storage. These buses are operating in two locations: 12 in San Francisco, California; and 4 in Hartford, Connecticut. This represents the largest FCEB demonstration in the United States.

Three of the FCEBs in the San Francisco Zero Emission Bay Area (ZEBA) demonstration are accumulating significant fuel cell power system operating hours—at 6,000, 7,500, and 10,000 hours without any significant issues or cell replacements. This represents significant progress toward meeting targets for reliability and durability of the fuel cell power system in this application.

Additionally, the newer buses that began operating this past year have increased the diversity of the fuel cell design options for transit buses. In previous years, the focus has been on fuel cell dominant hybrid electric bus designs (accounting for 19 of the current 25 FCEBs). Several new FCEBs have been introduced with battery dominant fuel cell hybrid electric designs. This bus design has a larger energy storage system and a relatively small fuel cell power system that charges the batteries and acts primarily as a range extender (accounting for 5 of the current 25 FCEBs). One of the new FCEBs uses a small fuel cell power system as an auxiliary power unit for electric accessories; this system can also be used to help propel the hybrid electric bus.

This report also provides a summary of evaluation results from the National Renewable Energy Laboratory (NREL) funded by the U.S. Department of Energy (DOE) and the U.S. Department of Transportation's (DOT) Federal Transit Administration (FTA). These evaluations cover 22 of the 25 FCEBs currently operating. Summary results through July 2011 for these buses account for nearly 400,000 miles and 37,500 hours of fuel cell power system operation. Fuel economy has achieved twice that of standard diesel buses, but these results are highly duty cycle dependent. Roadcall results for the FCEBs have shown great improvement, with some FCEBs achieving more than 10,000 miles between roadcalls (MBRC). Hydrogen dispensed into the buses includes more than 101,000 kg with no fueling safety incidents.

In the next year, several more FCEBs (a total of up to 32 buses) and operating sites are expected to begin demonstration; these will be included in next year's status report. And by the next report, the 16 new Van Hool/UTC Power FCEBs will have a full year's operation and analysis results.

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Introduction

This status report is the fifth in a series of annual status reports from the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL).[1] It summarizes status and progress from demonstrations of fuel cell transit buses in the United States. Since 2000, NREL has evaluated fuel cell bus demonstrations at transit agencies, including buses, infrastructure, and each transit agency's implementation experience. These evaluations were funded by both DOE and the U.S. Department of Transportation's (DOT) Federal Transit Administration (FTA). This work is described in a joint evaluation plan.[2]

Scope and Purpose

This annual status report discusses the achievements and challenges of fuel cell propulsion for transit and summarizes the introduction of fuel cell transit buses in the United States. It provides an analysis of the combined results from fuel cell transit bus demonstrations evaluated by NREL with a focus on the most recent data through July 2011. NREL also evaluates the operating experience and costs of these demonstrations individually and posts reports at http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html. The "References" section lists these reports, each of which is an unbiased assessment of a transit agency's experience implementing fuel cell buses into operation.

Because this report combines results for fuel cell transit bus demonstrations across the United States and discusses the path forward for commercial viability of fuel cell transit buses, its intent is to inform FTA and DOE decision makers who direct research and funding; state and local government agencies, such as the California Air Resources Board (CARB), that fund new propulsion technology transit buses; and interested transit agencies and industry manufacturers.

Organization

This report is organized into seven sections, beginning with this "Introduction." The section "Fuel Cell Electric Buses in Operation in the United States" summarizes existing and upcoming demonstrations in the United States including an overview of FTA's National Fuel Cell Bus Program (NFCBP). The section "Current Status of Fuel Cell Bus Introductions: Achievements and Challenges" discusses the status and challenges of fuel cell propulsion for transit.

The section "Update of Evaluation Results through July 2011" presents the results of the most recent NREL evaluations of fuel cell transit bus demonstrations with comparisons for availability, fuel economy, and roadcalls. The section "What's Next" looks ahead to the expected results to be presented in next year's assessment report. The "References" section provides references for NREL's periodic evaluations of the individual fuel cell bus demonstrations. Finally, the "Appendix" provides summary fuel cell bus data from each of the transit agencies.

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[1] Previous reports are *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status,* September 2007, NREL/TP-560-41967; *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008*, December 2008, NREL/TP-560-44133; and *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2009*, October 2009, NREL/TP-560-46490; *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2010*, November 2010, NREL/TP-560-49379.

[2] *Fuel Cell Transit Bus Evaluations, Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration,* 2010, NREL/TP-560-49342.

What's New since the Previous Report

The report from last year focused on the progress from five FCEBs with the same early generation fuel cell system design (from UTC Power) in operation at three agencies. As of this report, two of those buses are still in operation. The remaining three buses were retired; however, the fuel cell power systems from two of those buses were transferred into new buses and continue to accumulate operating hours. NREL has also begun data collection on several new-generation FCEB designs that entered service during the last year. Data and implementation experience from all of these buses are included in this report.

Fuel Cell Electric Buses in Operation in the United States

Table 1 lists current FCEB demonstrations in the United States. These demonstrations focus on identifying improvements to optimize reliability and durability. As of August 2011, 25 fuel cell buses were in service at seven locations in the United States. See the "References" section for details on the reports discussed. NREL is currently evaluating the first eight demonstrations shown in Table 1.

- **Zero Emission Bay Area (ZEBA) Demonstration Group led by Alameda-Contra Costa Transit District (AC Transit)—**Demonstration of 12 next-generation Van Hool fuel cell hybrid buses with a fuel cell system by UTC Power. The first bus was delivered in May 2010. NREL completed its first report on the demonstration in August 2011.

- **Connecticut Transit (CTTRANSIT) Nutmeg Project—**Demonstration of four Van Hool buses with UTC Power fuel cell power system and a Siemens hybrid drive integrated by the bus manufacturer. This project is part of the NFCBP. The first of four buses was delivered in May 2010. NREL data collection is underway with the first report scheduled for fall 2011.

- **Connecticut Transit (CTTRANSIT)—**Demonstration of one Van Hool bus with UTC Power fuel cell power system in a hybrid propulsion system. Data collection began in April 2007. NREL completed three evaluation reports for DOE with operations data through October 2009. **CT**TRANSIT continues to operate this bus in service.

- **SunLine Transit Agency—**Demonstration of one Van Hool bus with UTC Power fuel cell power system in a hybrid propulsion system. Data collection began in January 2006. NREL completed five evaluation reports for DOE with operations data through June 2009.

- **SunLine Transit Agency: Advanced Technology FCEB—**Demonstration of one New Flyer bus with a Bluways hybrid system and a Ballard fuel cell. This bus went into service in May 2010. NREL has completed two reports on this bus.

- **Capital Metro and the University of Texas (UT)—**Demonstration of one Proterra battery-dominant, plug-in hybrid bus with Hydrogenics fuel cells and lithium titanate batteries. This project is part of the NFCBP. After a short demonstration in Vancouver, British Columbia, during the 2010 Olympics, the bus was delivered to Columbia, South Carolina, for stage one of the demonstration. The bus was operated by Central Midlands

Regional Transit Authority and the University of South Carolina. NREL completed a report on the first year of demonstration in September 2011. At the end of its Columbia demonstration, the bus was shipped to the Proterra facility for upgrades and optimization based on lessons learned at the first demonstration site. The bus was then delivered to the second planned demonstration site in Austin, Texas. Operation of the FCEB is expected to start in October 2011.

- **City of Burbank, BurbankBus**—Demonstration of one Proterra battery-dominant, plug-in hybrid bus with Hydrogenics fuel cells and lithium titanate batteries. This bus was delivered in August 2011. Data collection is scheduled to begin in mid-September 2011 when the bus goes into service.

- **San Francisco Municipal Transportation Agency (SFMTA)**—Demonstration of one Daimler (Orion VII) diesel hybrid bus with a BAE Systems propulsion drive and a Hydrogenics fuel cell auxiliary power unit for electric accessories.

Table 1. Current Fuel Cell Transit Bus Demonstrations in the United States[a]

Bus Operator	Location	Total Buses	Technology Description
ZEBA (led by AC Transit)	San Francisco Bay Area, CA	12	Van Hool bus and hybrid system integration, UTC Power fuel cell
CTTRANSIT, Nutmeg	Hartford, CT	4	Van Hool bus and hybrid system integration, UTC Power fuel cell
CTTRANSIT	Hartford, CT	1	Van Hool bus with UTC Power fuel cell system, ISE hybrid system
SunLine Transit Agency	Thousand Palms, CA	1	Van Hool bus with UTC Power fuel cell system, ISE hybrid system
SunLine Transit Agency, AT FCEB	Thousand Palms, CA	1	New Flyer bus with ISE hybrid system and Ballard fuel cell
Capital Metro/ University of TX	Austin, TX	1	Proterra plug-in hybrid with Hydrogenics fuel cell
BurbankBus	Burbank, CA	1	Proterra plug-in hybrid with Hydrogenics fuel cell
SFMTA	San Francisco, CA	1	Daimler/BAE diesel hybrid with Hydrogenics fuel cell APU
University of Delaware (Phase 1 & 2)	Newark, DE	2	Ebus battery dominant plug-in hybrid using Ballard fuel cells (22-ft)
GNHTD	New Haven, CT	1	Ebus battery dominant plug-in hybrid using Ballard fuel cells (22-ft)
	Total	**25**	

[a] Blue shaded rows indicate the project is part of the NFCBP

During the last year, NREL completed an evaluation of three FCEBs at AC Transit. The demonstration, which began in March 2006, included three Van Hool buses with UTC Power fuel cell power system in a hybrid propulsion system—essentially the same as the Van Hool buses at **CT**TRANSIT and SunLine. As part of the NFCBP, AC Transit began accelerated testing of these three buses in late 2007. NREL completed five total reports on the demonstration: three reports under DOE funding and two reports for FTA covering the accelerated operation through September 2009. The first bus was removed from service in May 2010. By September 2010, all three buses were decommissioned.

The section "Update of Evaluation Results through July 2011" provides the most recent evaluation results for the demonstrations at AC Transit, **CT**TRANSIT, SunLine, and Columbia, South Carolina. A summary of the data on AC Transit's three early generation buses is also included.

National Fuel Cell Bus Program (NFCBP)

FTA initiated the National Fuel Cell Bus Program (NFCBP) in 2006, with an overall goal of developing and demonstrating commercially viable fuel cell technology for transit buses. This multi-year, cost-shared research program provided $49 million for various projects including fuel cell bus demonstrations, component development projects, and outreach projects. In 2010, FTA expanded the NFCBP with an additional $13.5 million in Bus and Bus Facilities funding that was made available in the FY 2010 DOT Appropriations Bill. The legislative language establishing the NFCBP required FTA to work with up to three geographically diverse non-profit organizations. Because of this, FTA accepted proposals for follow-on projects from the three existing consortia already selected through the original competitive process. The project proposals covered work in the following areas:

1. Extensions or enhancements to existing projects with existing teams
2. New development and demonstration projects
3. Outreach, education, or coordination projects.

The selected project awards were announced in December 2010 and included four development and demonstration projects, two component projects, one enhancement to an existing project, and one analysis, outreach, and communication project.

The demonstration projects that are currently underway are included in Table 1 (blue shaded rows). Table 2 lists the remaining demonstration projects that will field seven more fuel cell buses by the end of 2012. An additional $13.5 million in funding was appropriated in 2011, leading to another call to the three consortia for proposals that expand or enhance the current projects under the portfolio. Those proposals are under review and selected projects will be announced later in 2011.

Beyond the NFCBP, FTA funds fuel cell bus research at several universities and transit agencies around the country.

Table 2. New Fuel Cell Transit Buses Planned for the FTA NFCBP

Project	Location	Total Buses	Technology Description
American FCB – SunLine (CALSTART)	Thousand Palms, CA	1	ElDorado/BAE/Ballard next-generation advanced design to meet 'Buy America' requirements
Lightweight FCB Demo (NAVC)	Newark, DE	1	Lightweight bus with a GE hybrid system using advanced batteries and a Ballard fuel cell
Massachusetts FCB Demo (NAVC)	Boston, MA	1	Hybrid bus using Nuvera fuel cells and an advanced battery system
Advanced Composite FCB (CTE)	Columbia, SC; Washington, DC	1	Proterra composite body plug-in hybrid with Ballard fuel cell
Birmingham FCB Demo (CTE)	Birmingham, AL	1	EVAmerica 30-foot battery dominant FCB with advanced lithium ion battery technology. (Continuation of an existing program originally funded outside the NFCBP.)
Chicago Transit Authority FCB Demo (CALSTART)	Chicago, IL	1	ElDorado/BAE/Ballard next-generation advanced design to meet 'Buy America' requirements
EcoSaver IV FCB Demo (CTE)	Columbus, OH	1	DesignLine battery dominant FCB with a Ballard fuel cell

Current Status of FCEB Introductions: Summary of Achievements and Challenges

Over the last year, older-generation FCEB projects have begun to wind down while the newer-generation FCEBs are going into service. The technology continues to show progress toward meeting technical targets to increase reliability and durability and to reduce costs. This section discusses the progress being made and the challenges that remain to bring fuel cell electric buses to the market.

Prototype Bus Development Process

As described in the previous reports, manufacturers develop new prototype transit buses in several stages:

1. **Concept development**—determine concepts, market needs and strategy, and technology requirements

2. **Technology research and development**—research specific needs of the propulsion and vehicle powertrain as well as integration needs

3. **Vehicle development, design, and integration**—integrate system into first article prototype and conduct laboratory testing

4. **Manufacturing and assembly integration**—study component suppliers and needs for manufacturing a small number of vehicles

5. **Vehicle demonstration, testing, and preproduction**—a phase typically executed in three steps:

    a. Field testing and design shakedown (1 to 2 vehicles)

    b. Full-scale demonstration and reliability testing (5 to 10 vehicles at several locations)

    c. Limited production (50 to 100 vehicles at a small number of locations)

6. **Deployment, marketing, and support**—the first fully commercially-available products

Moving through these stages is an iterative process that can take a significant amount of time and resources. The manufacturer designs, develops, tests, and reconfigures the design based on early test results. Technical difficulties and setbacks are expected during these stages. Once the prototype bus reaches stage 5, the manufacturer needs to enlist the help of a transit agency partner to help conduct in-service tests on the bus.

The number of fuel cell bus demonstrations continues to increase. The last report documented 17 active FCEBs in operation in the United States. Over the year, several demonstrations ended and the buses have been retired, but new demonstrations and next-generation systems were introduced bringing the number of active buses to 25. New manufacturer teams are introducing next-generation designs of fuel cell buses in smaller numbers, placing those projects in the first step of the vehicle demonstration stage. Of the seven demonstration projects discussed in this report, the Columbia demonstration of the Proterra bus falls into this category. Three projects—the Van Hool/UTC Power/ISE buses at SunLine, AC Transit, and **CT**TRANSIT—are early-generation FCEB designs that have been in service for several years.

The remaining three projects—the AT bus at SunLine, the ZEBA project at AC Transit, and the Nutmeg project at **CT**TRANSIT—are next-generation designs involving larger numbers of buses. The ZEBA and Nutmeg projects demonstrate the same new-generation technology in two locations, totaling 16 buses. The AT bus at SunLine is the pilot bus from an order of 20 similar FCEBs operating in Whistler, BC, Canada, which were delivered in time for the 2010 Winter Olympics. These three projects are moving the technology into the second step of the vehicle demonstration stage.

Reliability/Durability

One of the key challenges for FCEBs is increasing the durability and reliability of the fuel cell system to meet FTA life cycle requirements for a full size bus – 12 years or 500,000 miles. Because transit agencies typically rebuild the diesel engines at approximately mid-life, a fuel cell power system should be able to operate for at least half the life of the bus. FTA has set an early performance target of 4–6 years (or 20,000–30,000 hours) durability for the fuel cell propulsion system. Manufacturers have made significant progress toward meeting this goal over the last year. During the demonstration of the early-generation FCEBs at AC Transit, the fuel cell manufacturer, UTC Power, tested several successive versions of fuel cell power systems in the buses.

At the end of the planned demonstration, two of the fuel cell power plants were transferred into the newer-generation FCEBs to continue to validate the system in service. As of July 2011, one of these systems reached 10,000 hours with no major repair or cell replacement.[3] This marks a significant achievement over the first version of the fuel cell power system that reached end of life before 2,000 hours. Two additional fuel cell power systems in the ZEBA buses have surpassed 7,000 and 5,000 hours of operation, clearly indicating strong progress in increasing durability. All three of these high-hour systems continue to operate.

An indicator of reliability for the transit industry is miles between roadcall (MBRC). The steady decrease in roadcalls due to fuel cell issues has continued over the last year. Most of the FCEBs discussed in this report have achieved more than 10,000 MBRC for the fuel cell system. (See the section "Update of Evaluation Results through July 2011" for data results.)

Integration/Optimization of Components

While the fuel cell system durability has continued to improve, there are still major challenges with integration of the fuel cell, energy storage, and other components into an optimized electric drive propulsion system. There is a continuum of development of the hybrid electric propulsion system, from integration of off-the-shelf components to customizing those components to optimize the integration. The development and optimization of the control software requires time and concerted effort to perfect.

Manufacturers continue to work on solutions to the existing designs, changing out components and suppliers as needed. This has been particularly challenging for the newer manufacturers such as Proterra. Their development team compressed the prototype bus development into a very short time frame to meet the schedules for demonstration. The fact that the bus design incorporated several new technologies that had never been used in this application added to the difficulties. The primary issue so far has been with the DC-DC converters. After the bus was first placed in service in Columbia, the converters failed, causing several months downtime for repairs. As a result, the demonstration time at the first site was limited to six months.

Proterra's second bus, planned for Burbank, experienced the same issues. This and other early development challenges have slowed the development; however, the manufacturer has made progress in addressing the problems and expects to have the original bus ready for the Austin demonstration by October. The Burbank bus has been re-delivered and should go into service during the same timeframe.

Preparation for Market Introduction

The largest fleet in the United States is now the ZEBA demonstration in the San Francisco, California, area with 12 FCEBs and another 4 FCEBs of the same design operating at **CT**TRANSIT. AC Transit (lead organization for ZEBA) reports that the greatest challenge with the new buses is completing and keeping up with familiarity training for mechanics, operators, and their control center staff. This familiarity training includes safety and bus features such as start-up and shutdown procedures. In order to place the FCEBs into service at AC Transit, there are several bus operators who are expected to operate the buses on a regular basis. In addition,

[3] UTC Power press release at http://www.utcpower.com/pressroom/pressreleases/utc-power-fuel-cell-system-sets-world-record-achieving-10000-hr-durability.

there are a large number of "extra board" operators who might provide operation of the buses during the day. All of the extra board operators must be familiar with the bus and its operation. The number of operators that need to be trained becomes much larger than just the number of operators at the beginning of the day for the 12 buses.

AC Transit has established a maintenance process that allows all of its mechanics to perform any maintenance of the FCEBs except for the electric propulsion system maintenance. Currently only two mechanics may perform the electric propulsion system maintenance but AC Transit plans to hire another mechanic for these duties.

CTTRANSIT reports that adding the four new buses into service was much easier than adding the first bus. With the first bus, the agency had no previous knowledge of hydrogen or fuel cells, which increased the learning curve. When the new buses were delivered, the agency only needed to learn the differences between the new bus design and the first design. Maintenance training was also less than that required for the first bus. **CT**TRANSIT reports a similar situation to AC Transit's with respect to bus operator training—more buses meant the need to train more drivers.

Hydrogen Fueling

As part of the ZEBA demonstration, AC Transit is installing two new hydrogen fueling stations, one at their Emeryville depot and another at their East Oakland depot. Each of these new hydrogen stations will be capable of fueling up to 25 FCEBs per night. These fueling stations have a much larger capacity than other locations with hydrogen fueling. This allows for additional understanding of what the fueling logistics might be for larger numbers of FCEBs in demonstrations and operations. Each station is designed for liquid hydrogen to be trucked into the station and stored. The liquid hydrogen is flashed to gaseous hydrogen and compressed for dispensing fuel at up to 5,000 psi settled pressure onboard the buses. Current fueling rates are reported to be up to 3.5 kg/min and potentially up to 6 kg/min with a new fueling receptacle on the buses. The second station at the East Oakland depot will integrate the hydrogen dispensers into the diesel fueling island. This is a major step toward transitioning these new technology buses into standard transit procedures.

CTTRANSIT is adding a small fueling station that can handle 30 kg/day at its facility. The station is expected to be operational by December. This will handle at least one bus each day, so the fleet will still utilize the UTC Power station. While the offsite fueling arrangement has worked well, it does require more labor hours than fueling at the facility. If the agency expands its fleet of hydrogen buses, it will need to increase the size of its onsite station to meet demands.

Hydrogen fueling at some of the newly started demonstrations includes small stations that have either liquid or compressed hydrogen gas trucked in and then gaseous hydrogen is dispensed into the buses. As more experience is gained with these fueling stations, summaries of that experience will be included in future reports.

Cost Reduction

As mentioned earlier, there are 25 FCEBs in operations as of the completion of this report. The cost of fuel cell dominant hybrid electric buses has dropped from more than $3 million per bus to around $2.3 million per bus. These capital costs are high due to the experimental nature of the buses, the complexity of the systems, and the potential for expensive maintenance and component replacement. With larger numbers of FCEBs of this design type, the cost will come down.

Another approach includes a battery dominant hybrid electric fuel cell bus design. This design has a battery system that is the primary source of energy to drive the wheels and a fuel cell power system that is used as a range extender by providing energy for charging the batteries while in operation. This bus design is significantly lower in cost than the fuel cell dominant design is.

Demonstration of a third design option is now under way. This third design uses a fuel cell power system as an auxiliary power unit in a standard diesel hybrid electric bus design. As part of this design, the accessory loads (air conditioning, power steering) have been electrified and powered by the fuel cell power system. This type of additional equipment also has a significantly lower cost than a full fuel cell dominant system does.

Update of Evaluation Results through July 2011

The data presented in this section represent the most recent results that have not been presented in a previous report. The exception for this is the original three FCEBs at AC Transit—because the demonstration for those buses has ended, we've included the final data summary here for comparison. With the addition of data on several new FCEB designs, presentation of the results becomes more complicated. To simplify, we have assigned each FCEB an identifier that includes a site abbreviation followed by a manufacturer or project designation. Table 3 provides the details of each FCEB by the unique ID.

Table 3. Key to FCEB Identifiers

FCEB ID	Bus OEM	FC OEM	Hybrid Integrator	Hybrid Propulsion Strategy
ACT VH	Van Hool	UTC Power	ISE	Fuel cell dominant
ACT ZEBA	Van Hool	UTC Power	Van Hool	Fuel cell dominant
CTT VH	Van Hool	UTC Power	ISE	Fuel cell dominant
CTT Nutmeg	Van Hool	UTC Power	Van Hool	Fuel cell dominant
SC PT	Proterra	Hydrogenics	Proterra	Battery dominant
SL VH	Van Hool	UTC Power	ISE	Fuel cell dominant
SL AT	New Flyer	Ballard	Bluways	Fuel cell dominant

Baseline buses—Conventional baseline bus data are provided where available. For AC Transit and **CT**TRANSIT, the diesel baseline bus data are from an earlier period. The baseline buses at SunLine are CNG because the agency doesn't operate diesel buses. The South Carolina demonstration site did not have conventional buses that could be considered comparable to the 35-ft Proterra bus. The Appendix summarizes the data results by demonstration location.

Figure 1. The early-generation FCEBs at SunLine (top left), AC Transit (right), and CTTRANSIT (bottom left)

Figure 2. Newer-generation FCEBs at SunLine (top left), Columbia (top right), AC Transit (bottom left), and CTTRANSIT (bottom right)

Total miles and hours—Table 4 shows miles, hours, average speed, and average monthly miles per bus for the FCEBs. The Nutmeg buses at **CT**TRANSIT had the highest average speed at 13.5 mph. This is in stark contrast to the agency's earlier-generation FCEB operating on the downtown shuttle route at an average of 6 mph. Average monthly bus use ranged from a low of just under 500 miles up to approximately 2,000 miles per month. The Proterra bus in South Carolina was only in operation for six months and experienced some early issues with its DC-DC converters.

Table 4. Miles and Hours for the Fuel Cell Buses

ID	Period	Months	No. of Buses	Miles	Hours	Avg. Speed (mph)	Avg. Monthly Miles
ACT VH	11/07 – 9/10	33	3	194,288	19,823	9.8	2,112
ACT ZEBA	9/10 – 7/11	11	7	96,209	8,663	11.1	1,755
CTT VH	8/10 – 7/11	12	1	9,265	1,528	6.1	926
CTT Nutmeg	10/10 – 7/11	10	4	50,708	3,756	13.5	1,334
SC PT	6/10 – 11/10	6	1	2,947	N/A	N/A	491
SL VH	8/10 – 7/11	12	1	22,176	1,837	12.1	1,848
SL AT	5/10 – 7/11	15	1	22,841	1,927	11.9	1,523

Bus use—Figure 3 shows the average monthly bus use for the fuel cell buses and their respective baseline buses. The transit agencies continue to operate their fuel cell buses fewer miles than they operate their baseline buses.

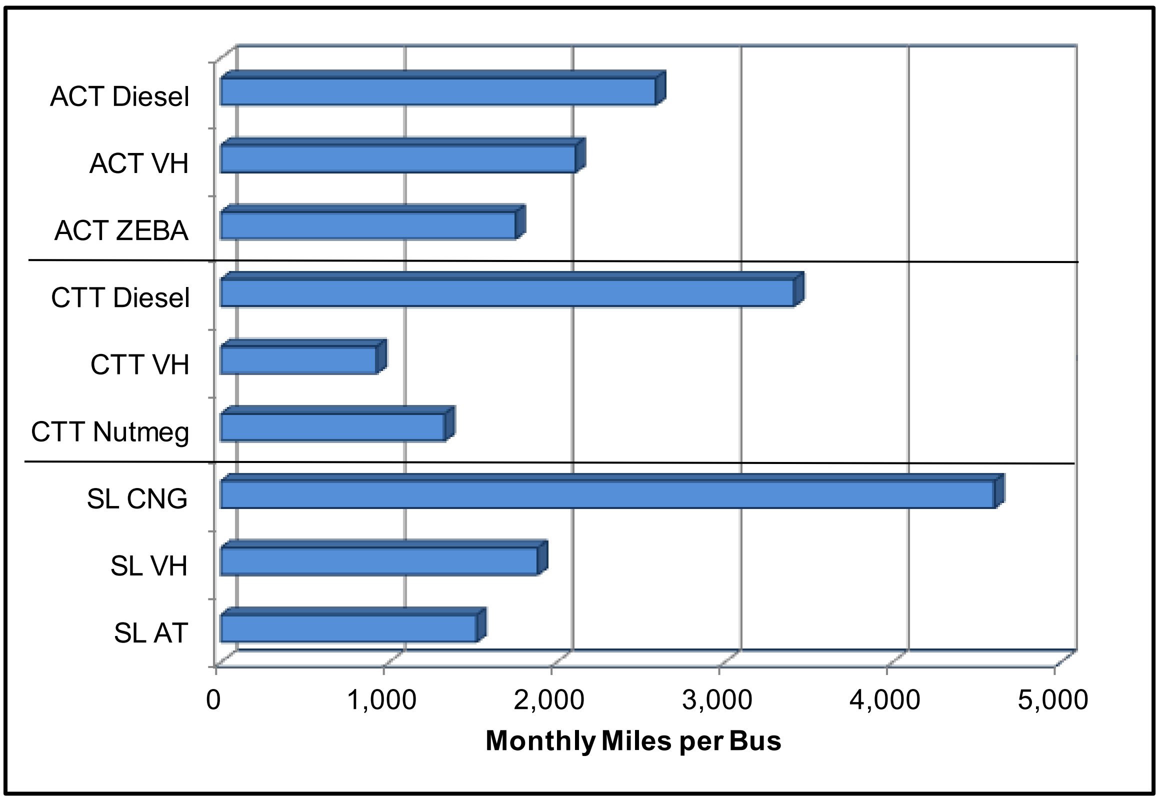

Figure 3. Average monthly miles per fuel cell and baseline buses

Availability—Availability is the percentage of days that buses are planned for operation compared to the percentage of days the buses are actually available. Table 5 summarizes the availability of the fuel cell buses at each transit agency. Availability varies from site to site with a low of 44% up to a high of 72%. The majority of the issues affecting availability were not due to the fuel cell power system. Some of the low availability can be attributed to start-up issues with the newer FCEB technologies just going into demonstration. This was especially true for the FCEB in Columbia, which is a completely new design that had never been tested. Overall, the majority of issues did not involve the fuel cell system but were due to the hybrid or battery systems and integration.

Figure 4 categorizes the reasons that the buses were not available by transit agency and bus technology. For the older-generation Van Hool buses at SunLine, AC Transit, and **CT**TRANSIT the primary issues were with the battery system. This has been the case for that design throughout its demonstration. For the new FCEBs at AC Transit and **CT**TRANSIT (ZEBA and Nutmeg) the issues were most often bus related. The AT bus at SunLine has had issues with the air conditioning, the fuel cell power system, and an accident that caused body damage.

Table 5. Availability for the Fuel Cell Buses

ID	Period	Months	No. of Buses	Planned Days	Days Avail.	% Avail.
ACT VH	11/07 – 1/10	33	3	1,736	1,142	66
ACT ZEBA	9/10 – 7/11	11	7	1,199	802	67
CTT VH	8/10 – 7/11	12	1	250	114	46
CTT Nutmeg	10/10 – 7/11	10	4	723	344	44
SC PT	6/10 – 11/10	6	1	86	46	53
SL VH	8/10 – 7/11	12	1	294	212	72
SL AT	5/10 – 7/11	15	1	371	233	63

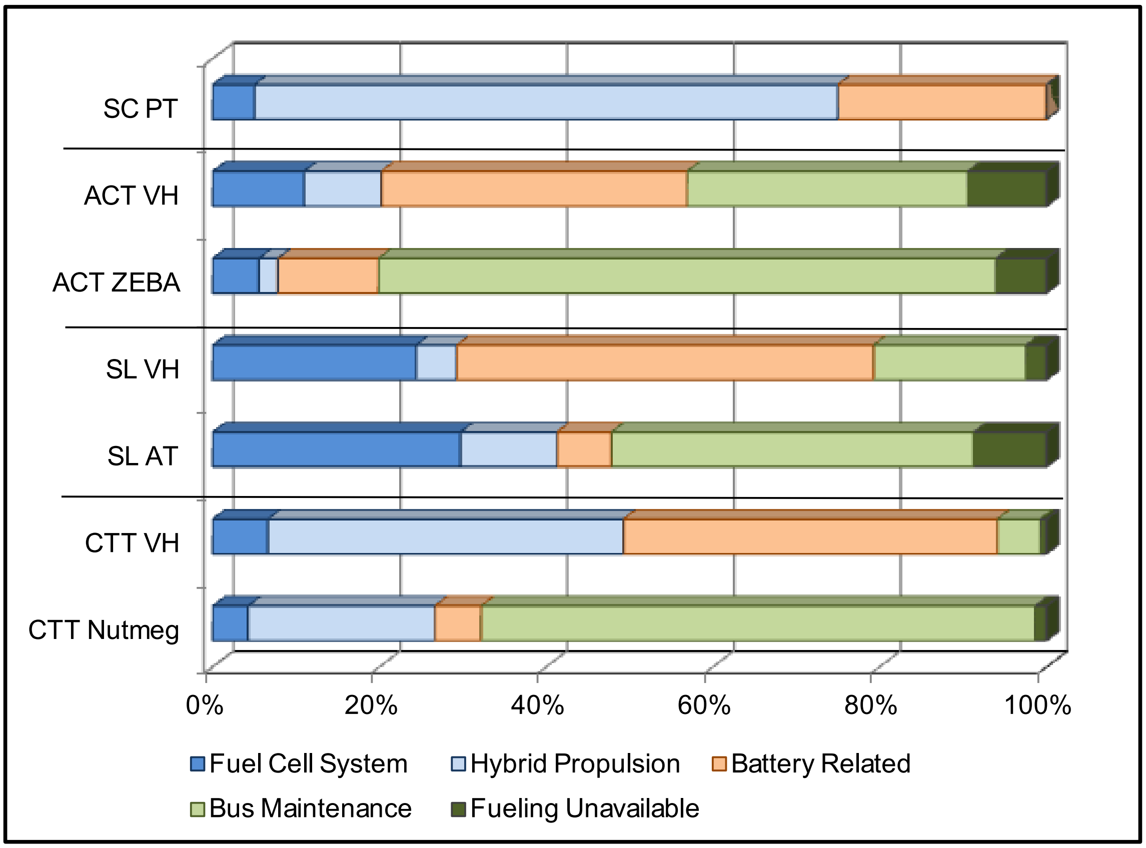

Figure 4. Reasons for unavailability of the fuel cell electric buses

Fuel economy—Table 6 shows the average fuel economy in diesel energy gallon equivalent (DGE) for each type of FCEB compared to the conventional baseline bus technology at the same site. Figure 5 shows the fuel economy by month over the last year.

All the FCEBs showed improved fuel economy compared to the baseline buses in similar service. The variation from site to site shows how the fuel economy for hybrid fuel cell systems is highly dependent on duty cycle.

The FCEBs showed fuel economy improvements ranging from 46% to 141% when compared to diesel and CNG baseline buses. **CT**TRANSIT's older Van Hool bus had the lowest overall fuel economy, primarily because it is operated on a downtown shuttle route that is slow-speed (6 mph average) with frequent stops and high idle time. The **CT**TRANSIT diesel buses operate at twice this average speed, which causes significantly lower fuel economy for its fuel cell bus compared to the fuel economies for the FCEBs of the same design at the other two transit agencies (ACT VH and SL VH). Both FCEBs at SunLine achieved fuel economies twice that of the conventional CNG buses in the same service. The data presented for the ACT ZEBA buses are preliminary and based on a temporary fueling station that does not measure fuel by direct mass flow. Once the agency's new permanent station is completed, these results could change significantly.

The FCEB demonstrated in South Carolina is not listed in the table because no comparable baseline bus was available. That bus is also a battery-dominant configuration that was plugged into the grid for overnight charging. Accounting for all of the energy used by this bus, the fuel economy for the demonstration period was 7.4 miles per diesel gallon equivalent.

Table 6. Average Fuel Economy Comparisons between the FCEBs and Baseline Buses

ID	Miles per kg/gge	Miles per Diesel Gallon Equivalent	% Difference from Baseline
ACT VH	5.93	6.70	75
ACT ZEBA	5.36	6.06	58
ACT diesel	–	3.87	–
CTT VH	5.01	5.66	46
CTT Nutmeg	6.97	7.87	103
CTT diesel	–	3.83	–
SL VH	6.67	7.53	126
SL AT	5.92	6.69	101
SL CNG	–	3.33	–

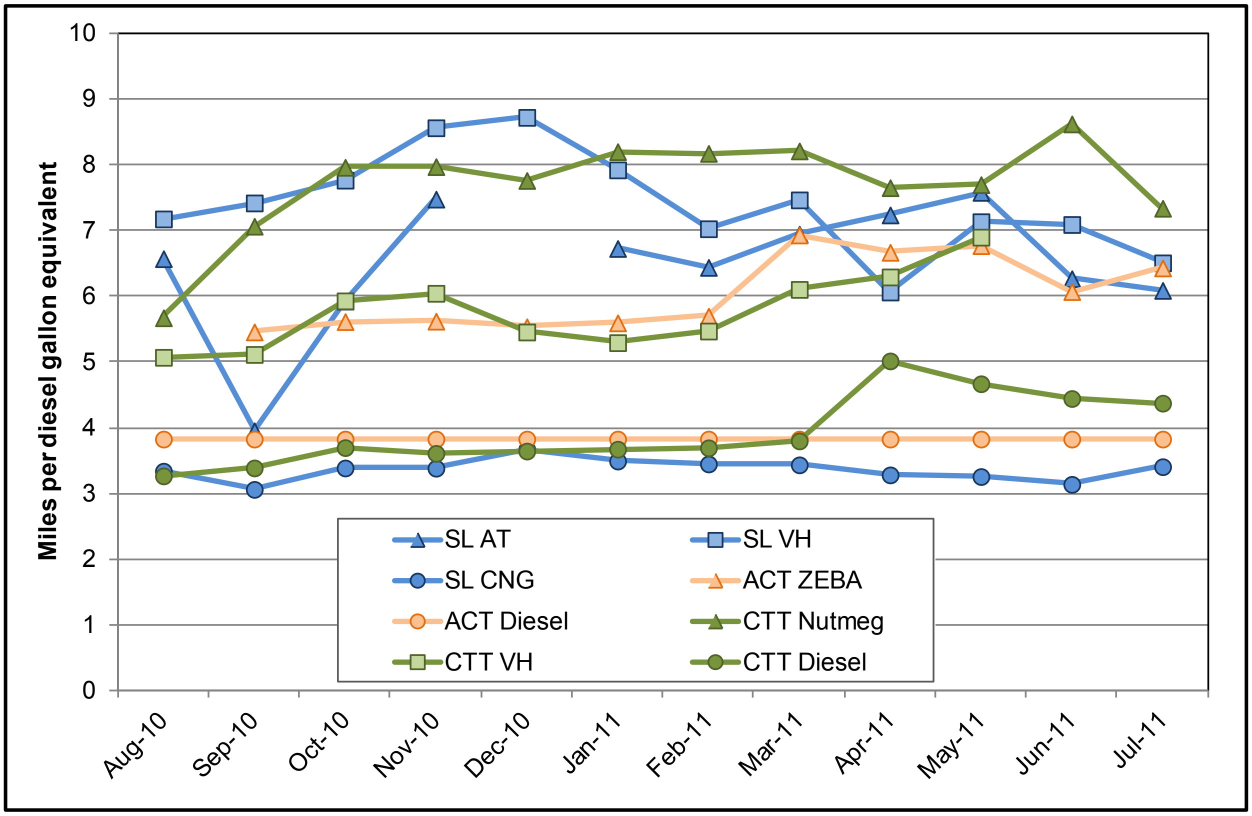

Figure 5. Fuel economy for fuel cell and baseline buses[4]

Roadcalls—A roadcall or revenue vehicle system failure (see the National Transit Database) is a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. If the bus is repaired during a layover and the schedule is maintained, then no RC is recorded. Figure 6 shows miles between roadcalls (MBRC) for all roadcalls, for propulsion-related-only roadcalls, and for fuel-cell-system-only roadcalls for the FCEBs. The black hashed line marks the target for all MBRC (4,000) and the red hashed line is the target for propulsion-related MBRC (10,000).

MBRC rates for the FCEBs continue to be significantly lower than the MBRC rates for the baseline buses, although recent data show improvements in all categories. Manufacturers and transit agencies continue to work to resolve the problems causing these low rates. Fuel cell manufacturers have made consistent progress over the last few years in improving durability and reliability.

[4] The fuel economy for the diesel buses at AC Transit is shown as a straight line because data collection on these buses has just begun. The value is based on the average fuel economy for three diesel buses.

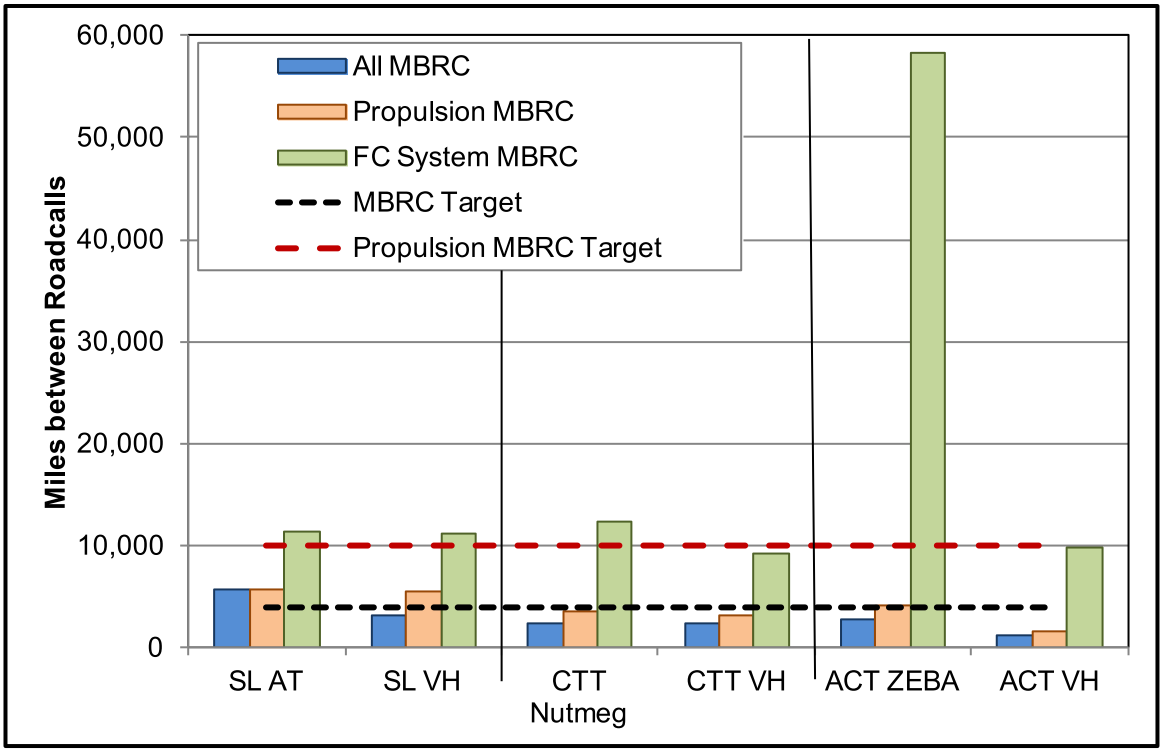

Figure 6. MBRC rates for fuel cell and baseline buses

Hydrogen fueling—Since the first of these buses went into service in January 2006 through July 2011, these FCEBs have been fueled with more than 101,000 kg of hydrogen with no fueling safety incidents. The fueling at each site is as follows:

- AC Transit—61,321 kg (January 2006 through July 2011)
- **CT**TRANSIT—18,217 kg (April 2007 through July 2011)
- Columbia, SC—400 kg (June 2010 through Nov 2010)
- SunLine—21,482 kg (January 2006 through July 2011)

The amount of hydrogen dispensed continues to grow as new buses are placed into service. Figure 7 shows the total hydrogen dispensed each year along with the total number of buses in service. The data for 2011 covers only the first half of that year. By the end of the year, a total of 22 FCEBs are expected to be in service at locations tracked by NREL.

The average fill amount for the fuel cell dominant FCEBs continues to run around 22.5 kg per fill, with a fill time around 16 minutes. As mentioned in the previous report, this time will need to be reduced to meet the needs of a full size fleet. For the one battery dominant FCEB, the average fill is approximately 11 kg; the total tank capacity on that bus model is only 29 kg.

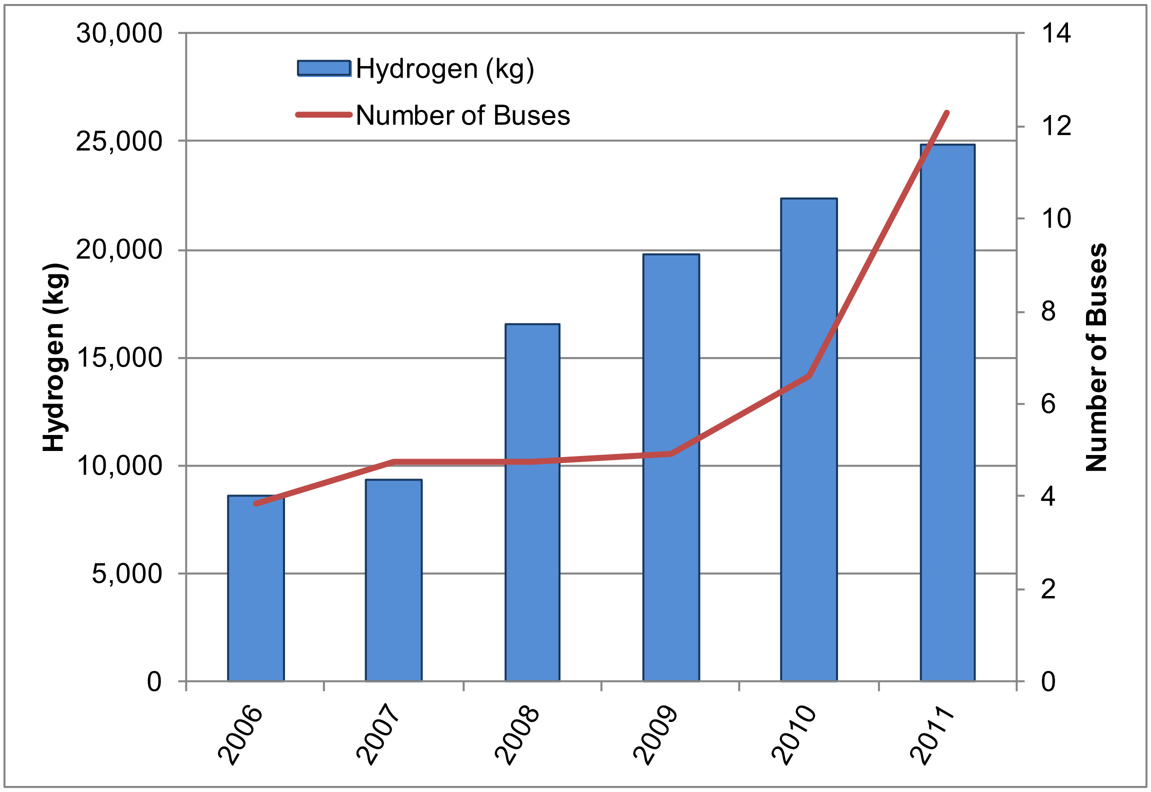

Figure 7. Hydrogen dispensed for the FCEBs by year[5]

[5] Note that the total hydrogen for 2011 is for only half the year.

What's Next

For this report, we have included data from seven different FCEB bus designs at four sites. In the next year, several new demonstrations are expected to be up-and-running, and NREL expects to monitor and evaluate those demonstrations with funding from DOE and FTA. The addition of the new fuel cell bus designs and locations is expected to expand this annual assessment report's scope for determining the status of development. NREL plans several new evaluation reports to present data and experiences from each of these sites.

In addition to the current FCEBs the following demonstrations are expected to be included in next year's assessment report:

- The Proterra plug-in hybrid fuel cell (Hydrogenics) bus moves from the first site (Columbia, South Carolina) to Austin, Texas
- A second Proterra plug-in hybrid fuel cell (Hydrogenics) bus operating in Burbank, California
- One Daimler (Orion VII) bus with hybrid propulsion from BAE Systems with an auxiliary power unit using a Hydrogenics fuel cell power system and electric accessories operating at SFMTA (NFCBP: Compound Hybrid Fuel Cell Bus or Bus 2010)
- One ElDorado bus with hybrid propulsion from BAE Systems and a Ballard fuel cell operating at SunLine (NFCBP: American Fuel Cell Bus)

Additional buses that may begin operation and be available for the next report are the following: a new bus with a Nuvera fuel cell in Massachusetts; a new bus with a GE hybrid system in Delaware; a second ElDorado/BAE/Ballard bus in Chicago, Illinois; and an EV America/Ballard bus in Birmingham, Alabama. These demonstrations may not have enough data available to be included in the next assessment report; however, a status update will be provided.

Figure 8. New FCEBs to be included in the next report: Proterra bus in Burbank (left) and Orion/BAE hybrid bus in San Francisco (right)

References and Related Reports

All NREL hydrogen and fuel cell-related evaluation reports can be downloaded from the following website: www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

General

Eudy, L. (2010). *Fuel Cell Transit Bus Evaluations, Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*. NREL/TP-560-49342. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Chandler, K.; Gikakis, C. (2010). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2010*. NREL/TP-560-49379. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Chandler, K.; Gikakis, C. (2009). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2009*. NREL/TP-560-46490. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Chandler, K.; Gikakis, C. (2008). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008*. NREL/TP-560-44133. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Chandler, K.; Gikakis, C. (2007). *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status.* NREL/TP-560-41967. Golden, CO: National Renewable Energy Laboratory.

AC Transit

Chandler, K.; Eudy, L. (2011). *Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: First Results Report*. NREL/TP-5600-52015. Golden, CO: National Renewable Energy Laboratory.

Eudy, L. (2010). *Bay Area Transit Agencies Propel Fuel Cell Buses Toward Commercialization.* DOE/GO-102010-3067. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2010). *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2 and Appendices*. FTA-CO-26-7004-2010.1. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2009). *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report and Appendices*. FTA-CO-26-7004-2009.1. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2007). *Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Third Evaluation Report and Appendices*. NREL/TP-560-43545-1, NREL/TP-560-43545-2. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2007). *Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Evaluation Results Update*. NREL/TP-560-42249. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2007). *AC Transit, Fuel Cell Transit Buses: Preliminary Evaluation Results.* NREL/TP-560-41041. Golden, CO: National Renewable Energy Laboratory.

Eudy, L. (2006). *AC Transit Demonstrates Three Prototype Fuel Cell Buses.* DOE/GO-102006-2286. Golden, CO: National Renewable Energy Laboratory.

BurbankBus

Eudy, L. (2010). *Fuel Cell Bus Takes a Starring Role in the BurbankBus Fleet.* DOE/GO-102010-3035. Golden, CO: National Renewable Energy Laboratory.

Columbia, SC

Eudy, L., Chandler, K. (2011). *National Fuel Cell Bus Program: CTE/Proterra Hydrogen Hybrid Bus Report, Columbia Demonstration*. FTA.

Connecticut Transit

Eudy, L. (2011). *Connecticut Nutmeg Fuel Cell Bus Project: Demonstrating Advanced-Design Fuel Cell Buses in Connecticut*. DOT/FTA - NFCBP – FS3 - July 2011. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2010). *Connecticut Transit (**CT**TRANSIT) Fuel Cell Transit Bus: Third Evaluation Report and Appendices*. NREL/TP-560-47334-1, NREL/TP-560-47334-2. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2009). *Connecticut Transit (**CT**TRANSIT) Fuel Cell Transit Bus: Second Evaluation Report and Appendices*. NREL/TP-560-45670-1, NREL/TP-560-45670-2. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2008). *Connecticut Transit (**CT**TRANSIT) Fuel Cell Transit Buses: Preliminary Evaluation Results.* NREL/TP-560-43847. Golden, CO: National Renewable Energy Laboratory.

Eudy, L. (2008). ***CT**TRANSIT Operates New England's First Fuel Cell Hybrid Bus*. DOE/GO12008-2529. Golden, CO: National Renewable Energy Laboratory.

Santa Clara Valley Transportation Authority

Chandler, K.; Eudy, L. (2006). *Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Evaluation Results*. NREL/TP-560-40615. Golden, CO: National Renewable Energy Laboratory.

Eudy, L. (2005). *VTA, SamTrans Look into Future with Bus Demo*. DOE/GO-102005-2147. Golden, CO: National Renewable Energy Laboratory.

San Francisco MTA

Eudy, L. (2011). *Compound Fuel Cell Hybrid Bus Hits the Streets of San Francisco*. DOT/FTA - NFCBP - FS2 - July 2011. Golden, CO: National Renewable Energy Laboratory.

SunLine

Eudy, L.; Chandler, K. (2011). *SunLine Transit Agency, Advanced Technology Fuel Cell Bus Evaluation: Second Results Report & Appendices*. NREL/TP-5600-52349-1, NREL/TP-5600-52349-2. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Chandler, K. (2011). *SunLine Transit Agency, Advanced Technology Fuel Cell Bus Evaluation: First Results Report*. NREL/TP-5600-50500. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Chandler, K. (2009). *SunLine Transit Agency, Fuel Cell Transit Bus: Fifth Evaluation Report and Appendices*. NREL/TP-560-46346-1, NREL/TP-560-46346-2. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2009). *SunLine Transit Agency, Fuel Cell Transit Bus: Fourth Evaluation Report and Appendices*. NREL/TP-560-44646-1, NREL/TP-560-44646-2. Golden, CO: National Renewable Energy Laboratory.

Eudy, L. (2008). *SunLine Begins Extended Testing of Hybrid Fuel Cell Bus*. DOE/GO-102008-2610. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2008). *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Third Evaluation Report and Appendices.* NREL/TP-560-43741-1, NREL/TP-560-43741-2. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2007). *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Evaluation Results Update*. NREL/TP-560-42080. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2007). *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Preliminary Evaluation Results*. NREL/TP-560-41001. Golden, CO: National Renewable Energy Laboratory.

Eudy, L. (2006). *SunLine Expands Horizons with Fuel Cell Bus Demo*. DOE/GO-102006-2287. Golden, CO: National Renewable Energy Laboratory.

Appendix: Summary Statistics

Table A-1. AC Transit Data Summary

	ACT VH	ACT ZEBA
Data period	11/07 – 9/10	9/10 – 7/11
Number of buses	3	7
Number of months	~33	~11
Total miles	194,288	96,209
Total FC hours	19,823	8,663
Average speed (mph)	9.8	11.1
Average miles per month	2,112	1,755
Availability	66%	67
Fuel economy (mi/kg)	5.9	5.36
Fuel economy (mpdge)	6.70	6.06
All MBRC	1,193	2,711
Propulsion-only MBRC	1,519	4,164
FC system-only MBRC	9,719	58,290
Total hydrogen used (kg)	42,787	18,535

Table A-2. SunLine Data Summary

	SL VH	SL AT
Data period	8/10 – 7/11	5/10 – 7/10
Number of buses	1	1
Number of months	12	15
Total miles	22,176	22,841
Total FC hours	1,837	1,927
Average speed (mph)	12.1	11.9
Average miles per month	1,848	2,128
Availability	72%	63%
Fuel economy (mi/kg)	6.67	5.92
Fuel economy (mpdge)	7.53	6.69
All MBRC	3,168	5,710
Propulsion-only MBRC	5,544	5,710
FC system-only MBRC	11,088	11,421
Total hydrogen used (kg)	3,326	18,535

Table A-3. CTTRANSIT Data Summary

	CTT VH	CTT Nutmeg
Data period	8/10 – 7/11	10/10 – 7/11
Number of buses	1	4
Number of months	12	10
Total miles	9,265	50,708
Total FC hours	1,528	3,756
Average speed (mph)	6.1	13.5
Average miles per month	926	1,334
Availability	46%	48%
Fuel economy (mi/kg)	5.01	6.97
Fuel economy (mpdge)	5.66	7.87
All MBRC	2,316	2,454
Propulsion-only MBRC	3,088	3,506
FC system-only MBRC	9,265	12,272
Total hydrogen used (kg)	1,850	7,726

Table A-4. Columbia, SC Data Summary

	SC PT
Data period	6/10 – 11/10
Number of buses	1
Number of months	6
Total miles	2,947
Total FC hours	N/A
Average speed (mph)	14.7
Average miles per month	491
Availability	53%
Fuel economy (mi/kg)	7.37
Fuel economy (mpdge)	8.33
Fuel economy – adjusted for charge energy (mpdge)	7.4
All MBRC	N/A
Propulsion-only MBRC	N/A
FC system-only MBRC	N/A
Total hydrogen used (kg)	400