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**NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.**

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## Acronyms and Abbreviations

AC Transit	Alameda Contra-Costa Transit District
AFCB	American Fuel Cell Bus
AT	advanced technology
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
FC	fuel cell
FCEB	fuel cell electric bus
FCPP	fuel cell power plant
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
OEM	original equipment manufacturer
SFMTA	San Francisco Municipal Transportation Agency
UT	University of Texas
ZEBA	Zero Emission Bay Area

## Executive Summary

This report is the sixth in an annual series of reports that summarize the progress of fuel cell electric bus (FCEB) development in the United States and discuss the achievements and challenges of introducing fuel cell propulsion in transit. The report also provides a snapshot of current FCEB performance results over the last year. There are 25 active FCEBs in demonstrations this year at eight locations.

Previous reports outlined the six-stage process that manufacturers typically use in developing new prototype transit buses. To better align this status report with other programs within DOE, NREL developed a guideline for assessing the technology readiness level (TRL) for FCEBs. This TRL guide begins with basic technology research at TRL 1—early concept development—and moves through the TRLs to demonstration and eventually to TRL9—deployment. The technology demonstration/commissioning phase that includes TRLs 6 through 8 begins the iterative process to validate the design, analyze the results, and reconfigure or optimize the design as needed.

This report also provides a summary of results from evaluations performed by the National Renewable Energy Laboratory (NREL) and 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 21 of the 25 FCEBs currently operating. Summary results from August 2011 through July 2012 for these buses account for more than 248,200 miles traveled and 24,930 hours of fuel cell power system operation. The summary results are from four demonstrations at three transit agencies:

- Zero Emission Bay Area (ZEBA) Demonstration Group led by Alameda-Contra Costa Transit District (AC Transit)
- Connecticut Transit (CTTRANSIT) Nutmeg Project
- SunLine Transit Agency: Advanced Technology FCEB and American Fuel Cell Bus Project

DOE and FTA have established performance, cost, and durability targets for FCEBs. These targets, established with industry input, include interim targets for 2016 and ultimate targets for commercialization. Table ES-1 summarizes the performance of the FCEBs in the report compared to these targets. DOE/FTA set an ultimate performance target of 4–6 years (or 25,000 hours) durability for the fuel cell propulsion system, with an interim target of 18,000 hours by 2016. Manufacturers have continued to make significant progress toward meeting the target over the last year. As of July 2012, NREL documented a single fuel cell power plant (FCPP) that has reached 12,000 hours. Two more FCPPs are approaching 10,000 and 8,000 hours.

Availability varies from site to site with a low of 53% up to a high of 71%, with the overall average at 57%. Although this is much lower than the target of 90%, it is not unexpected for technology at this stage of development. The reasons for unavailability are most often attributed to bus-related and battery issues rather than to the fuel cell system.

The targets for roadcall frequency include miles between roadcalls (MBRC) for the entire bus and MBRC for the fuel cell (FC) system only. The FC system MBRC includes any roadcalls due to issues with the FC stack or associated balance of plant. NREL tracks an additional metric of

propulsion system MBRC. This category includes all roadcalls due to propulsion-related bus systems. Overall bus MBRC for the time period was 2,288; propulsion system MBRC was 3,239; and FC system MBRC was 12,328.

The FCEBs continue to show improved fuel economy compared to the baseline buses in similar service. FTA's performance target for FCEB fuel economy is 8 miles per diesel gallon equivalent (mi/DGE), which is two times higher than that of diesel buses. The FCEBs showed improved fuel economy ranging from 1.8 to 2.4 times higher than that of diesel and CNG baseline buses. Fuel economy for the FCEBs ranged from 5.97 mi/DGE up to 7.84 mi/DGE for an average of 7.41 mi/DGE.

While bus performance and fuel cell system durability have continued to improve, there are still challenges to overcome to move FCEB technology to a commercial product. Over the past year, manufacturers continued to work on issues with systems integration and optimization, which is still one of the major challenges for FCEBs. When new FCEB designs first go into service, there is a characteristic break-in period where the manufacturers review the early performance results and make changes to optimize and correct any issues that occur. This break-in period can take many months as new issues arise that did not show up in laboratory testing. The current economic situation has also made it difficult for all development partners to remain committed to the project as resources are limited.

Access to hydrogen fuel continues to be one of the biggest hurdles to adoption of any fuel cell vehicle. Several demonstration projects have been delayed because of issues with access to fuel. An incident at AC Transit's new hydrogen station in May 2012 resulted in a temporary suspension of the demonstration while the cause of the incident was investigated. The investigation team was comprised of AC Transit, Linde, CARB, Sandia National Laboratories (funded by CARB), and the Alameda County Fire Department. The root cause of the incident was a failed pressure relief device. Analysis showed the nozzle sub-assembly was made of a material that was a poor choice for use with hydrogen. This choice of material as well as deviations in process during production of the valve led to the failure. Other factors, such as the lack of timely communication, contributed to the escalation of the event. Although there were no injuries or major damage, several lessons were learned from the event that should be considered when planning a hydrogen station for FCEBs or other applications.

Despite the remaining challenges, FCEBs continue to show progress toward meeting the technical targets for commercialization. When comparing the commercialization progress of FCEBs to that of more recently commercialized propulsion technologies such as CNG and diesel hybrid buses, FCEB development is following a similar path and timeframe.

In the next year, several more FCEBs and operating sites are expected to begin demonstration; these will be included in next year's status report.

**Table ES-1. Summary of FCEB Performance Compared to DOE/FTA Targets<sup>1</sup>**

	Units	November 2012 Report <sup>a</sup> (Range)	2012 Status <sup>1</sup>	2016 Target <sup>1</sup>	Ultimate Target <sup>1</sup>
Bus lifetime	years/miles	<1–2.5/ 8,669–54,927 <sup>c</sup>	5/100,000	12/500,000	12/500,000
Power plant lifetime <sup>b</sup>	hours	940–12,038 <sup>c,d,e</sup>	12,000	18,000	25,000
Bus availability	%	53–71	60	85	90
Fuel fills <sup>f</sup>	per day	1	1	1 (< 10 min)	1 (< 10 min)
Bus cost <sup>g</sup>	\$	2,000,000	2,000,000	1,000,000	600,000
Power plant cost <sup>b,g</sup>	\$	N/A <sup>h</sup>	700,000	450,000	200,000
Hydrogen storage cost	\$	N/A <sup>h</sup>	100,000	75,000	50,000
Roadcall frequency (bus/fuel cell system)	miles between roadcalls	1,692–2,479/ 6,838–19,005	2,500/ 10,000	3,500/ 15,000	4,000/ 20,000
Operation time	hours per day/days per week	7–19/ 5–7	19/7	20/7	20/7
Scheduled and unscheduled maintenance cost <sup>i</sup>	\$/mile	N/A <sup>i</sup>	1.20	0.75	0.40
Range	miles	227–346 <sup>k</sup>	270	300	300
Fuel economy	miles per gallon diesel equivalent	5.97–7.84	7	8	8

<sup>a</sup> Summary of the results in this report: data from August 2011–July 2012.

<sup>b</sup> For the DOE/FTA targets, the power plant is defined as the fuel cell system and the battery system. The fuel cell system includes supporting subsystems such as the air, fuel, coolant, and control subsystems. Power electronics, electric drive, and hydrogen storage tanks are excluded.

<sup>c</sup> Accumulated totals for existing fleet through July 2012; these buses have not reached end of life.

<sup>d</sup> The status for power plant hours is for the fuel cell system only; battery lifetime hours were not available.

<sup>e</sup> The highest-hour power plant was transferred from an older generation bus that had accumulated more than 6,000 hours prior to transfer.

<sup>f</sup> Multiple sequential fuel fills should be possible without increase in fill time.

<sup>g</sup> Cost targets projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only and does not represent an anticipated level of sales.

<sup>h</sup> Capital costs for subsystems are not currently reported by the manufacturers.

<sup>i</sup> Excludes mid-life overhaul of power plant.

<sup>j</sup> Maintenance costs are not available for this report. See individual project reports on the NREL website.

<sup>k</sup> Based on fuel economy and tank capacity.

<sup>1</sup> Fuel Cell Technologies Program Record # 12012, September 12, 2012, [http://www.hydrogen.energy.gov/pdfs/12012\\_fuel\\_cell\\_bus\\_targets.pdf](http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf).



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## Introduction

This report is the sixth in a series of annual status reports from the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL).<sup>2</sup> It summarizes status and progress from demonstrations of fuel cell transit buses in the United States. Since 2000, NREL has evaluated fuel cell electric bus (FCEB) demonstrations at transit agencies, including the 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.<sup>3</sup>

## 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 2012). 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](http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html). The "References" section lists the most recent reports, each of which is an unbiased assessment of a transit agency's experience implementing fuel cell electric buses into its 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 "FCEB Development Process – Technology Readiness Levels" outlines the steps for developing and commercializing FCEBs and indicates where each of the current designs falls in the process. The section "Development Status of FCEBs Compared to CNG and Diesel Hybrid Buses" discusses the progress in FCEB commercialization in comparison to that of the most recent technologies commercialized for transit buses. The section "Update of Evaluation Results through July 2012" 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 "Current Status of Fuel Cell Bus Introductions: Achievements and Challenges" discusses the status and challenges of fuel cell propulsion for transit. The section "What's Next" looks ahead to the expected results to be presented in next year's assessment report.

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<sup>2</sup> Previous reports are listed in the References section of the report.

<sup>3</sup> *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.

Additionally, the “References” section provides references for NREL’s periodic evaluations of the individual fuel cell bus demonstrations, and the “Appendix” provides summary fuel cell bus data from each of the transit agencies.

### What’s New since the Previous Report

Table 1 outlines which FCEB designs were included in the 2011 and 2012 (current) status reports. The 2011 report presented the final results from five FCEBs with the same early-generation fuel cell system design (first three rows in the table) in operation at three agencies and began reporting results from three new FCEB designs at four transit agencies. As of this report, none of the first-generation buses are in operation. Three are permanently retired; however, two of the fuel cell power systems were transferred into new buses and continue to accumulate operating hours. Of the remaining two buses, one is expected to go back into service after repair of the hybrid system; the other could potentially be returned to service if funding is available to replace the fuel cell system. Early data on the Proterra bus was included in the last report. This bus has been moved to the second demonstration site, but it was not in service during the last year. NREL has continued to collect data from two additional FCEB designs that were included in the 2011 data summary and has added a third system that entered service in early 2012. Data and implementation experience from all of the newer buses are included in this report.

**Table 1. Technologies Included in the 2011 and 2012 Status Reports**

FCEB Demonstration	Included in 2011 Report	Status	Included in Current Report
AC Transit Van Hool	✓	Retired	
CTTRANSIT Van Hool	✓	Not in service	
SunLine Van Hool	✓	Not in service	
Proterra, South Carolina	✓	Between sites	
AC Transit ZEBA	✓	Active	✓
CTTRANSIT Nutmeg	✓	Active	✓
SunLine AT FCEB	✓	Active	✓
SunLine AFCB		In service 12/11	✓

## Fuel Cell Electric Buses in Operation in the United States

Table 2 lists current FCEB demonstrations in the United States. These demonstrations focus on identifying improvements to optimize reliability and durability. As of August 2012, 25 fuel cell buses were in demonstrations at 10 locations in the United States.

**Table 2. Current Fuel Cell Transit Bus Demonstrations in the United States<sup>a</sup>**

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; Flint, MI	4	Van Hool bus and hybrid system integration, UTC Power fuel cell
SunLine Transit Agency, AT FCEB	Thousand Palms, CA	1	New Flyer bus with Bluways hybrid system and Ballard fuel cell
SunLine Transit Agency, AFCB	Thousand Palms, CA	1	EIDorado/BAE/Ballard next-generation advanced design to meet 'Buy America' requirements
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)
Dept. of Defense – Joint Base Lewis-McChord	Lewis-McChord, WA	1	Proterra plug-in hybrid with Hydrogenics fuel cell
<b>Total</b>		<b>25</b>	

<sup>a</sup> Blue shaded rows indicate the project received funding through the NFCBP.

NREL is currently evaluating the first seven demonstrations shown in Table 2. These demonstrations are described in more detail below along with the current status.

- 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. This program received funding through the NFCBP for accelerated testing of the first generation buses and to purchase eight of the fuel cell systems for these new buses. The first bus was delivered in May 2010 and all 12 were in service by the end of November 2011. NREL completed two reports on the demonstration (in August 2011 and July 2012). An incident at the AC Transit hydrogen station in early May 2012 resulted in a temporary shutdown of the station. The FCEB fleet was pulled from service at that time while the incident was investigated. Once the station is back on-line, the buses will go back into service.

- **Connecticut Transit (CTTRANSIT) Nutmeg Project**—Demonstration of four Van Hool buses with a UTC Power fuel cell power system and a Siemens hybrid drive integrated by the bus manufacturer. These buses are the same configuration as the ZEB A FCEBs. This project is part of the NFCBP. The first of four buses was delivered in May 2010 and all were in service by January 2011. In April 2012, one of the buses was moved to Flint, Michigan, and is now in service with the Mass Transportation Authority (MTA) for a one-year period. A second of the four buses is expected to be operated in Cleveland, Ohio, beginning later in the year. NREL completed a report on the Nutmeg demonstration in August 2012.
- **SunLine Transit Agency: Advanced Technology (AT) 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 completed three reports on this bus (in March 2011, October 2011, and May 2012).
- **SunLine Transit Agency: American Fuel Cell Bus (AFCB) Project**—Demonstration of one EIDorado National bus with a BAE Systems hybrid propulsion system and Ballard fuel cell power system. This project is part of the NFCBP. NREL began data collection in December 2011 and the first report is expected in late 2012.
- **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 during the 2010 Olympics in Vancouver, British Columbia, 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, where it is expected to go into service in fall 2012.
- **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 and is the second of three FCEBs from this manufacturer. Proterra has been working through several issues and upgrades to the bus, similar to those for the Austin bus. Data collection is scheduled to begin in October 2012.
- **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 (APU) for electric accessories. The bus was delivered to the agency in 2011; however it has not entered service because of difficulties getting access to hydrogen fuel.

During the last year, NREL continued to collect data on the FCEBs demonstrated in the first three projects in Table 2. Data collection began on the fourth project, the American Fuel Cell

Bus, in December 2011. The section “Update of Evaluation Results through July 2012” provides the most recent evaluation results for these four demonstrations.

### National Fuel Cell Bus Program (NFCBP)

FTA established 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. Additional funding was added to the program over the following three years, bringing the total funds to nearly \$90 million. The 50 percent cost share requirement brings the total NFCBP funding to more than \$180 million. The projects were competitively selected by FTA to best advance FCEB commercialization and are managed through three nonprofit consortia—CALSTART (Pasadena, California), the Center for Transportation and the Environment (CTE, Atlanta, Georgia), and the Northeast Advanced Vehicle Consortium (NAVC, Boston, Massachusetts). NREL was funded as a third-party evaluator to assess the viability of the buses demonstrated under the program.

The demonstration projects that are currently underway are included in Table 2 (blue shaded rows). Table 3 lists the remaining demonstration projects that will field seven more fuel cell buses over the next year. An additional \$13.5 million in funding was appropriated in 2012, leading to another call to the three consortia for proposals that expand or enhance the current projects under the portfolio. The new projects to be added to the program will be announced once the selection process is complete, probably in early to mid-2013.

**Table 3. New Fuel Cell Transit Buses Planned for the FTA NFCBP**

Project	Location	Total Buses	Technology Description
Lightweight FCEB Demo (NAVC)	Newark, DE	1	Lightweight bus with a GE hybrid system using advanced batteries and a Ballard fuel cell
Massachusetts FCEB Demo (NAVC)	Boston, MA	1	Hybrid bus using Nuvera fuel cells and an advanced battery system
Advanced Composite FCEB (CTE)	Washington, DC	1	Proterra composite body with a next generation fuel cell hybrid system
Birmingham FCEB Demo (CTE)	Birmingham, AL	1	EVAmerica 30-foot battery dominant FCB with advanced lithium ion battery technology.
Chicago Transit Authority FCEB Demo (CALSTART)	Chicago, IL	1	EIDorado/BAE/Ballard next-generation American Fuel Cell Bus
EcoSaver IV FCEB Demo (CTE)	Columbus, OH	1	DesignLine battery dominant FCB with a Ballard fuel cell
Advanced Generation FCEB (CALSTART)	Hartford, CT	1	New Flyer bus with next generation UTC Power fuel cell and BAE Systems hybrid propulsion

Beyond the NFCBP, FTA funds fuel cell bus research at several universities and transit agencies around the country. Details on FTA’s research for hydrogen and fuel cell electric bus technology, including the NFCBP and university projects, were documented in a recent FTA report.<sup>4</sup>

<sup>4</sup> *FTA Fuel Cell Bus Program: Research Accomplishments through 2011*, March 2012, FTA Report No. 0014.

## FCEB Development Process – Technology Readiness Levels

In the previous reports, we described the six-stage process that manufacturers typically use in developing new prototype transit buses:

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.

To better align this status report with other programs within DOE, we developed a guideline for assessing the technology readiness level (TRL) for FCEBs. In October 2009, DOE published a Technology Readiness Assessment Guide<sup>5</sup> to assist researchers conducting technology assessment projects. The guide was based on a proven model originally developed by the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD). The guide was updated in September 2011.<sup>6</sup>

Table 4 provides a TRL guide tailored for the commercialization of FCEBs. The column ‘Relative Level of Technology Development’ includes a reference to the associated stage in the original process. Figure 1 provides a graphic representation of this process.

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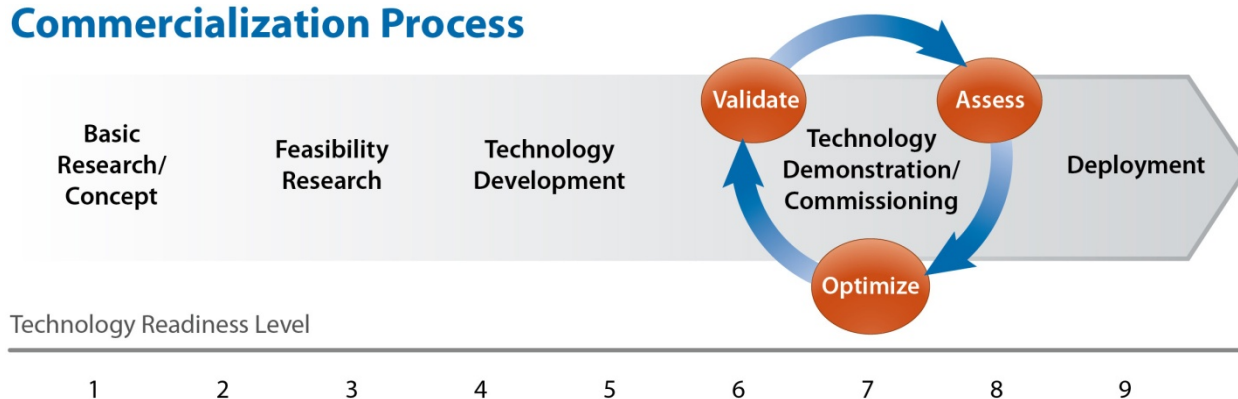
<sup>5</sup> DOE Technology Readiness Assessment Guide, G 143.3-4, <https://www.directives.doe.gov/directives/0413.3-EGuide-04/view>.

<sup>6</sup> DOE Technology Readiness Assessment Guide, G 143.3-4a, <https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view>.

**Table 4. Technology Readiness Levels for FCEB Commercialization**

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Deployment (Stage 6)	TRL 9	Actual system operated over the full range of expected conditions	The technology is in its final form. Deployment, marketing, and support begin for the first fully commercial products.
Technology Demonstration/Commissioning (Stage 5)	TRL 8	Actual system completed and qualified through test and demonstration	The last step in true system development. Demonstration of a limited production of 50 to 100 buses at a small number of locations. Beginning the transition of all maintenance to transit staff.
	TRL 7	Full-scale validation in relevant environment	A major step up from TRL 6 by adding larger numbers of buses and increasing the hours of service. Full-scale demonstration and reliability testing of 5 to 10 buses at several locations. Manufacturers begin to train larger numbers of transit staff in operation and maintenance.
	TRL 6	Engineering/pilot-scale validation in relevant environment	First tests of prototype buses in actual transit service. Field testing and design shakedown of 1 to 2 prototypes. Manufacturers assist in operation and typically handle all maintenance. Begin to introduce transit staff to technology.
Technology Development (Stage 3–4)	TRL 5	Laboratory scale, similar system validation in relevant environment	Integrated system is tested in a laboratory under simulated conditions based on early modeling. System is integrated into an early prototype or mule platform for some on-road testing.
	TRL 4	Component and system validation in laboratory environment	Basic technological components are integrated into the system and begin laboratory testing and modeling of potential duty-cycles.
Research to Prove Feasibility (Stage 2)	TRL 3	Analytical and experimental critical function and/or proof of concept	Active research into components and system integration needs. Investigate what requirements might be met with existing commercial components.
	TRL 2	Technology concept and/or application formulated	Research technology needed to meet market requirements. Define strategy for moving through development stages.
Basic Technology Research (Stage 1)	TRL 1	Basic principles observed and reported	Scientific research and early development of FCEB concepts.

## Commercialization Process



**Figure 1. Graphic representation of the commercialization process defined in Table 4**

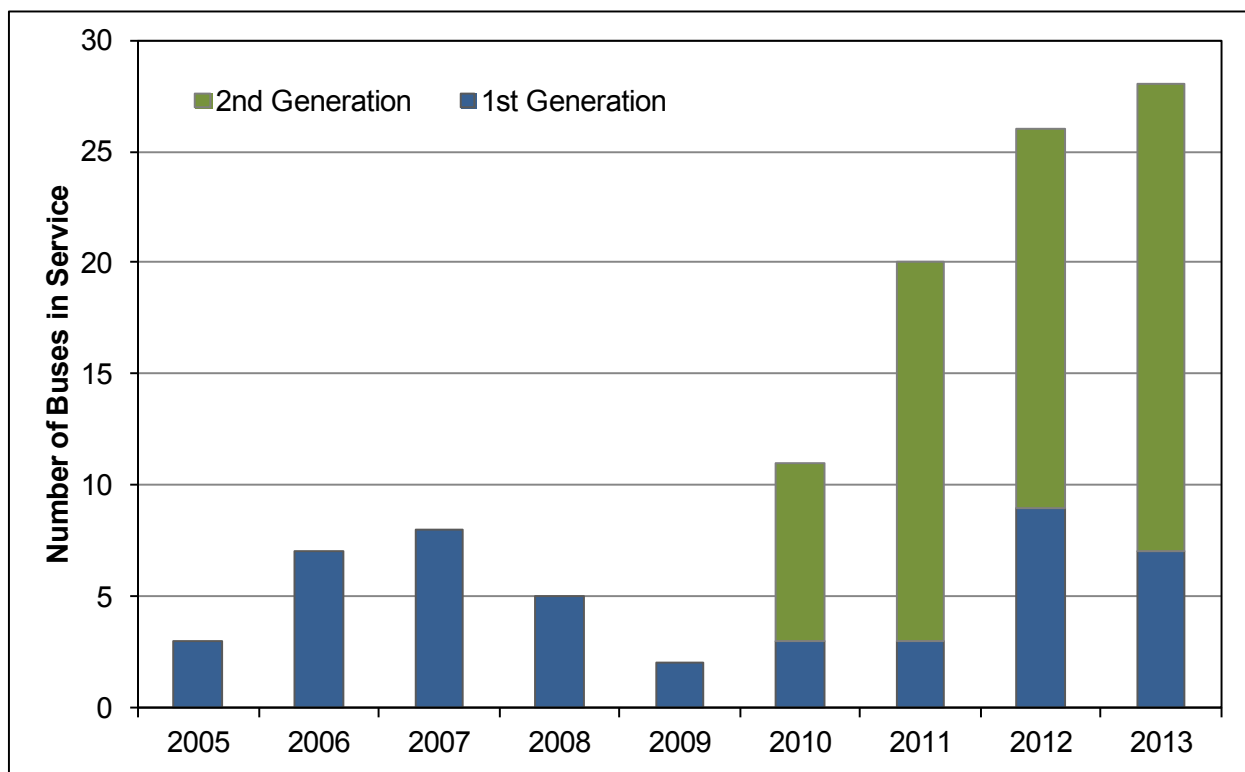
Moving through the nine TRLs can take a significant amount of time and resources. In the technology demonstration/commissioning phase that includes TRLs 6 through 8, the manufacturer begins the iterative process to validate the design, analyze the results, and reconfigure or optimize the design as needed. The manufacturer needs to enlist the help of a



transit agency partner to help conduct in-service tests on the bus. Updated products go back into demonstration and through the cycle until the design meets the performance requirements. Technical difficulties and setbacks are expected during this development phase.

The number of fuel cell bus demonstrations continues to increase. The last report documented 25 active FCEBs in operation in the United States. Over the last year, several demonstrations ended and the buses were retired; however several new buses were introduced to keep the total at 25 active buses. New manufacturer teams are introducing designs of fuel cell buses in smaller numbers, placing those projects in the first step of the technology demonstration/commissioning phase. For this report, a designation of 1<sup>st</sup>-generation is given to the prototype designs from new manufacturer teams that fall in TRL 6; a 2<sup>nd</sup>-generation system is typically a follow-on design from an existing team that falls in TRL 7. These designations are used in this report for simplicity and do not necessarily coincide with any version or designation made by the manufacturers.

Figure 2 shows the increase in active FCEBs. This figure includes only FCEBs that were placed into service during 2005 or beyond. Some 1<sup>st</sup>-generation FCEBs have been retired and were removed from the chart, causing the lower numbers in 2008 and 2009. If the new demonstrations are implemented as scheduled, 28 FCEBs should be in operation/active by the end of 2013.



**Figure 2. Growth in fuel cell electric buses since 2005**

Table 5 lists the manufacturer teams with FCEB designs currently in operation in the United States. At this stage of development, some partners are more active in the development and demonstration effort, while others are primarily providing a product. This section describes each of these FCEBs and where they fall in the commercialization process outlined in Table 4. NREL

made the TRL determination for each FCEB type based on the descriptions in Table 4. The demonstration teams involved in the evaluations reviewed the report.

**Table 5. Manufacturer Teams for FCEBs Currently Operating in the United States**

Bus OEM	Length (ft)	Fuel Cell System	Hybrid System	Design Strategy	Energy Storage
Van Hool	40	UTC Power	Siemens ELFA integrated by Van Hool	Fuel cell dominant	Lithium-based batteries
New Flyer	40	Ballard	Siemens ELFA integrated by Bluways	Fuel cell dominant	Lithium-based batteries
EIDorado	40	Ballard	BAE Systems	Fuel cell dominant	Lithium-based batteries
Proterra	35	Hydrogenics	Proterra integration	Battery dominant	Lithium-based batteries
Daimler (Orion)	40	Hydrogenics	BAE Systems	Diesel hybrid w/ FC	Lithium-based batteries
Ebus	22	Ballard	Ebus integration	Battery dominant	Nickel cadmium

**Van Hool**—UTC Power and Van Hool have been collaborating on this FCEB product that is operating in the ZEBAs and Nutmeg demonstrations in California and Connecticut. The design builds on the lessons learned from the previous FCEB and the demonstration involves a total of 16 buses, making this a 2<sup>nd</sup>-generation product at TRL 7. This 2<sup>nd</sup>-generation FCEB includes several major modifications from the original design to improve reliability and durability. Improvements include a redesigned bus chassis to lower weight, a hybrid propulsion system integrated by the manufacturer, the newest version fuel cell power system, and a different battery manufacturer.

**New Flyer**—This bus design is considered a 2<sup>nd</sup>-generation product at TRL 7. The development of this bus was led by the hybrid system integrator, ISE Corporation, in coordination with the fuel cell manufacturer, Ballard Power Systems. Both companies had experience with earlier-generation FCEBs. The design was developed for an order of 20 FCEBs to be operated in Whistler, British Columbia, Canada, beginning during the 2010 Winter Olympic Games. The pilot bus was delivered to the transit operator, BC Transit, who put the bus through a series of acceptance tests over a period of about six months. The data results from those tests enabled the manufacturers to make changes and optimize the design prior to building the larger fleet, which began service in early 2010. The pilot bus was then upgraded to match the final design of the rest of the BC Transit fleet and was eventually purchased by SunLine. (Note: since the early development of this bus design, ISE Corporation declared bankruptcy. In February 2011, Bluways acquired substantial assets and technology from ISE Corporation and assumed a role in the bus development and demonstration.)

**EIDorado**—This is a new FCEB design led by the hybrid manufacturer/integrator, BAE Systems. Both BAE Systems and EIDorado are new to FCEB development but are working with a fuel cell manufacturer with significant experience in the industry, Ballard. This bus is

considered a 1<sup>st</sup>-generation product in the field testing stage of development, or TRL 6. This team has several advantages that are expected to move this bus design into a 2<sup>nd</sup>-generation product quickly. While relatively new to fuel cell propulsion, BAE Systems has more than a decade of experience with hybrid electric drivetrains and manufactures a commercial hybrid product that is currently in operation in transit fleets around the United States. Building on this proven platform could accelerate the design/shakedown stage of the commercialization process.

**Proterra**—Proterra developed its first prototype fuel cell electric bus as part of the NFCBP. This prototype bus was designed to be an electric drive bus and was developed using a whole vehicle approach. While most of the current FCEBs began by using a standard bus chassis, Proterra's FCEB development included designing a light-weight composite body. The propulsion system design can be produced as a battery-only version or combined with the fuel cell system as a range extender. Two additional FCEBs were produced based on the original prototype. This FCEB is considered a 1<sup>st</sup>-generation design at TRL 6.

**Daimler**—This is the only bus included in the report that is not primarily powered by a fuel cell. BAE Systems began with its diesel hybrid bus design and added all-electric accessories operated by a fuel cell. In the original plan, the fuel cell was intended to power the accessories only. During development, BAE Systems modified the system to allow the fuel cell to provide some motive power in addition to powering the accessories. This bus is considered a 1<sup>st</sup>-generation product in the field testing stage of development. Because the system is based on BAE Systems' proven hybrid propulsion system the TRL is closer to 7 than 6. The development of this design was funded through the NFCBP as an option to enable adoption of fuel cells in transit fleets. Adding a smaller, lower cost fuel cell to an existing diesel hybrid bus to power the accessories could increase the fuel efficiency of the bus and introduce transit agencies to hydrogen as a fuel for future expansion.

**Ebus**—This design is a battery-dominant system for a smaller bus developed under FTA funding outside the NFCBP. Three buses are currently operating in two locations in the United States. This bus is considered a 1<sup>st</sup>-generation product at TRL 6. NREL has not collected data on these buses.

## Development Status of FCEBs Compared to CNG and Diesel Hybrid Buses

NREL has been assessing and evaluating the development of new propulsion systems for transit buses in the United States for more than 20 years. These evaluations focused on determining the commercial status of new transit bus technologies with respect to how ready the technology was for full transit service (from the user's, not the manufacturer's, perspective). Through these evaluations, NREL monitored and recorded the full development of compressed natural gas (CNG) and diesel hybrid electric propulsion for commercial/full transit service.

The intent of this section is to explore how the development of these two commercial propulsion technologies progressed from pilot/prototype demonstration (TRL 6) to full deployment (TRL 9). This experience and history provides perspective in measuring the progress of FCEB development and in making comparisons to battery electric propulsion, which is now being presented as a potentially lower-cost alternative to FCEBs.

### CNG Propulsion Development for Transit Buses

Testing of the current heavy-duty natural gas engine for transit buses began in 1988 with single demonstration buses. Alternative fuels had emerged as a priority through national policy (Alternative Motor Fuels Act of 1988). At that time, it was widely believed that alcohol fuels would be the alternative fuel of choice. The development of a heavy-duty natural gas engine for transit buses had several challenges, including converting a heavy-duty spark-ignited engine design to run on natural gas and determining the design and integration of gaseous fuel tanks into a transit bus. These challenges for CNG propulsion also indicated that this alternative technology would be significantly more expensive to purchase than the standard diesel propulsion system.

The federal government made significant investments in field test demonstrations, providing incentives for several hundred transit buses, to determine the potential of alternative fuels for transit (FTA funded the transit buses and DOE funded technology development, testing, and evaluation). Several transit agencies tested pilot bus versions with multiple alternative fuels (methanol, ethanol, CNG, LNG, and biodiesel), and these buses were demonstrated and evaluated in comparison to standard/baseline diesel buses at each location.<sup>7</sup> This four-year study determined that CNG buses at Pierce Transit (Tacoma, Washington) showed great promise for full implementation, far and away the best experience from the study of eight transit agencies and five alternative fuels.

In 1994, Cummins began producing their early production CNG engine (L10-240G and L10-260G versions), and several transit agencies, including SunLine Transit Agency (Palm Springs, California area) and Pierce Transit, started to convert their operations to CNG buses (ultimately switching to 100% CNG buses). Detroit Diesel Corporation (DDC) also developed its CNG engine for the transit market (Series 50G). The development of these CNG heavy-duty engines moved the technology into TRL 7 and TRL 8 starting in 1994 through about 2000. The challenge to the CNG engine technology at this point was trying to maximize fuel economy and provide reliably lower emissions of particulate matter (PM) and oxides of nitrogen (NO<sub>x</sub>) compared to

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<sup>7</sup> *Alternative Fuel Transit Buses, Final Results from the National Renewable Energy Laboratory Vehicle Evaluation Program*, October 1996, NREL/TP-425-20513.

diesel engine technology. The transit industry was also learning how to manage new safety systems needed to manage large amounts of natural gas stored onboard the buses in maintenance and bus storage facilities. In addition, the industry needed to understand operations and maintenance of large CNG fueling stations.

The engine and bus manufacturers worked to optimize integration of the CNG engine and fueling systems, along with reliable safety systems, into the bus. This work occurred over a time period from 2000 to 2006 and resulted in a CNG transit bus that was ready for commercial transit service (TRL 9). Also during this timeframe, the emissions requirements for heavy-duty engines became much more stringent, specifically for PM and NO<sub>x</sub>, and CNG buses provided the cleanest emissions for the transit market. Ultimately, the availability of CNG as an alternative clean propulsion technology led to the adoption of lower NO<sub>x</sub> emissions requirements in 2010 at 0.2 g/bhp-h (grams per brake horsepower hour) for all heavy-duty on-road engines. For diesel engine manufacturers to meet this low NO<sub>x</sub> emissions level required significant work, including the development of regenerative diesel emissions traps, exhaust gas recirculation (EGR), and selective catalytic reduction (SCR). The emissions reductions also required the use of ultra-low-sulfur diesel fuel before the low emissions requirements could be enforced.

The CNG engine technology was able to meet the 2010 emissions levels in 2007. There was some speculation that once diesel engine technology could meet the 2010 emissions levels, there would be no need for CNG buses. For some time after 2010, CNG bus purchases started to decline until the more recent increase in diesel fuel prices and the discovery of significant domestic reserves of natural gas. Currently, natural gas prices are significantly lower than diesel fuel prices and this situation is expected to continue into the future. CNG transit buses currently represent nearly 20% of the U.S. transit fleet.<sup>8</sup> Overall, CNG transit bus development required 12–14 years to progress from TRL 6 into TRL 9.

### **Diesel Hybrid Electric Propulsion Development for Transit Buses**

After CNG transit buses emerged as a clean alternative to diesel transit buses, interest grew in hybrid electric propulsion for transit buses using a diesel engine. The transit industry was interested in developing an alternative to the CNG transit bus because of the cost of the CNG infrastructure and because not every transit operating location could easily accommodate the CNG equipment. This was especially true if space for the fueling infrastructure was not available, as was the case for New York City Transit (NYCT) and their Manhattan operating depots. In the mid-1990s, NYCT was experiencing significant pressure to field cleaner-emissions transit buses (such as CNG); however, the cost for converting depots in Manhattan was going to be extremely expensive, and in some cases the safety requirements might have made it impossible.

NYCT, working with BAE Systems and Orion Bus Industries, purchased 10 newly developed prototype diesel hybrid electric transit buses in 1998; this demonstration moved hybrid electric propulsion technology into TRL 6 and TRL 7.<sup>9</sup> NREL evaluated NYCT's experience with these 10 prototype diesel hybrid electric transit buses and published a technical report in November

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<sup>8</sup> American Public Transportation Association (APTA) *2011 Public Transportation Fact Book*, Table 12.

<sup>9</sup> NREL evaluated these 10 prototype diesel hybrid electric buses in *Hybrid-Electric Transit Buses, NYCT Diesel Hybrid-Electric Buses, Final Results*, July 2002, NREL/BR-540-32427.

2003 that explored the challenges and experience with implementing electric propulsion transit buses.<sup>10</sup>

Based on the experience with the prototype diesel hybrid electric buses, NYCT and BAE Systems agreed to invest in developing significantly larger numbers of buses in two orders—the first for 125 buses and the second for 200 buses with delivery completed in 2004. These large orders were intended to accelerate the development of this propulsion technology for transit buses into TRL 8.<sup>11</sup> In 2006, NYCT and BAE Systems agreed to another order of 500 diesel hybrid electric buses. BAE Systems and the bus manufacturer (Orion) worked together to improve integration and component selection for each of these three orders over several years. The first two orders used lead-acid traction batteries, and the newer order of 500 buses switched to lithium-based traction batteries. Also, by the third order of diesel hybrid electric buses, BAE Systems had revised and optimized the integration of several systems into the hybrid propulsion product.

Concurrently with BAE Systems' hybrid propulsion system development, Allison was developing its own diesel hybrid electric propulsion system. King County Metro in Seattle, Washington, was looking for a replacement for its specially built dual-mode diesel engine/electric propulsion trolley buses. These buses operated as electric trolleys within the downtown Seattle tunnel but could leave the catenary and operate on diesel outside of the tunnel. These dual-mode buses were expensive to maintain and were getting close to the end of their useful life. King County Metro worked with Allison to develop and test its diesel hybrid electric buses as replacements for the dual-mode buses. Ultimately, King County Metro placed an order for 235 diesel hybrid electric buses that replaced the dual-mode bus fleet.<sup>12</sup>

These two large fleets of diesel hybrid electric buses accelerated the development of this propulsion technology directly into TRL 8. As of about 2010, the diesel hybrid electric propulsion system for transit buses was considered a fully developed baseline product in TRL 9. Similar to the experience with CNG propulsion, the maturation of the diesel electric propulsion system for transit buses took about 12–14 years. However, without the significant investments in large bus orders by NYCT and King County Metro, this development might have taken several more years.

### **FCEB Propulsion Development Status**

This discussion is focused on FCEBs designed with a fuel cell dominant hybrid electric propulsion system. This design is more mature and has benefited from more investment up to this point. This design is also more similar to the CNG and diesel hybrid electric propulsion transit buses already discussed. Two FCEB products are considered for this discussion – the Van Hool/UTC Power/Siemens FCEB and the El Dorado/Ballard/BAE Systems FCEB. These two

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<sup>10</sup> NREL, *Challenges and Experiences with Electric Propulsion Transit Buses in the United States*, November 2003, DOE/GO-102003-1791.

<sup>11</sup> NREL, *New York City Transit (NYCT) Hybrid and CNG Transit Buses: Final Evaluation Results*, June 2006, NREL/TP-540-40125.

<sup>12</sup> NREL, *King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results*, December 2006, NREL/TP-540-40585.

designs are at TRL 7. These FCEBs went into TRL 6 starting in 2005,<sup>13</sup> so the technology is seven years into the development cycle.

Table 6 compares the technology development experience from NREL evaluations for CNG, diesel hybrid, and FCEB propulsion technologies to date. Fuel economy has been tracked because of its impact on any cost benefit study of the new technology. Propulsion-only miles between roadcalls (MBRC) is intended to represent the reliability of the product. Note that these two measures have been generalized here to account for differences in transit agency duty cycle, which causes significant differences in both fuel economy and propulsion MBRC.

**Table 6 Technology Development Progress by TRL**

Propulsion Technology	Development Timeframe	Fuel Economy Compared to Baseline	Propulsion MBRC
<b>CNG</b>	Pilot scale (TRL 6)	-25% to -35%	1,000 to 5,000
	Full scale validation (TRL 7)	-25% to -30%	10,000
	Full demonstration (TRL 8)	-20% to -25%	23,000
	Deployment (TRL 9)	-20 to -25%	30,000
<b>Diesel Hybrid</b>	Pilot scale (TRL 6)	+10%	2,000
	Full scale validation (TRL 7)	+25% to +30%	10,000
	Full demonstration (TRL 8)	+30%	10,000
	Deployment (TRL 9)	+30%	10,000
<b>FCEB</b>	Pilot scale (TRL 6)	+45% to 75%	2,000 to 4,000
	Full scale validation (TRL 7)	+90% to 100%	4,000

The table provides generalized results for comparison. A summary of the development experience for each propulsion technology is summarized here:

- **CNG buses** have always had a lower fuel economy than diesel buses because of the ignition cycle used in the engine. As discussed above, this is off-set by the much lower cost of CNG fuel. Note that the current MBRC for the CNG propulsion system is quite high. There are continuing maintenance and reliability issues with this engine technology, including spark plug life and valves (i.e., exhaust), which continue to be worked on by the manufacturer.
- **Diesel hybrid buses** have significantly higher fuel economy but are significantly affected by duty cycle. Diesel hybrid propulsion needs an average duty cycle around 10–15 mph in order to maximize fuel economy gains. The diesel hybrid propulsion system continues to have integration issues that are being worked on by the manufacturers, as indicated by the average propulsion MBRC of 10,000 (unlike the higher rate for CNG buses).
- **FCEBs** show great potential for fuel economy increases as promised by the manufacturers. The current demonstrations have consistently shown fuel economies two times higher than that of standard diesel baseline buses in the same service. The major issues are in optimizing the integration of the complex hybrid electric systems

<sup>13</sup> Note that the El Dorado and BAE Systems FCEB is somewhere between TRL 6 and TRL 7. The higher TRL level is indicated because the hybrid propulsion system used is already a commercial product.

with the traction batteries and the fuel cell power plant. As shown later in this report, the fuel cell power plant (including the balance of plant) has shown progress in increasing MBRC to 12,000; however, there are still issues with the integration of the hybrid propulsion system.

Table 6 shows that FCEB development is progressing along a similar path to that of CNG and diesel hybrid propulsion systems, but at a slightly slower pace. This slower pace might be explained by the complexity of combining gaseous fuels and hybrid electric propulsion into one system. Another major issue is the current high cost of purchasing an FCEB, which limits the numbers of buses being demonstrated and tested. Both the CNG and diesel hybrid bus technology development experiences benefited from significantly large orders of buses to push the technology into TRL 8. Up to this point, there is excitement about FCEBs and the progress with development, but there has not yet been a commitment to a larger demonstration program.

DOE and FTA also support and track the development of battery dominant fuel cell propulsion system buses. This propulsion system design is helpful for keeping the overall cost of the FCEB lower by having a smaller, lower cost fuel cell power system and a higher capacity traction battery system.

### **Battery-Only Propulsion Development Status**

As the development of diesel hybrid propulsion systems has progressed, the development of higher energy capacity traction battery designs has improved significantly with the introduction of lithium-based batteries. The improved performance that lithium-based batteries provide has now caused renewed interest in developing battery-only propulsion for full-sized transit buses. This new approach to battery-only propulsion includes opportunity charging of the batteries while the bus is out on-route, usually at layover points in the route design. Note that this type of route design is more like a fixed guideway approach such as bus rapid transit (BRT) or trolley bus operation; however, with a range of only 30 miles or so, the battery bus has limited flexibility to go off the fixed route.

When comparing a battery-only full-sized transit bus with an FCEB, care must be taken in understanding how the transit agency might use the bus and the infrastructure that might be required. It is expected that there will continue to be a need for multiple solutions for clean and efficient transit bus propulsion designs, including several types of propulsion alternatives.



## Update of Evaluation Results through July 2012

The data presented in this section represent the most recent results that have not been presented in a previous status report. These data come from four different FCEB demonstrations at three agencies. To simplify the presentation of the data, we have assigned each FCEB an identifier that includes a site abbreviation followed by a manufacturer or project designation. All of the FCEBs presented in this section have hybrid systems that are fuel cell dominant. Table 7 provides some specifications of each FCEB by the unique ID. The FCEBs are pictured in Figure 3.

**Table 7. FCEB Identifiers and Selected Specifications**

	ACT ZEB A	CTT Nutmeg	SL AT	SL AFCB
Transit agency	AC Transit	CTTRANSIT	SunLine	SunLine
Number of buses	12	4	1	1
Bus OEM	Van Hool	Van Hool	New Flyer	EIDorado
Bus length	40 ft	40 ft	40 ft	40 ft
Fuel cell OEM	UTC Power	UTC Power	Ballard	Ballard
Fuel cell power (kW)	120	120	150	150
Hybrid system integrator	Van Hool	Van Hool	Bluways	BAE Systems
Design strategy	FC dominant	FC dominant	FC dominant	FC dominant
Energy storage OEM	EnerDel	EnerDel	Valence	A123
Energy storage type	Li-ion	Li-ion	Li-ion	Li-ion
Energy storage power	21 kWh	21 kWh	47 kWh	11 kWh
Hydrogen storage pressure (psi)	5,000	5,000	5,000	5,000
Hydrogen cylinders	8	8	6	8
Hydrogen capacity (kg)	40	40	43	50

**Baseline buses**—Conventional baseline bus data are provided for all three agencies for comparison with FCEB data. For AC Transit and CTTRANSIT, the primary comparisons are with diesel buses. The baseline buses at SunLine are CNG because the agency doesn't operate diesel buses. Fuel economy from diesel hybrid buses is also included for CTTRANSIT; the agency operates a number of hybrid buses at several of its divisions. Fuel economy is highly variable based on duty-cycle, and the most accurate comparisons require similarly sized buses operated in the same service. CTTRANSIT's FCEBs operate out of the Hartford Division; the hybrid buses most similar to the FCEBs operate out of the New Haven Division. The fuel economy for standard diesel buses at the New Haven Division is typically 0.1 mpg lower than it is at the Hartford Division (or 2 to 3 percent lower fuel economy on average at New Haven compared to Hartford). This fact should be noted when comparing the results presented in the report; however, this indicates that the duty-cycles are reasonably similar enough to compare. The Appendix summarizes the data results by demonstration location and provides additional charts that detail some of the results by agency.



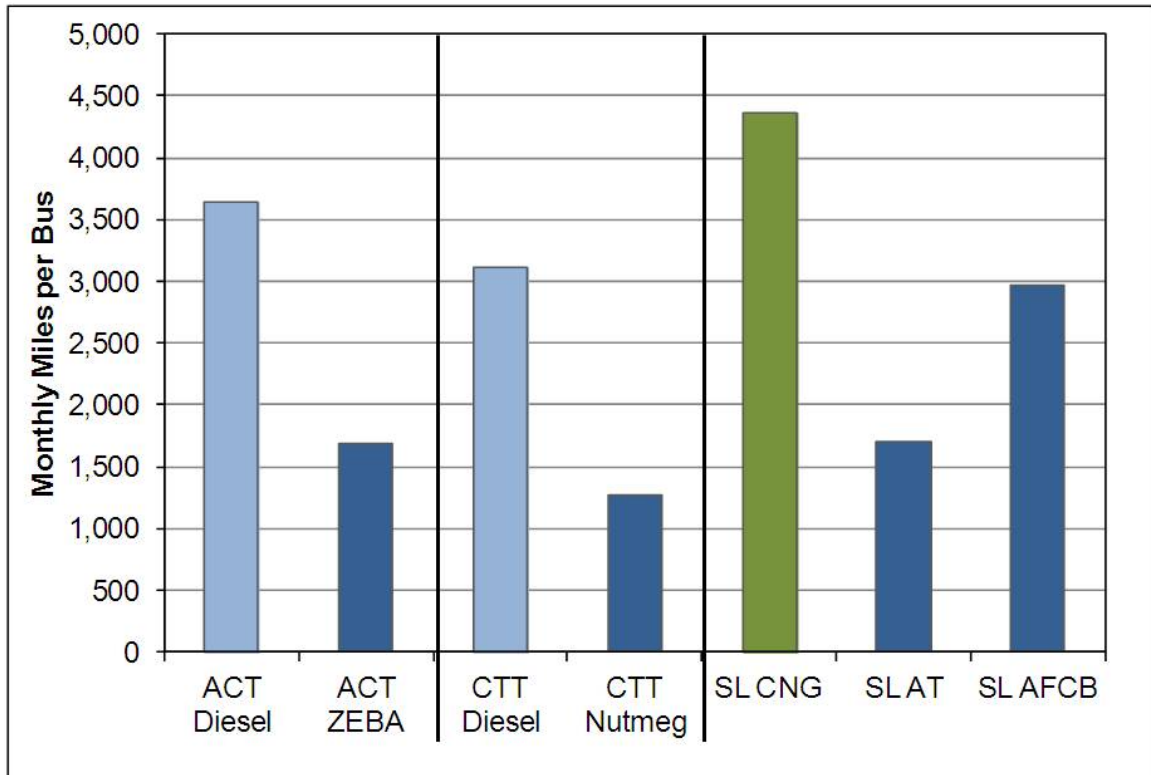
**Figure 3. FCEBs included in the data summary: AC Transit ZEBAs (top left), CTTTRANSIT Nutmeg (top right), SunLine AFCB (bottom left), SunLine AT (bottom right)**

**Total miles and hours**—Table 8 shows miles, hours, average speed, and average monthly miles per bus for the FCEBs. The AFCB at SunLine has the highest average speed at 15.7 mph, followed by the Nutmeg buses at 14 mph. SunLine’s AT bus operates primarily on one specific route, while the AFCB has operated on several routes within the service area. The ZEBAs in service at AC Transit have the lowest average speed of the group. Average monthly bus use ranged from a low of approximately 1,200 miles up to just under 3,000 miles per month.

**Table 8. Miles and Hours for the Fuel Cell Buses**

ID	Period	Months	No. of Buses	Miles	Hours	Avg. Speed (mph)	Avg. Monthly Miles
ACT ZEBAs	9/11 – 4/12	9	12	147,069	17,619	8.3	1,690
CTT Nutmeg	8/11 – 7/12	12	4	57,014	4,077	14.0	1,267
SL AT	8/11 – 7/12	12	1	20,514	1,724	11.9	1,710
SL AFCB	12/11 – 7/12	8	1	23,683	1,510	15.7	2,960

**Bus use**—Figure 4 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.

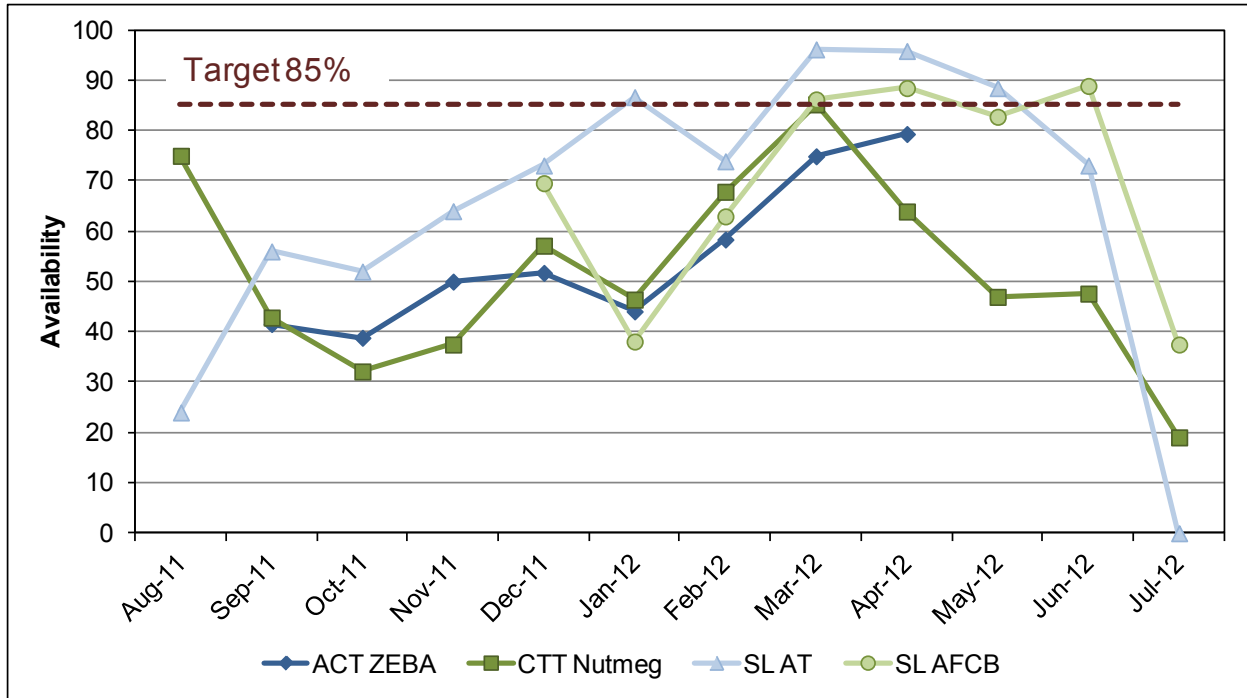


**Figure 4. Average monthly miles per fuel cell and baseline buses**

**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 9 summarizes the availability of the fuel cell buses at each transit agency. Availability varies from site to site with a low of 53% up to a high of 71%. Average availability for the data period doesn't show the entire picture of what occurred during that time. Figure 5 tracks the monthly availability for the FCEBs by project. The SunLine AT bus (light blue line in the figure) availability was higher than 50% for the majority of the 12-month period. The months with the lowest availability—August 2011 and July 2012—pulled the overall average down. In August 2011, the bus experienced issues with the traction batteries and a hydrogen leak at one of the tank valves. The bus was down for battery issues the entire month of July 2012. The availability for the SL AT bus increased throughout the data period until battery issues took the bus out of service in July 2012.

**Table 9. Availability for the Fuel Cell Buses**

ID	Period	Months	No. of Buses	Planned Days	Days Avail.	% Avail.
ACT ZEBA	9/11 – 4/12	9	12	1,943	1,087	56
CTT Nutmeg	8/11 – 7/12	12	4	933	493	53
SL AT	8/11 – 7/12	12	1	302	201	67
SL AFCEB	12/11 – 7/12	8	1	206	146	71

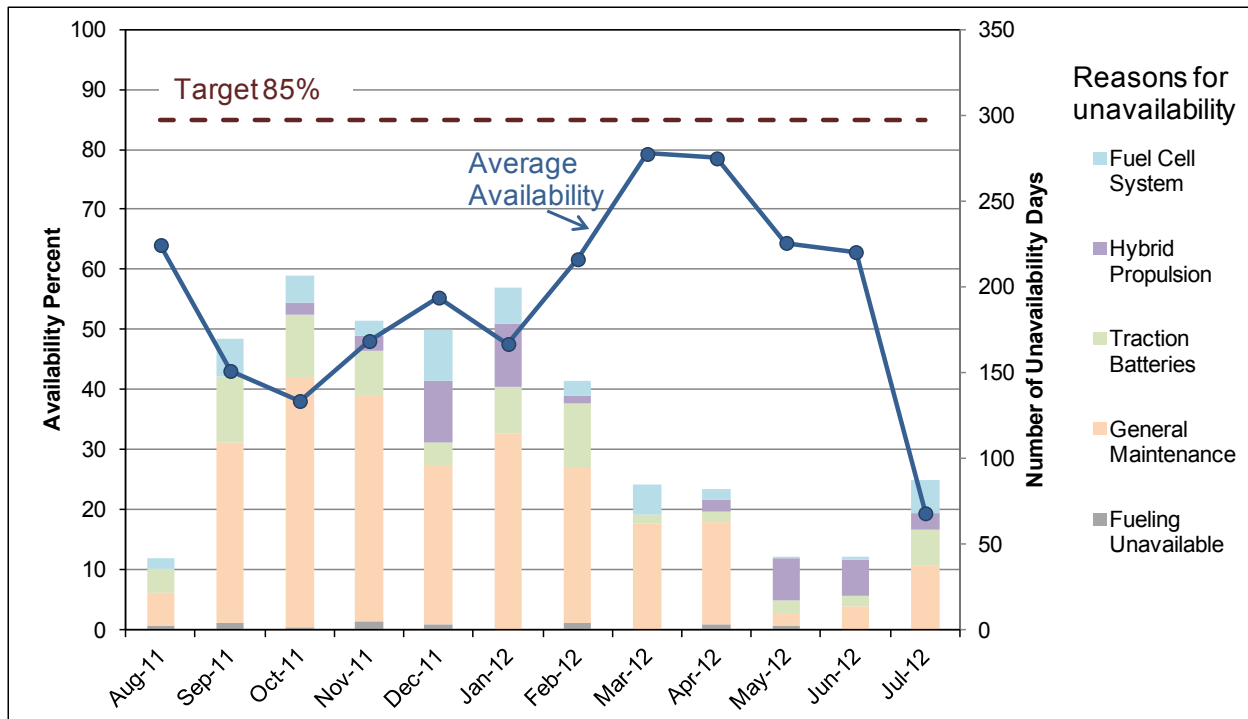


**Figure 5. Monthly availability for the FCEBs**

The ACT ZEBAs (dark blue line in the graph) buses began with lower availability but show a steady increase toward the end of the data period. During this period, the manufacturer was making several modifications primarily to address issues with the energy storage system. Changes to software and the communication between the batteries and the hybrid system appear to have solved the problems. Although the buses at CTTTRANSIT (dark green line) are the same design as the ZEBAs buses, the availability was lowered by several issues throughout the data period. The majority of those issues (69%) were related to bus systems such as fuel tank regulators and air compressors; however, several hybrid propulsion problems led to significant downtime (21%). Propulsion system issues included a motor failure, inverter/software issues, and battery problems. Fuel cell power system issues only counted for 6% of the downtime. Long lead time for getting replacement parts—especially for those from overseas sources—contributed to extended downtime.

The availability for the SL AFCB (shown as a light green line in the graph) has been quite good, at or over the 85% target for four of the eight months in service. The low point in January 2012 was caused by several problems including a hydrogen tank valve issue, faults with the drive system, and a fuel cell issue. The low point for July 2012 was for bus-related issues—air conditioning and doors.

Figure 6 presents the overall monthly availability and shows the reasons that the buses were not available by category. The blue line on the graph is the combined monthly availability for the buses in all four demonstration projects. The stacked bars show the total number of days the buses were unavailable each month by primary system category. The majority of issues affecting the availability for the buses were general maintenance (60%), followed by traction batteries (17%), hybrid system (11%), and fuel cell system (11%).



**Figure 6. Average monthly availability and number of unavailability days by category**

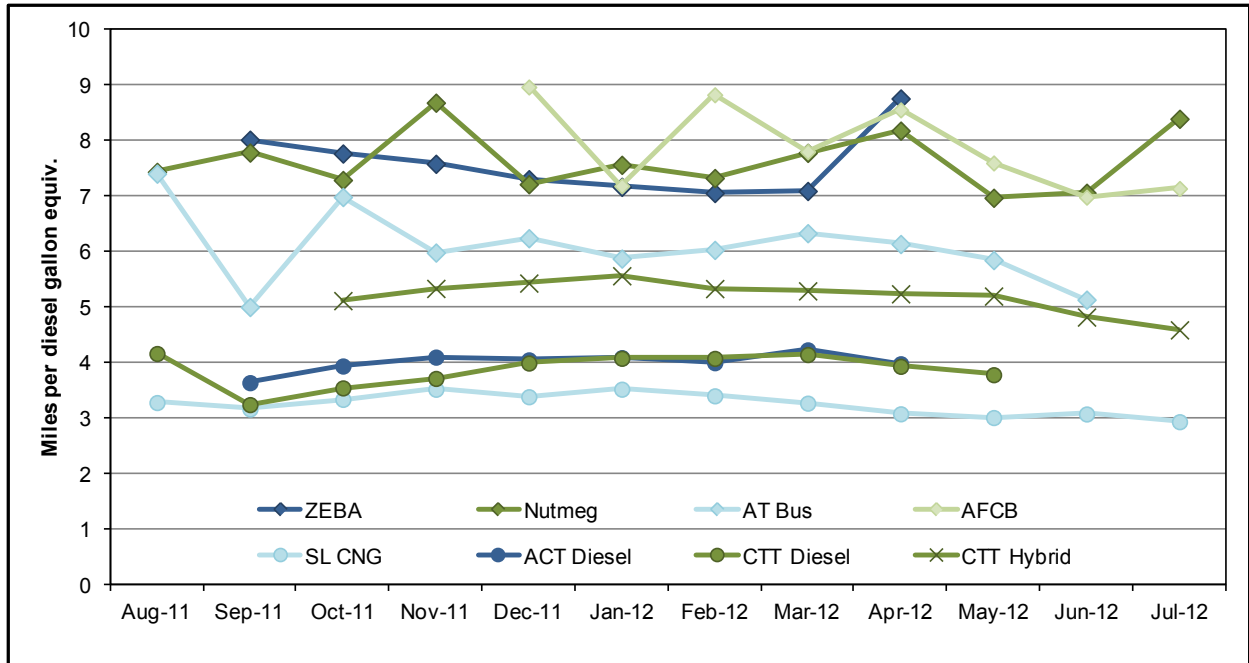
**Fuel economy**—Table 10 shows the average fuel economy in miles per diesel gallon equivalent (DGE) for each type of FCEB compared to the conventional baseline bus technology at the same site. Figure 7 shows the fuel economy by month over the last year.

The FCEBs continued to show improved fuel economy compared to the baseline buses in similar service. The fuel economy for hybrid fuel cell systems tends to vary from site to site depending on the duty-cycle.

**Table 10. Average Fuel Economy Comparisons between the FCEBs and Baseline Buses**

ID	Miles per kg/gge	Miles per Diesel Gallon Equivalent	Difference from Baseline
ACT ZEBA	6.68	7.55	1.89x
ACT diesel	–	4.00	–
CTT Nutmeg	6.72	7.60	2.01x / 1.46x <sup>14</sup>
CTT diesel	–	3.79	–
CTT diesel hybrid	–	5.19	1.37x
SL AT	5.29	5.97	1.84x
SL AFCB	6.93	7.84	2.41x
SL CNG	2.91	3.25	–

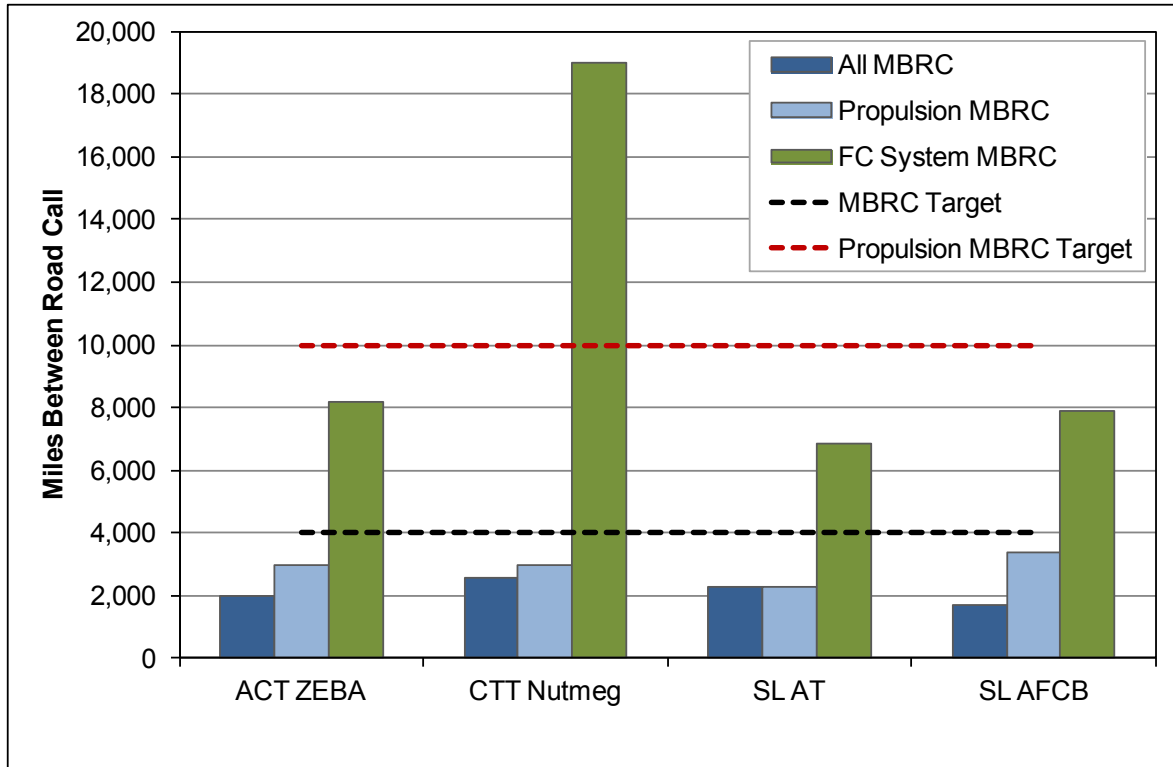
<sup>14</sup> The CTT Nutmeg buses are compared to both the CTT diesel buses and CTT diesel hybrid buses.



**Figure 7. Fuel economy for fuel cell and baseline buses**

FTA’s performance target for FCEB fuel economy is at least two times higher than that of diesel buses. The FCEBs showed improved fuel economy ranging from 1.8 to 2.4 times higher than that of diesel and CNG baseline buses.

**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 roadcall is recorded. Figure 8 shows miles between roadcalls (MBRC) for all roadcalls, for propulsion-related-only roadcalls, and for fuel-cell-system-only roadcalls for the FCEBs during the data period. 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). While the MBRC rates are still lower than the targets, the MBRC for fuel-cell-system-only roadcalls shows that the reasons are not typically due to the fuel cell.



**Figure 8. MBRC rates for fuel cell buses compared to the targets**

**Hydrogen fueling**—NREL has tracked total hydrogen use for FCEBs at a total of five sites. Since the first bus went into service in January 2006 through July 2012, these FCEBs have been fueled with more than 136,000 kg of hydrogen with no fueling safety incidents. The amount of hydrogen dispensed continues to grow as new buses are placed into service. Figure 9 shows the total hydrogen dispensed each year along with the total number of buses in service. The data for 2012 cover only seven months of that year. By the end of the year, we expect a total of 26 FCEBs to be in service at locations tracked by NREL.

During the data period from August 2011 through July 2012, the FCEBs at the four demonstrations were fueled 1,819 times with a total of 33,793 kg of hydrogen. The average fill amount for these fuel cell dominant FCEBs was 18.6 kg per fill.

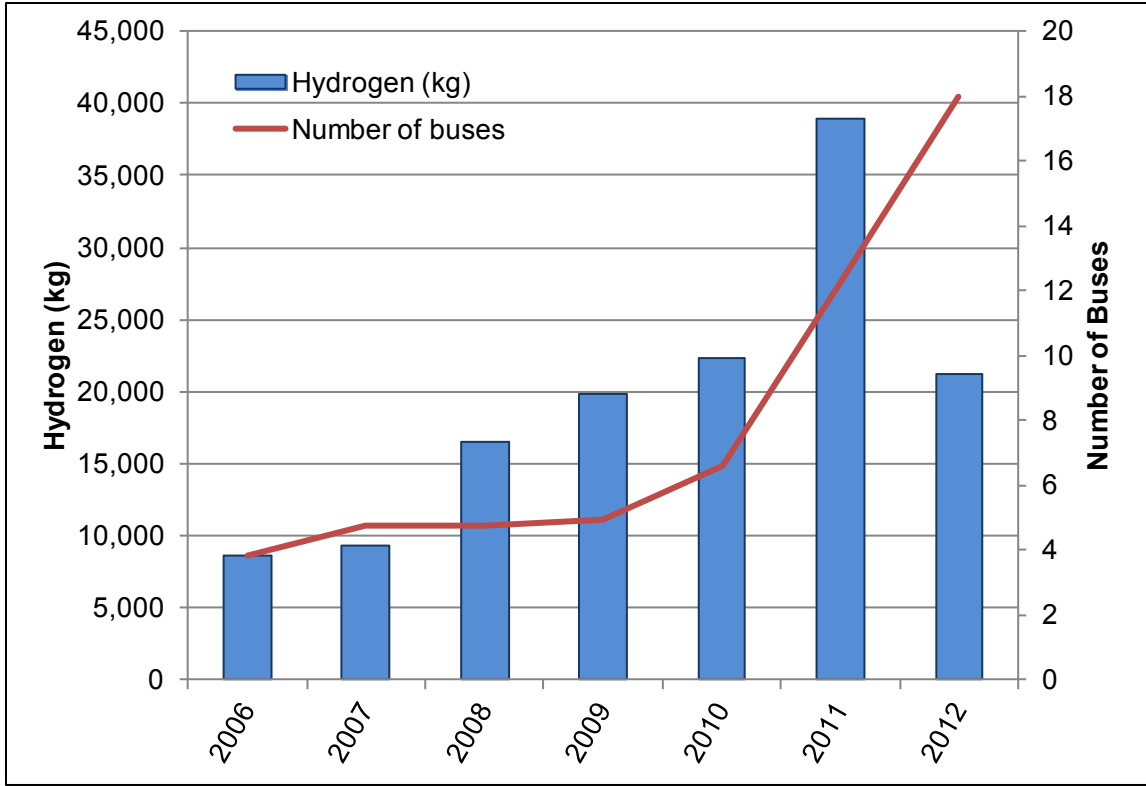


Figure 9. Hydrogen dispensed for the FCEBs by year<sup>15</sup>

<sup>15</sup> Note that the total hydrogen for 2012 is for only half the year.



## Current Status of FCEB Introductions: Summary of Achievements and Challenges

Over the last year, several FCEB projects ended while newer FCEBs were placed 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 FCEBs to the market.

### Progress Toward Meeting Technical Targets

DOE and FTA have established performance, cost, and durability targets for FCEBs. The process to develop these targets began in 2010 with a joint DOE/FTA workshop to invite comment and discussion from the industry. The workshop was followed by a request for information (RFI, DE-FOA-0000542<sup>16</sup>) to solicit further comments on the proposed targets that resulted from the workshop discussion. Table 11 shows selected technical targets for FCEBs developed in this process and published in a Fuel Cell Technologies Program Record.<sup>17</sup> Interim targets were set for 2016 along with ultimate targets that FCEBs would need to meet to compete with current commercial technology buses.

**Table 11. DOE/FTA Performance, Cost, and Durability Targets for FCEBs<sup>a</sup>**

	Units	2016 Target	Ultimate Target
Bus lifetime	years/miles	12/500,000	12/500,000
Power plant lifetime <sup>b</sup>	hours	18,000	25,000
Bus availability	%	85	90
Fuel fills	per day	1 (< 10 min)	1 (< 10 min)
Bus cost <sup>c</sup>	\$	1,000,000	600,000
Roadcall frequency (Bus/fuel cell system)	miles between roadcalls	3,500/15,000	4,000/20,000
Operation time	hours per day/days per week	20/7	20/7
Scheduled and unscheduled maintenance cost <sup>d</sup>	\$/mile	0.75	0.40
Range	miles	300	300
Fuel economy	miles per gallon diesel equivalent	8	8

<sup>a</sup> The cost targets for sub-systems (power plant and hydrogen storage) are not included.

<sup>b</sup> The powerplant is defined as the fuel cell system and the battery system.

<sup>c</sup> Cost projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only and does not represent an anticipated level of sales.

<sup>d</sup> Excludes mid-life overhaul of power plant.

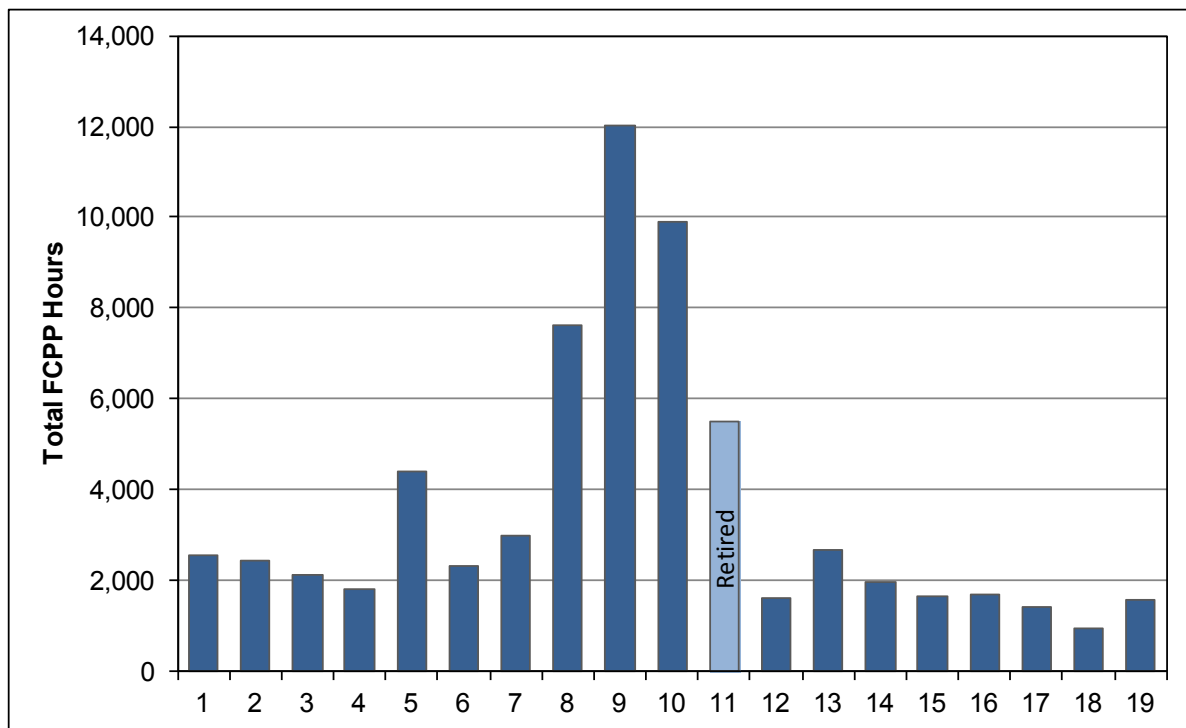
<sup>16</sup> Fuel Cell Transit Bus Targets. DE-FOA-0000542, [https://www.fedconnect.net/FedConnect/PublicPages/PublicSearch/Public\\_Opportunities.aspx?doc=DE-FOA-0000542&agency=DOE](https://www.fedconnect.net/FedConnect/PublicPages/PublicSearch/Public_Opportunities.aspx?doc=DE-FOA-0000542&agency=DOE).

<sup>17</sup> Fuel Cell Technologies Program Record # 12012, September 12, 2012, [http://www.hydrogen.energy.gov/pdfs/12012\\_fuel\\_cell\\_bus\\_targets.pdf](http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf).

**Bus and power plant lifetime**—Increasing the durability and reliability of the fuel cell system continues to be a key challenge for manufacturers. The FTA life cycle requirement for a full size bus is 12 years or 500,000 miles. A fuel cell power plant (FCPP) needs to last about half of that time; this is similar to a diesel engine that is typically rebuilt at about mid-life of the bus.

DOE/FTA set an ultimate performance target of 4–6 years (or 25,000 hours) durability for the fuel cell propulsion system, with an interim target of 18,000 hours by 2016. In last year’s report, NREL documented a single FCPP surpassing 10,000 hours without repair or cell replacement. Manufacturers have continued to make significant progress toward meeting the target over the last year. As of July 2012, that FCPP has reached 12,000 hours. Figure 10 shows the total FCPP hours for each unit NREL has tracked over the last few years. Of the 19 FCPPs shown in the figure, 18 are still operating in the current FCEB fleet. The FCPP shown in light blue was retired and replaced with a new FCPP.

The buses included in this data summary have only been in service for two years or less. It takes a significant amount of time to reach the higher hours shown in the figure. The three FCPPs with the highest hours were originally operated in the 1<sup>st</sup>-generation buses at AC Transit. During the demonstration, the fuel cell manufacturer tested several successive versions of fuel cell power systems in the buses. At the end of that demonstration, two of the FCPPs were transferred into the 2<sup>nd</sup>-generation FCEBs to continue to validate the systems in service. The third high-hour FCPP was transferred from another 1<sup>st</sup>-generation bus that had been in service at another location. All three of these high-hour systems continue to operate.

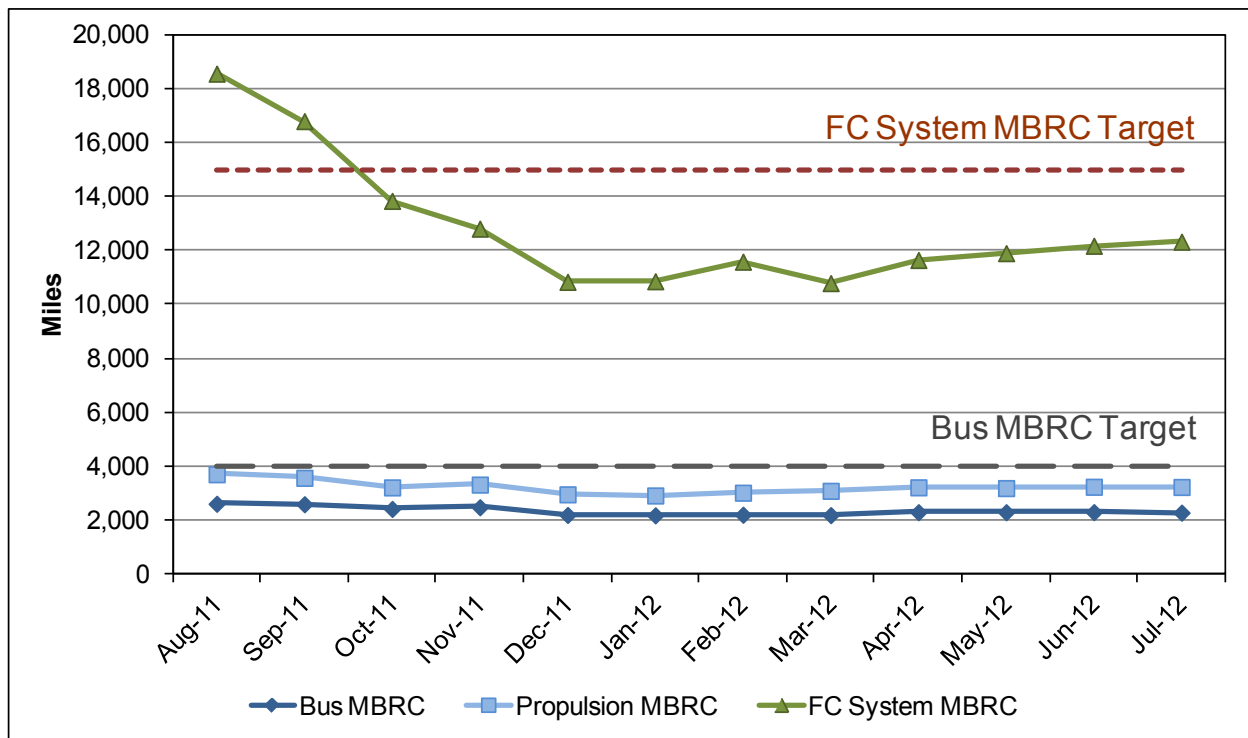


**Figure 10. Total FCPP hours by system through July 2012**

**Bus availability**—As shown in the data summary section, the average bus availability for the four FCEB demonstrations ranges from a low of 53% to a high of 71%, with the overall average at 57%. Although this is much lower than the target, it is not unexpected for technology at this

stage of development. The reasons for unavailability have most often been attributed to bus-related and battery issues rather than to the fuel cell system. Also, three of the four bus designs are 2<sup>nd</sup>-generation systems and the fourth is a new design in its first series of demonstration. The manufacturers are working through issues with the integration and communication software between new systems. As the manufacturers identify and solve the issues, the availability is expected to increase.

**Roadcall frequency**—The targets for roadcall frequency include MBRC for the entire bus and MBRC for the fuel cell system only. Bus MBRC includes all chargeable roadcalls, which means any issue that could physically disable the bus from operating on route. It does not include roadcalls for items such as fair boxes, radios, or destination signs. The FC System MBRC includes any roadcalls due to issues with the FC stack or associated balance of plant. NREL tracks an additional metric of propulsion system MBRC. This category includes all roadcalls due to propulsion-related bus systems. Propulsion-related systems include the FC system (or engine for a conventional bus), electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, and transmission systems. Figure 11 shows the cumulative MBRC for all four bus demonstrations combined. The targets for Bus MBRC and FC System MBRC are included as dashed lines on the chart. Overall Bus MBRC for the time period was 2,288; Propulsion MBRC was 3,239; and FC System MBRC was 12,328.



**Figure 11. Cumulative MBRC for the FCEBs**

**Range and fuel economy**—Fuel economy for the FCEBs ranged from 5.29 mi/kg up to 6.93 mi/kg for an average of 6.41 mi/kg. Table 12 lists the fuel economy and hydrogen capacity for the FCEBs in four demonstrations. The estimated range is calculated based on those numbers. The overall average range for the entire group is 278 miles.

**Table 12. Fuel Economy and Range for the FCEBs**

ID	Period	Fuel Economy (mi/kg)	H2 Capacity (kg)	Range (miles)
ACT ZEBA	9/11 – 4/12	6.68	40	267
CTT Nutmeg	8/11 – 7/12	6.72	40	269
SL AT	8/11 – 7/12	5.29	43	227
SL AFCB	12/11 – 7/12	6.93	50	346
<b>Average</b>		<b>6.41</b>		<b>278</b>

### **Achievements and Challenges**

While bus performance and fuel cell system durability have continued to improve, there are still major challenges to overcome to move FCEB technology to a commercial product. This section outlines the on-going challenges as well as lessons learned from recent issues that occurred over the last year.

**Integration/optimization of components**—Over the past year, manufacturers continued to work on issues with systems integration and optimization, which is still one of the major challenges for FCEBs. When new FCEB designs first go into service, there is a characteristic break-in period where the manufacturers review the early performance results and make changes to optimize and correct any issues that occur. This break-in period can take many months as new issues arise that did not show up in laboratory testing. This was the case for the SunLine AFCB. The FCEB design in operation at AC Transit and CTTRANSIT may be a 2<sup>nd</sup>-generation system, but there were several major design changes that required additional effort to optimize once the buses were delivered. The hybrid system was integrated by the bus OEM and included a new energy storage system that was significantly different than the previous battery technology. Some of the early issues were intermittent, which made troubleshooting difficult. In many cases, the issue was due to communication problems between the different sub-systems that could be resolved through software updates.

**Hydrogen fueling**—Access to hydrogen fuel continues to be one of the biggest hurdles to adoption of any fuel cell vehicle. Several demonstration projects have been delayed because of issues with access to fuel. This is the case for the bus demonstration at SFMTA in San Francisco. The bus was delivered in early 2011, but it has not been placed in service primarily because of the fueling issue. CTTRANSIT has been using the fueling station at the headquarters of UTC Power to fuel the Nutmeg buses. The agency is in the process of adding a small fueling station at its facility that can handle 30 kg/day. The agency completed the preparation work for the concrete pad and electric hookups for the site; however, there have been delays in completing the electrolyzer, dispensing, and storage equipment. The planned hydrogen storage is not sufficient to allow full fills of all the buses at once, but it will reduce the need to take all of the buses to UTC Power every night for fuel.

Last year we reported plans for several new stations at transit agencies that could handle larger fleets of buses. One of those stations began operation in August 2011 at AC Transit’s Emeryville Division. The Emeryville station is a combined facility for light-duty fuel cell electric vehicles and FCEBs. Hydrogen is provided from two sources: liquid hydrogen delivery and a solar-powered electrolyzer. The electrolyzer is capable of producing 65 kg of hydrogen per day. When

combined with the delivered liquid hydrogen, the station has the capacity to dispense up to 600 kg of hydrogen.

There was a safety incident at the station since it was commissioned. In early May 2012, a mechanical failure of a pressure relief device (PRD) valve on one of the high pressure storage tubes resulted in venting and igniting of pressurized hydrogen through the vent stacks. The emergency systems worked as designed. There were no injuries or threats of injuries, and no damage occurred, except for minor singeing on a corrugated canopy roof on one side of the station. The local authorities evacuated the area for several hours as a precaution. AC Transit's FCEB operations were suspended while this incident was fully investigated.

The investigation team was comprised of representatives from AC Transit, Linde, CARB, Sandia National Laboratories (funded by CARB), and the Alameda County Fire Department.<sup>18</sup> The root cause of the incident was the failed PRD. Analysis showed the nozzle sub-assembly was made of a material that was a poor choice for use with hydrogen. This choice of material as well as deviations in process during production of the valve led to the failure. Other factors, such as the lack of timely communication, contributed to the escalation of the event. Although there were no injuries or major damage, several lessons were learned from the event that should be considered when planning a hydrogen station for FCEBs or other application, including:

- Evaluate the components, sub-components, and other parts of the station to ensure all materials used are appropriate for hydrogen.
- Plan for isolation of different sub-systems within the station in the case of a hydrogen release and ensure vent outlets are sufficiently above and oriented away from other equipment.
- Define and update communications plans to establish responsibility for specific processes, such as assigning which staff members are responsible for contacting first responders in an emergency. Ensure that critical information is accessible by emergency responders.
- Educate staff early on and provide refresher training on a regular basis. Performing mock drills can be particularly effective to ensure employee response to an event is appropriate.

**FCEB development teams**—Developing a new propulsion system for buses takes a cohesive team of manufacturers working closely to identify and solve some potentially complex problems. Transit bus orders in the United States are typically produced by the bus manufacturer. The bus original equipment manufacturer (OEM) orders the specified components—such as engine, transmission, and seats—which are installed at the factory. When the first hybrid-electric propulsion systems were designed, the hybrid system manufacturer took the lead in the installation and testing of the first diesel-hybrid buses. Once the system was optimized and ready for commercial production, the hybrid system manufacturer worked with the bus OEM to train them to install the system at the factory. At that time, the propulsion system became another

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<sup>18</sup> Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility (Revised), SANDIA2012-8642, October 2012, <http://www.osti.gov/energycitations/servlets/purl/1055884/1055884.pdf>.

standard system installed in the bus just like any other sub-system. This is the eventual goal for a fuel-cell-hybrid system.

The development teams for FCEBs are facing challenges similar to those of the hybrid bus developers, but with the added difficulty of optimizing communication and interfaces between advanced systems. The hybrid system, fuel cell, and batteries must all work together to propel the bus. These systems are produced by different companies, each with its own concerns over intellectual property. Overcoming issues of sharing sensitive data is a challenge within the teams. In the current economic climate, many manufacturers have had difficulties remaining engaged in the process. In some instances, a partner drops out of the team because of resource constraints. In some cases, a company declares bankruptcy. These unforeseen problems are difficult to overcome if other partners can't step up their level of support. These types of issues have caused delays in getting buses ready for service but have also contributed to extended downtime for the buses.

## What's Next

In this report, we have included data from three different FCEB bus designs at four sites. In the next year, several new demonstrations should begin, and NREL expects to monitor and evaluate those demonstrations with funding from DOE and FTA. The addition of new fuel cell electric bus designs and demonstration 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 scheduled to begin service at the second demonstration site: 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).

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 Boston, Massachusetts
- A new bus with a GE hybrid system in Newark, Delaware
- A second ElDorado/BAE/Ballard bus in Chicago, Illinois
- 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.

## 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](http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html).

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## **SunLine**

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## Appendix: Summary Statistics

### AC Transit ZEBa Demonstration Summary

Table A-1. AC Transit Data Summary

	ACT ZEBa	ACT Diesel
Data period	9/11 – 4/12	9/11 – 4/12
Number of buses	12	3
Number of months	8	8
Total miles	147,069	82,098
Total FC hours	17,619	–
Average speed (mph)	8.3	–
Average miles per month	1,690	3,635
Availability	56%	77%
Fuel economy (mi/kg)	6.68	–
Fuel economy (mpdgc)	7.55	4.00
Bus MBRC	2,015	2,117
Propulsion-only MBRC	3,001	3,629
FC system-only MBRC	8,171	–
Total hydrogen used (kg)	18,016	–
<b>SI Units</b>		
Total kilometers	236,685	132,120
Average speed (kph)	13.4	–
Average km per month	2,572	5,850
Fuel consumption (kg/100 km)	9.30	–
Fuel consumption (liter/100 km)	31.15	59.14
Bus km between roadcalls (KBRC)	3,241	3,856
Propulsion-only KBRC	4,828	6,336
FC system-only KBRC	13,143	–

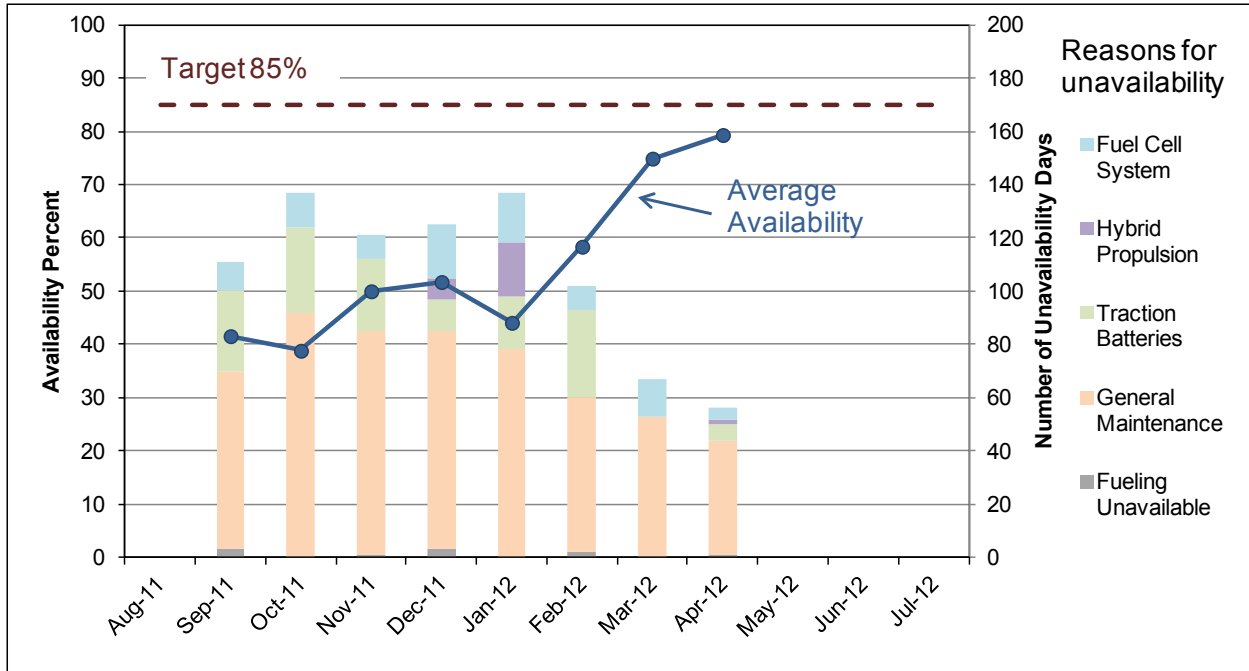


Figure A-1. Monthly availability and number of unavailability days for the ACT ZEBAs

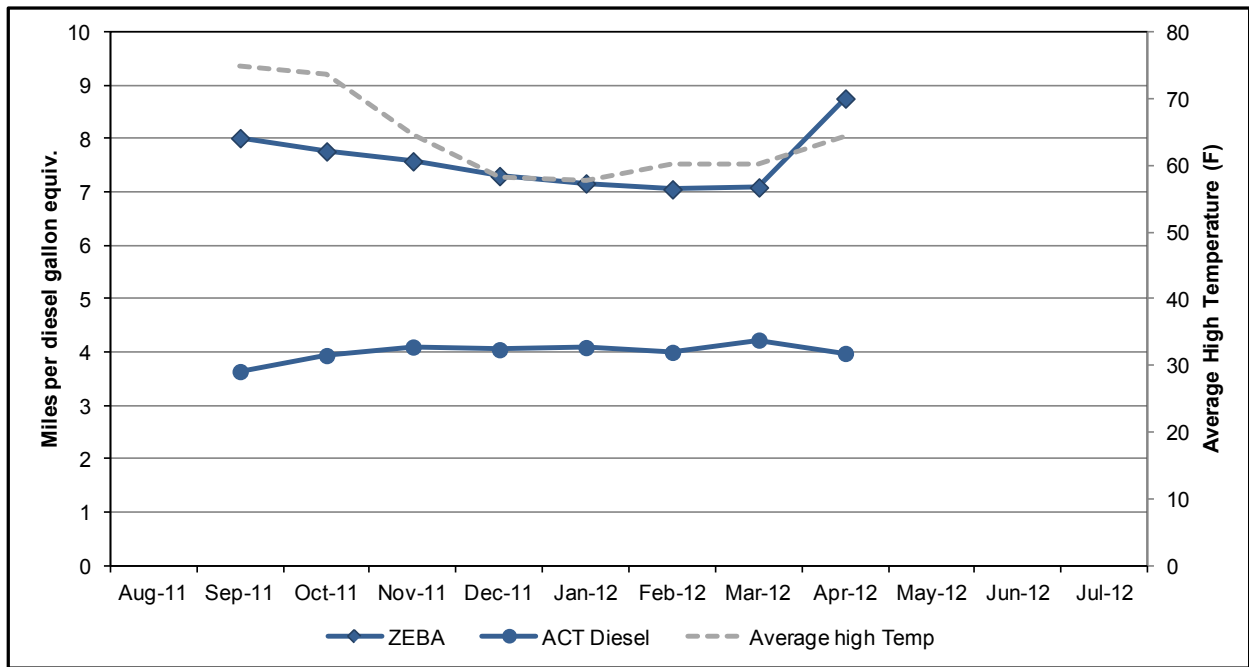


Figure A-2. Monthly fuel economy for the ACT ZEBAs and diesel buses

## CTTRANSIT Nutmeg Demonstration Summary

Table A-2. CTTRANSIT Data Summary

	CTT Nutmeg	CTT Diesel	CTT Hybrid
Data period	8/11 – 7/12	8/11 – 7/12	10/11 – 7/12
Number of buses	4	3	13
Number of months	12	12	10
Total miles	57,014	112,308	396,672
Total FC hours	4,077	–	–
Average speed (mph)	14.0	–	–
Average miles per month	1,267	3,120	3,148
Availability	53%	–	–
Fuel economy (mi/kg)	6.72	–	–
Fuel economy (mpdgc)	7.60	3.79	5.19
Bus MBRC	2,479	4,640	–
Propulsion-only MBRC	2,851	6,801	–
FC system-only MBRC	19,005	–	–
Total hydrogen used (kg)	8,481	–	–
<b>SI Units</b>			
Total kilometers	91,755	180,742	638,382
Average speed (kph)	22.5	–	–
Average km per month	2,039	5,021	5,066
Fuel consumption (kg/100 km)	9.24	–	–
Fuel consumption (liter/100 km)	30.95	62.06	45.32
Bus km between roadcalls (KBRC)	3,989	7,467	–
Propulsion-only KBRC	4,588	10,946	–
FC system-only KBRC	30,585	–	–

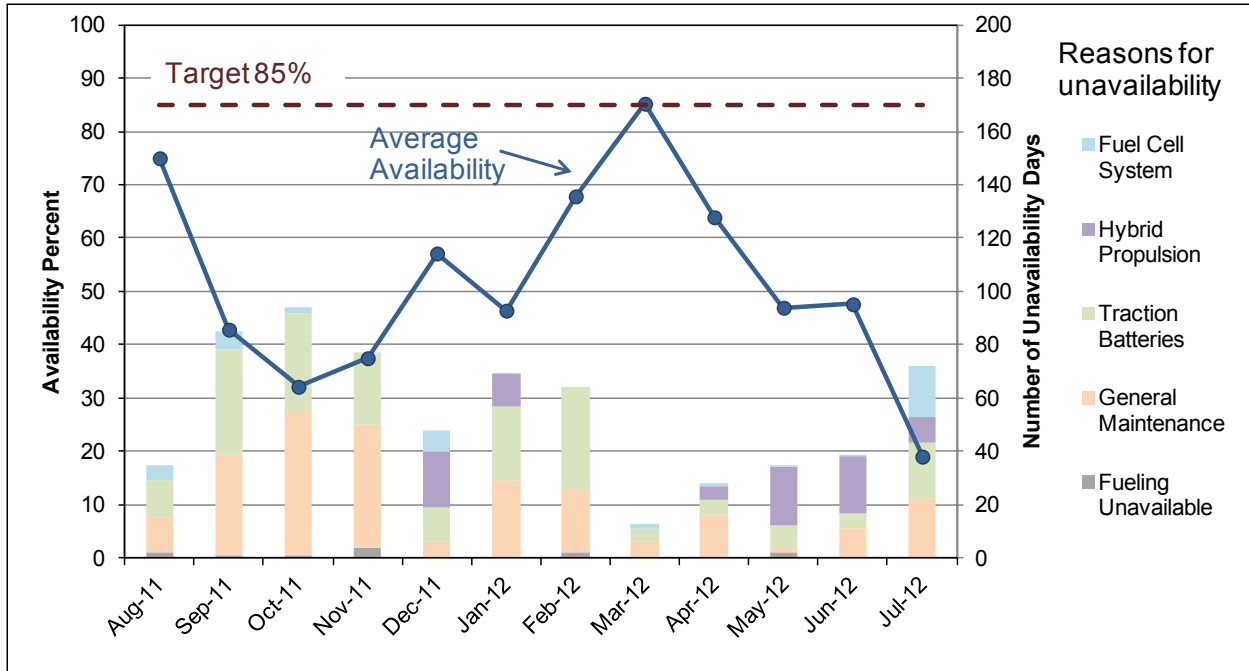


Figure A-3. Monthly availability and number of unavailability days for the CTT Nutmeg buses

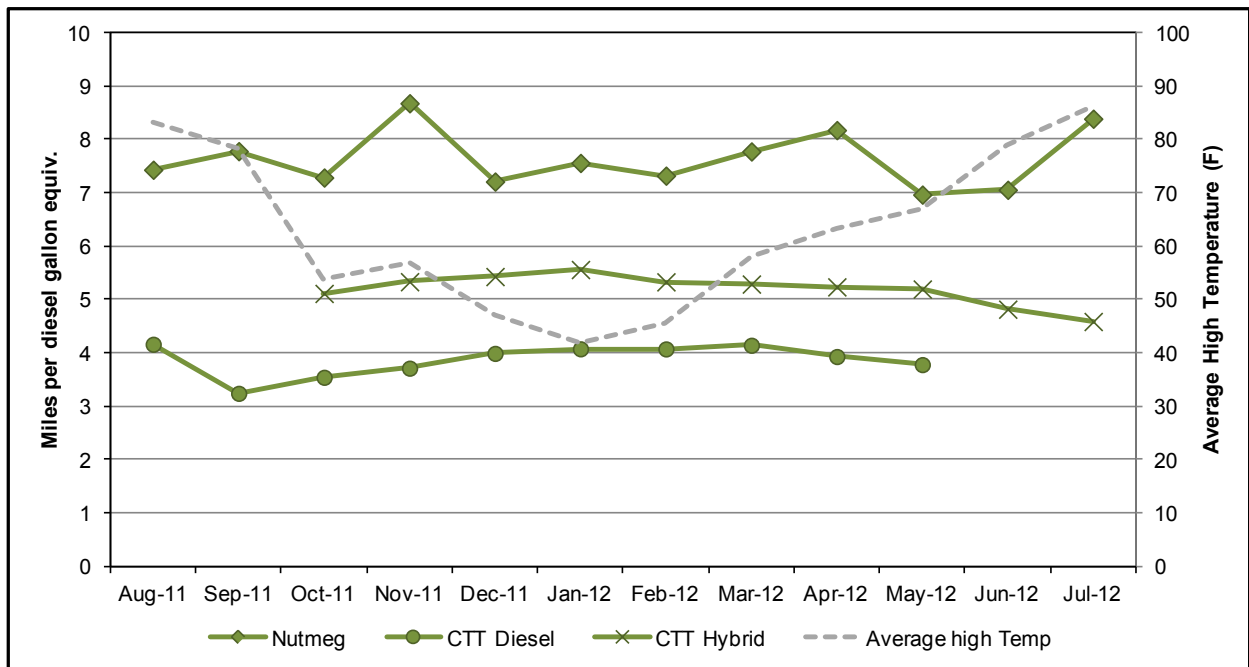


Figure A-4. Monthly fuel economy for the CTT Nutmeg and diesel buses

## SunLine AT and AFCB Demonstration Summary

Table A-3. SunLine Data Summary

	SL AT	SL AFCB	SL CNG
Data period	8/11 – 7/12	12/11 – 7/12	8/11 – 7/12
Number of buses	1	1	5
Number of months	12	8	12
Total miles	20,514	23,683	261,817
Total FC hours	1,724	1,510	–
Average speed (mph)	11.9	15.7	–
Average miles per month	1,710	2,960	4,364
Availability	67%	71%	82%
Fuel economy (mi/kg or gge)	5.29	6.93	2.91
Fuel economy (mpdgc)	7.97	7.84	3.25
Bus MBRC	2,279	1,692	26,182
Propulsion-only MBRC	2,279	3,383	43,636
FC system-only MBRC	6,838	7,894	–
Total hydrogen used (kg)	3,881	3,415	–
<b>SI Units</b>			
Total kilometers	33,014	38,114	421,354
Average speed (kph)	19.1	25.2	–
Average km per month	2,751	4,764	7,023
Fuel consumption (kg/100 km)	11.75	8.96	–
Fuel consumption (liter/100 km)	39.40	30.00	72.37
Bus km between roadcalls (KBRC)	3,668	2,722	42,135
Propulsion-only KBRC	3,668	4,554	70,226
FC system-only KBRC	11,005	12,705	–

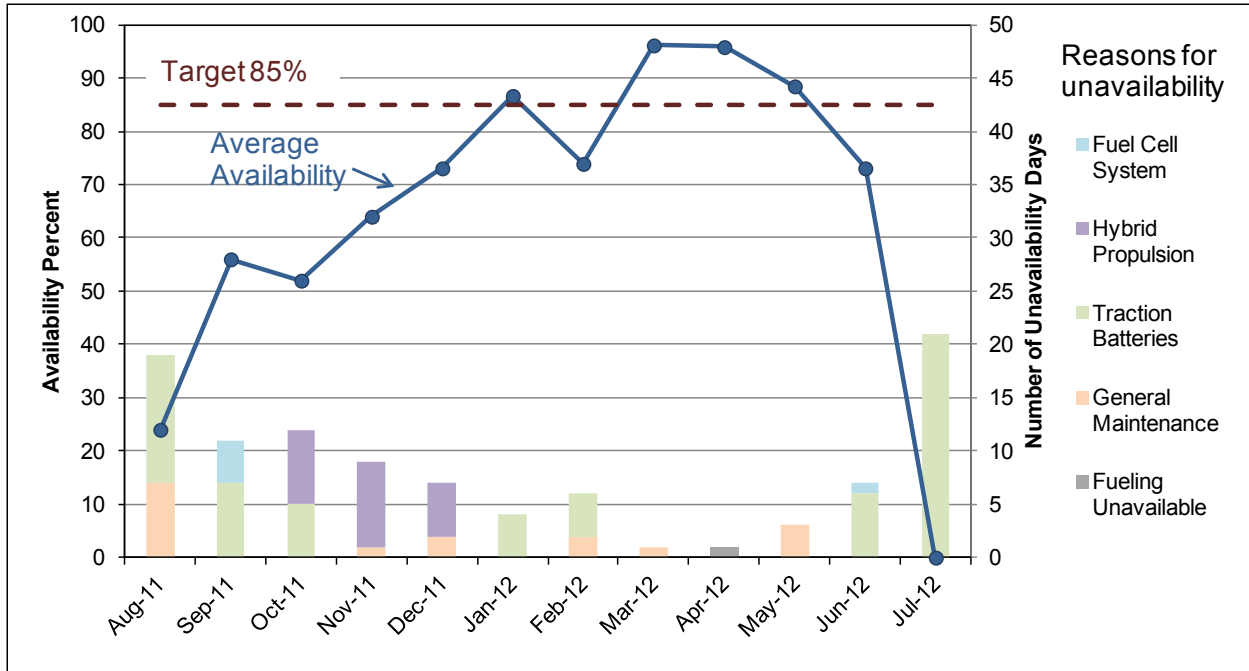


Figure A-5. Monthly availability and number of unavailability days for the SunLine AT FCBE

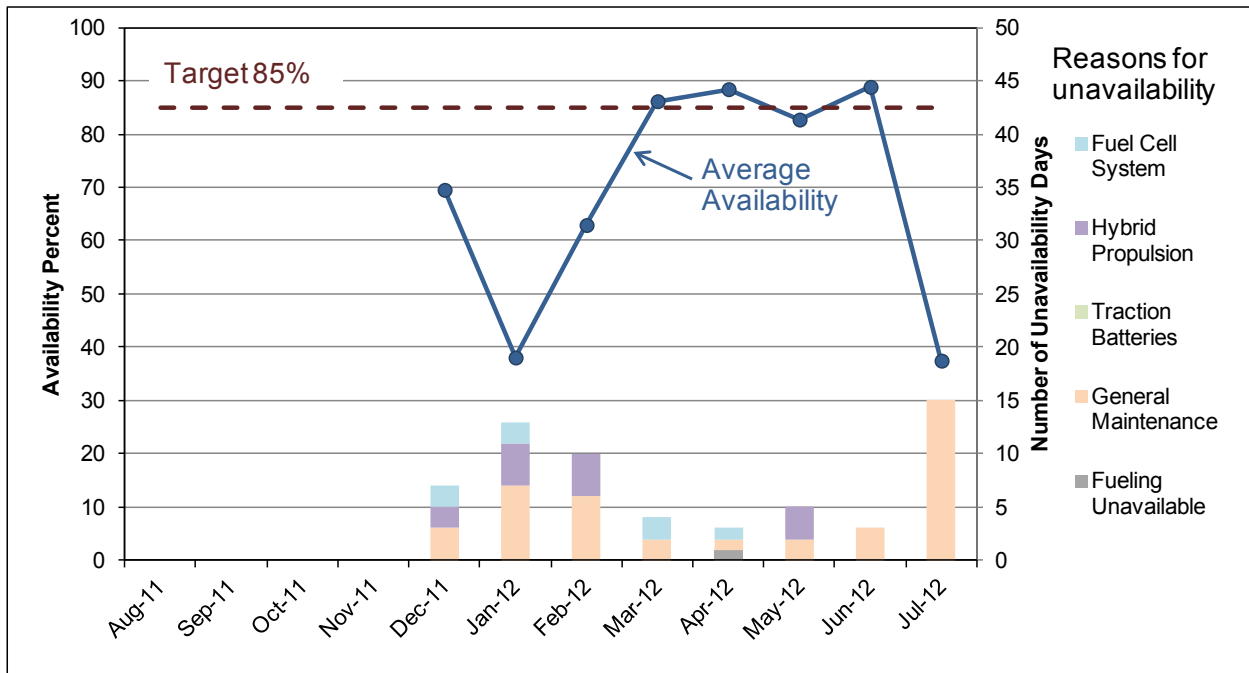
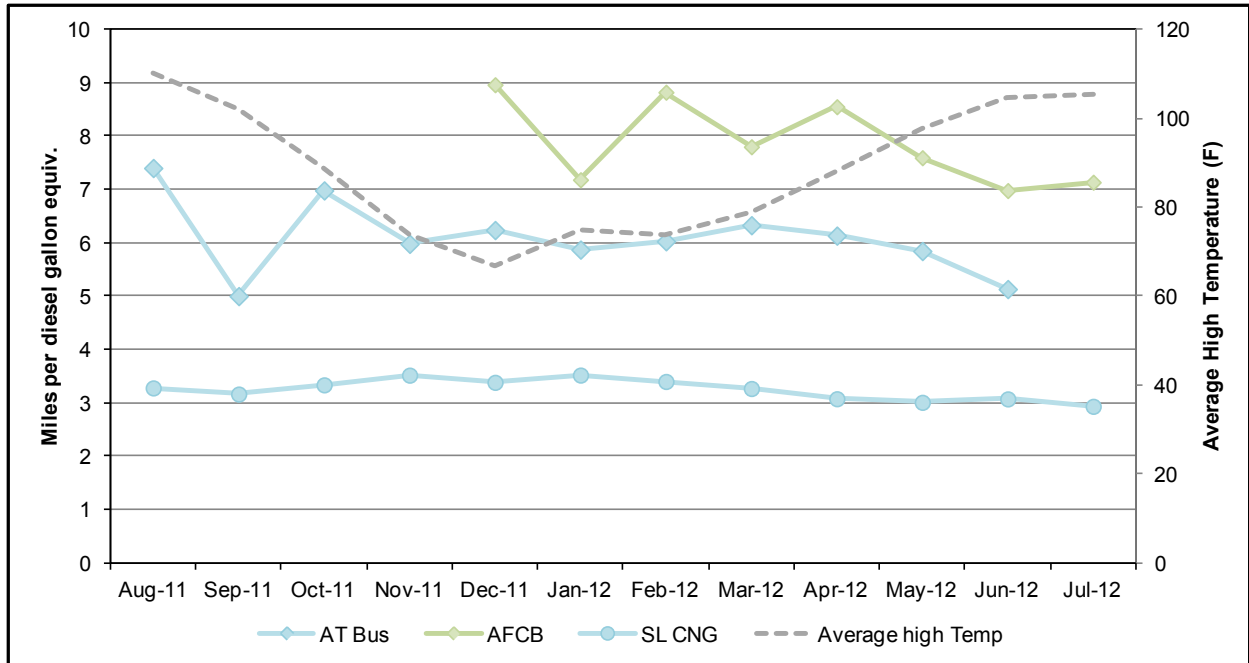


Figure A-6. Monthly availability and number of unavailability days for the SunLine AFCB



**Figure A-7. Monthly fuel economy for the SunLine FCEB and CNG buses**