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Fuel Cell Buses in U.S. Transit Fleets: Current Status 2013

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Office of Energy Efficiency & Renewable Energy
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Technical Report
NREL/TP-5400-60490
December 2013

Contract No. DE-AC36-08GO28308

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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
GGE	gasoline gallon equivalent
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 seventh 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. This report provides a summary of results from evaluations performed by the National Renewable Energy Laboratory (NREL) and funded by the U.S. Department of Energy's (DOE) Fuel Cell Technologies Office and the U.S. Department of Transportation's (DOT) Federal Transit Administration (FTA). Summary results from August 2012 through July 2013 for these buses account for more than 241,579 miles traveled and 21,301 hours of fuel cell power system operation. The summary results are from five demonstrations at four 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
- Proterra bus demonstration at Capital Metro in Austin, Texas.

In late July 2013, NREL began working with British Columbia (BC) Transit to conduct a third-party evaluation of the FCEB fleet in Whistler, Canada. This evaluation is being funded by the California Air Resources Board. Because of that involvement, NREL is expanding the annual status report to include FCEB demonstrations in Canada. NREL is currently analyzing data on the BC Transit buses. Because the analysis is not complete, the results are not included in this report. A summary of the results will be included in the 2014 status report. With the addition of the BC Transit buses, NREL's evaluations cover 35 of the 38 FCEBs currently operating in North America.

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 2013, NREL documented a single fuel cell power plant (FCPP) that has reached 13,800 hours. Two more FCPPs have reached 10,000 and 9,000 hours.

Availability continues to vary from site to site with data from the last year ranging from a low of 31% up to a high of 81%, with the overall average at 69%. There appears to be a general upward trend for availability over time, despite extensive downtime for two of the projects. The most common issue affecting the availability for the buses was general bus maintenance, followed by traction batteries and 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 the cumulative MBRC through July 2013 was 2,728 for bus MBRC; 3,999 for propulsion MBRC; and 11,043 for FC system MBRC.

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 5.8 mi/DGE up to 7.3 mi/DGE for an average of 6.8 mi/DGE.

Over the past year, AC Transit successfully re-introduced the ZEBA fleet into service after a 9-month downtime while an incident at the hydrogen station was investigated and issues were resolved. The station was repaired, upgraded, and re-commissioned by the end of January 2013. During the 9-month period that the station was down, the FCEBs were parked at the depot. Once the station was back online, the agency began the start-up procedure to get the 12-bus fleet operational. The agency reports that the start-up procedure went extremely well and that anticipated problems did not occur. There have been no reported problems with the buses as a result of the downtime.

The current economic climate has resulted in changing players within the FCEB market as companies have left the market through restructuring or bankruptcy. This makes conducting long-term demonstrations a challenge when the partners no longer provide technical support or produce parts needed for repair. The primary change over the last year involved one of the fuel cell manufacturers, UTC Power. This fuel cell technology division of United Technologies was sold to ClearEdge Power, which then announced its intention to sell the transit bus power plant portion of the company. US Hybrid, a California technology development company, has taken over that portion of the business and will complete the NFCBP projects originally led by UTC Power.

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. Technical challenges include increasing reliability of components and lowering capital and operating costs. Despite the remaining challenges, FCEBs continue to show progress toward meeting the technical targets for commercialization. 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[1]

	Units	This Report[a] (Range)	2012 Status[1]	2016 Target[1]	Ultimate Target[1]
Bus lifetime	years/miles	1–3.5 / 9,899–64,267[b]	5/100,000	12/500,000	12/500,000
Power plant lifetime[c]	hours	940–13,843[b,d,e]	12,000	18,000	25,000
Bus availability	%	31–81	60	85	90
Fuel fills[f]	per day	1	1	1 (<10 min)	1 (<10 min)
Bus cost[g]	$	2,000,000	2,000,000	1,000,000	600,000
Power plant cost[c,g]	$	N/A[h]	700,000	450,000	200,000
Hydrogen storage cost	$	N/A[h]	100,000	75,000	50,000
Roadcall frequency (bus/fuel cell system)	miles between roadcalls	344–6,057 / 1,374–36,339	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[i]	$/mile	N/A[j]	1.20	0.75	0.40
Range	miles	227–347[k]	270	300	300
Fuel economy	miles per gallon diesel equivalent	5.82–7.46	7	8	8

[a] Summary of the results in this report: data from August 2012–July 2013.
[b] Accumulated totals for existing fleet through July 2013; these buses have not reached end of life.
[c] 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.
[d] The status for power plant hours is for the fuel cell system only; battery lifetime hours were not available.
[e] The highest-hour power plant was transferred from an older-generation bus that had accumulated more than 6,000 hours prior to transfer.
[f] Multiple sequential fuel fills should be possible without an increase in fill time.
[g] Cost targets are 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.
[h] Capital costs for subsystems are not currently reported by the manufacturers.
[i] Excludes mid-life overhaul of power plant.
[j] Maintenance costs are not available for this report. See individual project reports on the NREL website.
[k] Based on fuel economy and tank capacity.

[1] Fuel Cell Technologies Program Record # 12012, September 12, 2012, http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf.

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Introduction

This report is the seventh in a series of annual status reports from the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL).[2] 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 have been 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.[3]

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 2013). 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 the most recent reports, each of which documents the performance and provides an unbiased assessment of a transit agency's experience implementing FCEBs 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 six sections, beginning with this "Introduction." The section "Fuel Cell Electric Buses in Operation in North America" summarizes existing and upcoming demonstrations in the United States and Canada 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 "Update of Evaluation Results through July 2013" 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.

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.

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[2] Previous reports are listed in the References section of this report.

[3] *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

Table 1 outlines which FCEB designs were included in the 2012 and 2013 (current) status reports. The 2012 report presented the results from four FCEB demonstrations. These four projects represent three fuel cell dominant FCEB designs at three transit agencies. The buses at Alameda-Contra Costa Transit District (AC Transit) and Connecticut Transit (CTTRANSIT) are the same design. The Proterra battery dominant FCEB was first reported on in the 2011 report. This bus was not included in last year's status report because it was between demonstration sites. The bus was placed in service in Austin, Texas, in 2012, and the data summary for that time period is included in this report.

Table 1. Technologies Included in the 2012 and 2013 Status Reports

FCEB Demonstration	Included in 2012 Report	Status	Included in Current Report
AC Transit ZEBA	✓	Active	✓
CTTRANSIT Nutmeg	✓	One bus active	✓
SunLine AT FCEB	✓	Active	✓
SunLine AFCB	✓	Active	✓
Proterra, Austin, Texas		Demonstration ended	✓

In late July 2013, NREL began working with British Columbia (BC) Transit to conduct a third-party evaluation of the FCEB fleet in Whistler, Canada. This evaluation is being funded by CARB. Because of that involvement, NREL will expand the next report to include FCEB demonstrations in Canada. NREL is currently analyzing data on the BC Transit buses covering a period from April 2011 through March 2013. Because the analysis is not complete, the results are not included in this report. A summary of the results will be included in the 2014 status report.

Fuel Cell Electric Buses in Operation in North America

In past reports, NREL reported on fleets specifically in the United States. Table 2 lists current FCEB demonstrations in North America. These demonstrations focus on identifying improvements to optimize reliability and durability. As of August 2013, 38 fuel cell buses were active in demonstrations at seven locations in North America.

Table 2. Current Fuel Cell Transit Bus Demonstrations in North America[a]

Bus Operator	Location	Total Buses	Active Buses[b]	Technology Description
ZEBA (led by AC Transit)	San Francisco Bay Area, CA	12	12	Van Hool bus and hybrid system integration, ClearEdge Power fuel cell
CTTRANSIT, Nutmeg	Hartford, CT; Flint, MI	4	1	Van Hool bus and hybrid system integration, ClearEdge Power fuel cell
SunLine Transit Agency, AT FCEB	Thousand Palms, CA	1	1	New Flyer bus with Bluways hybrid system and Ballard fuel cell
SunLine Transit Agency, AFCB	Thousand Palms, CA	1	1	ElDorado/BAE/Ballard next-generation advanced design to meet 'Buy America' requirements
BC Transit, FCEB	Whistler, BC, Canada	20	20	New Flyer bus with Bluways hybrid system and Ballard fuel cell
Capital Metro/University of Texas	Austin, TX	1	0	Proterra plug-in hybrid with Hydrogenics fuel cell
BurbankBus	Burbank, CA	1	0	Proterra plug-in hybrid with Hydrogenics fuel cell
SFMTA	San Francisco, CA	1	0	Daimler/BAE diesel hybrid with Hydrogenics fuel cell auxiliary power unit
University of Delaware (Phase 1 & 2)	Newark, DE	2	2	Ebus battery dominant plug-in hybrid using Ballard fuel cells (22-ft)
GNHTD	New Haven, CT	1	1	Ebus battery dominant plug-in hybrid using Ballard fuel cells (22-ft)
	Total	**44**	**38**	

[a] Blue shaded rows indicate the project received funding through the NFCBP.
[b] Total of buses in actual service as of August 2013.

NREL is currently evaluating the first eight 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 AC Transit—** Demonstration of 12 next-generation Van Hool fuel cell hybrid buses with a fuel cell system by ClearEdge Power. This program received funding through the NFCBP to perform 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 and the issues were addressed. In January 2013, the station was brought back online and the buses went back into service in mid-February.

- **CTTRANSIT Nutmeg Project—**Demonstration of four Van Hool buses with a ClearEdge Power fuel cell power system and a Siemens hybrid drive integrated by the bus manufacturer. These buses are the same configuration as the ZEBA 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). The remaining three buses were taken out of service in early 2013 because the demonstration period under the Nutmeg Project had ended. One of these buses was sold to North Augusta, South Carolina, another will be shipped to California to join the ZEBA bus fleet, and the last bus will be used by US Hybrid to continue fuel cell development. 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 four reports on this bus (in March 2011, October 2011, May 2012, and January 2013).
- **SunLine Transit Agency: American Fuel Cell Bus (AFCB) Project—**Demonstration of one ElDorado National bus with a BAE Systems hybrid propulsion system and a Ballard fuel cell power system. This project is part of the NFCBP. NREL began data collection in December 2011 and the first report was completed in June 2013.
- **BC Transit: Fuel Cell Bus Project—**BC Transit has been demonstrating a fleet of 20 FCEBs in the Whistler Resort area of British Columbia, Canada, since February 2010 during the Winter Olympic Games. These New Flyer buses feature a Bluways hybrid system with a Ballard fuel cell. The program was a 5-year demonstration of the technology and included operation and maintenance of the FCEB fleet through March 2014. Under funding from CARB, NREL began collecting data on this fleet in July 2013 and is currently analyzing two years of data covering April 2011 through March 2013. A report on this data period is planned for early 2014. NREL will continue collecting data on the buses through their planned demonstration period and will publish a second report in mid-2014.
- **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 the first stage 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 was placed into service in October 2012. The demonstration ended in March 2013.

- **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 worked through several issues and upgrades to the bus since that time. Once the bus has been prepped for service, the demonstration will begin. Data collection is scheduled to begin in late 2013.
- **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. 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 four projects in Table 2. NREL collected data on the Proterra bus in Austin during its demonstration. Data collection began on the BC Transit FCEBs in July 2013. NREL is currently working on the analysis of two years of data, and those results will be published in the early 2014. Data results for that fleet will be included in the next status report. The section “Update of Evaluation Results through July 2013” provides the most recent evaluation results for these six demonstrations.

National Fuel Cell Bus Program (NFCBP)

FTA established the 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 four 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). In September 2013, FTA announced the awards for an additional $13.5 million appropriated for the NFCBP. Table 3 lists the remaining demonstration projects (including the recently announced projects) that will field 10 more fuel cell buses over the next few years.

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	ElDorado/BAE Systems/Ballard next-generation American Fuel Cell Bus
Advanced Composite FCEB (CTE)	Austin, TX; Washington, DC	1	Proterra composite body with a next generation battery-dominant hybrid system and a Hydrogenics fuel cell
Birmingham FCEB Demo (CTE)	Birmingham, AL	1	EVAmerica 30-foot battery dominant FCEB with advanced lithium ion battery technology and a Ballard fuel cell.
Chicago Transit Authority FCEB Demo (CALSTART)	Chicago, IL	1	ElDorado/BAE Systems/Ballard next-generation American Fuel Cell Bus
EcoSaver IV FCEB Demo (CTE)	Columbus, OH	1	DesignLine fuel cell dominant FCEB with a Ballard fuel cell
Advanced Generation FCEB (CALSTART)	Hartford, CT	1	New Flyer bus with next-generation fuel cell and BAE Systems hybrid propulsion
American Fuel Cell Bus (CALSTART)	Cleveland, OH	1	ElDorado/BAE Systems/Ballard next-generation American Fuel Cell Bus
Battery Dominant FCEB (CALSTART)	Palm Springs, CA	1	ElDorado bus with a battery dominant fuel cell system from BAE Systems and a Ballard fuel cell
Central NY Fuel Cell Transportation Program (CTE)	Ithaca, NY	1	ElDorado/BAE Systems/Ballard next-generation American Fuel Cell Bus

Beyond the NFCBP, FTA has funded 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 previously documented in an FTA report.[4]

[4] *FTA Fuel Cell Bus Program: Research Accomplishments through 2011*, March 2012, FTA Report No. 0014.

FCEB Development Process—Technology Readiness Levels

In the previous report, NREL introduced a guideline for assessing the technology readiness level (TRL) for FCEBs. This guideline was developed using a Technology Readiness Assessment Guide[5] published by DOE in September 2011. NREL presented a TRL guide tailored for the commercialization of FCEBs. Figure 1 provides a graphic representation of this process. The table outlining the TRLs and definitions is included in the Appendix.

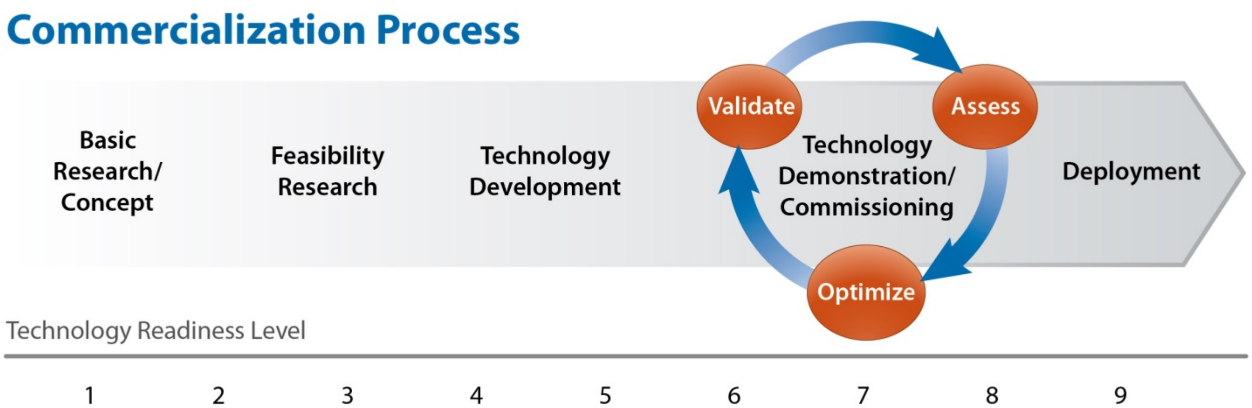

Figure 1. Graphic representation of the commercialization process developed for FCEBs

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. The manufacturer typically works with a transit agency partner to conduct in-service tests on the bus. Updates to the design are made based on the performance results, and the buses go back into demonstration and through the cycle until the design meets the performance requirements. This can be a time-consuming process as manufacturers work through technical difficulties.

Figure 2 shows the number of active buses in North America since 2005. The last report documented 25 active FCEBs in operation in the United States. For this report, the chart has been expanded to include FCEBs in North America. New manufacturer teams introducing designs of fuel cell electric buses in smaller numbers are placed in the first step of the technology demonstration/commissioning phase. For this report, a designation of first-generation is given to the prototype designs from new manufacturer teams that fall in TRL 6; a second-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.

This figure includes only FCEBs that were placed into service during 2005 or beyond. Some first-generation FCEBs have been retired and were removed from the chart, causing the lower

[5] DOE Technology Readiness Assessment Guide, G 143.3-4a, https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view.

numbers in 2008 and 2009. A total of 43 FCEBs were in operation in 2013. The addition of the BC Transit FCEB fleet is the primary reason for the significant increase in active buses.

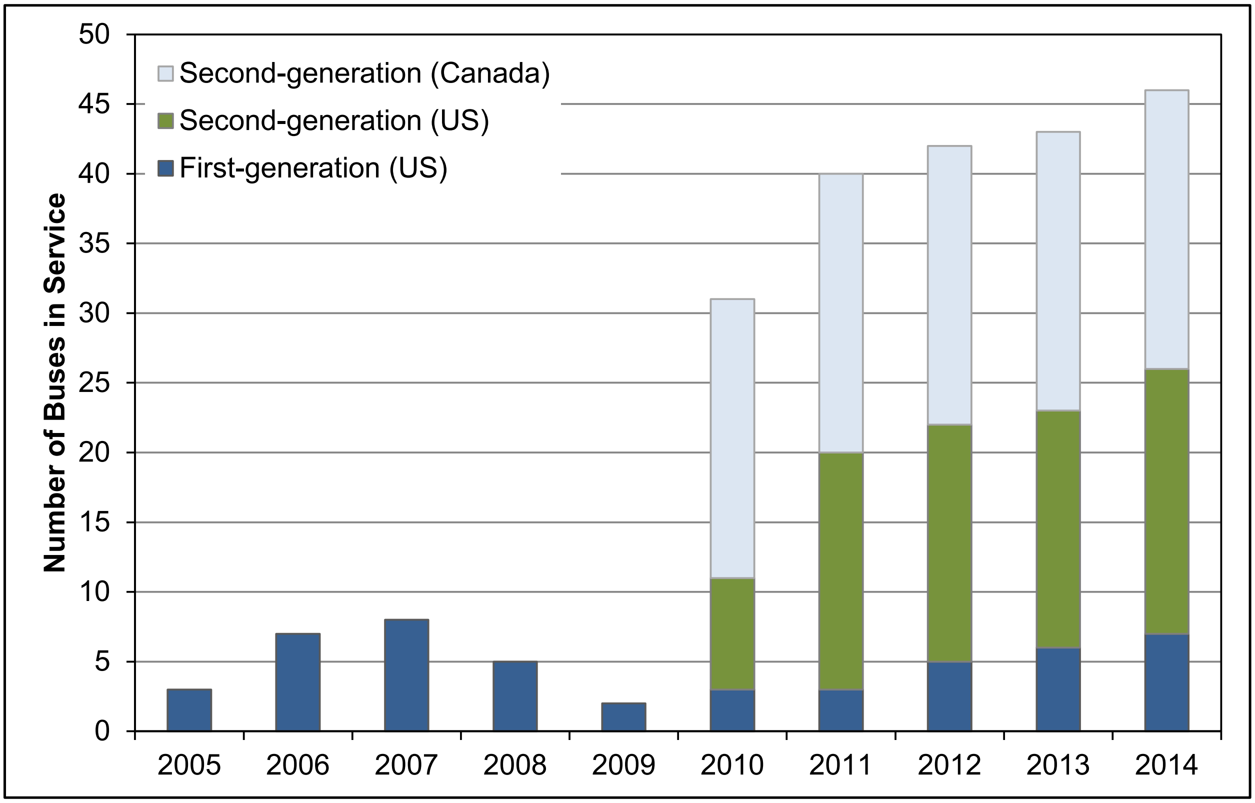

Figure 2. Growth in fuel cell electric buses since 2005

Table 4 lists the manufacturer teams with FCEB designs currently in operation in North America. 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, organized by bus original equipment manufacturer (OEM), describes each of these FCEBs and where they fall in the commercialization process outlined in Figure 1. The TRL determination for each FCEB type was made by NREL based on the descriptions in the FCEB TRL guide table (see Appendix). The designations are for each bus design as a whole package; individual components within the design might be commercially available products or prototypes. The report was reviewed by the demonstration teams involved in the evaluations.

Table 4. Manufacturer Teams for FCEBs Currently Operating in North America

Bus OEM	Length (ft)	Fuel Cell System	Hybrid System	Design Strategy	Energy Storage
Van Hool	40	ClearEdge 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
ElDorado	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—ClearEdge Power (formerly UTC Power) and Van Hool collaborated on this FCEB product that is operating in the ZEBA and Nutmeg demonstrations in California, Connecticut, and Michigan. As reported previously, this design is considered a second-generation product at TRL 7 because it involves 16 buses and the design includes upgrades based on the lessons learned from the previous FCEB.

New Flyer—This bus design is considered a second-generation product at TRL 7 because the design of the bus was led by manufacturers experienced with FCEB development and the deployment includes the 20-bus FCEB fleet in Whistler, Canada. The AT bus in operation at SunLine, which was the pilot bus for the Whistler fleet, was upgraded to match the final design of the rest of the Whistler fleet before it was eventually purchased by SunLine.

ElDorado—The development of this NFCBP-funded FCEB design was led by the hybrid manufacturer/integrator BAE Systems in partnership with Ballard Power Systems and ElDorado. The system is based on BAE Systems' proven hybrid electric propulsion system that is commercially available for transit buses. In the 2012 status report, NREL designated this bus as a first-generation product in the field testing stage of development, or TRL 6. Since that time, NREL has collected and analyzed more than a year of operational data on the bus, which has shown exceptional performance. The team is currently building five additional AFCBs that will incorporate upgrades based on the early demonstration results. As a result, we have elevated this bus design to TRL 7.

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 on a lightweight 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. The NFCBP bus was Proterra's very first bus and included a number of new technologies that had never been demonstrated in a transit application. Two additional FCEBs were produced based on the original prototype. This FCEB is considered a first-generation design at TRL 6. Proterra is working with its partners to develop a next-generation system based on the lessons learned with the early prototype.

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 first-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. Daimler no longer markets this bus in the United States; therefore commercialization of the system would have to be accomplished using another bus platform.

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 first-generation product at TRL 6. NREL has not collected data on these buses.

Update of Evaluation Results Through July 2013

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 five different FCEB demonstrations at four 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 but one of the FCEBs presented in this section have hybrid systems that are fuel cell dominant. The Proterra bus is a battery dominant system. Table 5 provides some specifications for each FCEB by the unique ID. The four fuel cell dominant FCEBs are pictured in Figure 3. The Proterra battery dominant FCEB is shown in Figure 4.

Table 5. FCEB Identifiers and Selected Specifications

	ACT ZEBA	CTT Nutmeg	SL AT	SL AFCB	TX Proterra
Transit agency	AC Transit	CTTRANSIT	SunLine	SunLine	Capital Metro
Number of buses	12	4	1	1	1
Bus OEM	Van Hool	Van Hool	New Flyer	ElDorado	Proterra
Model/year	A300L/2010	A300L/2010	H40LFR/2010	Axcess/2011	HFC-35/ 2009
Bus length	40 ft	40 ft	40 ft	40 ft	35 ft
Gross Vehicle Weight	39,350 lb	39,350 lb	44,530 lb	43,420 lb	36,000 lb
Fuel cell OEM	ClearEdge Power	ClearEdge Power	Ballard	Ballard	Hydrogenics
Fuel cell model	Puremotion 120	Puremotion 120	HD6	HD6	HyPM 16
Fuel cell power (kW)	120	120	150	150	16 (x2)
Hybrid system integrator	Van Hool	Van Hool	Bluways	BAE Systems	Proterra
Design strategy	FC dominant	FC dominant	FC dominant	FC dominant	Battery dominant
Energy storage OEM	EnerDel	EnerDel	Valence	A123	Altairnano
Energy storage type	Li-ion	Li-ion	Li-ion	Li-ion	Li-titanate
Energy storage capacity	21 kWh	21 kWh	47 kWh	11 kWh	54 kWh
Hydrogen storage pressure (psi)	5,000	5,000	5,000	5,000	5,000
Hydrogen cylinders	8	8	6	8	4
Hydrogen capacity (kg)	40	40	43	50	29
TRL	7	7	7	7	6

Baseline buses—Conventional baseline bus data are provided for comparison with FCEB data when comparable buses are available. Data on baseline buses were included for all sites except Austin, Texas. The Proterra bus is shorter than a standard 40-foot transit bus and there were no close matches in size available at Capital Metro. 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. The Appendix summarizes the data results by demonstration location and provides additional charts that detail some of the results by agency.

Data periods included in the report—Although the report is focused on data from August 2012 through July 2013, the data period for each demonstration varies depending on the project status. The two buses at SunLine were in service the entire 12-month period. The ZEBA buses were out of service in the beginning of the data period because of an issue with the hydrogen station (described earlier in the report). The buses went back into service in mid-February 2013 so the data period for that fleet begins in March and is 5 months. The Nutmeg buses reached the end of the planned demonstration in early 2013, resulting in a 6-month data period ending after January. The Proterra bus was operated over a 6-month period from October 2012 through March 2013.

Figure 3. Fuel cell dominant FCEBs included in the data summary: AC Transit ZEBA (top left), CTTRANSIT Nutmeg (top right), SunLine AFCB (bottom left), SunLine AT (bottom right)

Figure 4. Battery dominant FCEB included in the data summary: Proterra bus in Austin, Texas

Total miles and hours—Table 6 shows miles, hours, average speed, and average monthly miles per bus for the FCEBs. The AFCB at SunLine has the highest average speed at 15.3 mph, followed by the Nutmeg buses at 12.8 mph. SunLine's AT bus operates primarily on one specific route, while the AFCB has operated on several routes within the service area. The ZEBA buses in service at AC Transit have the lowest average speed at just under 9 mph. Average monthly bus use ranged from a low of approximately 299 miles up to slightly more than 3,000 miles per month. Average miles per month for the group are 1,534. The low number of miles accumulated on the TX Proterra bus, due to several issues during the demonstration period that kept the bus out of service, was the primary contributor to this lower average. SunLine's AT bus also experienced significant downtime because of issues with the traction batteries.

Table 6. Miles and Hours for the Fuel Cell Buses

ID	Period	Months	No. of Buses	Miles	Hours	Avg. Speed (mph)	Avg. Monthly Miles
ACT ZEBA	3/13–7/13	5	12	156,789	18,251	8.6	2,613
CTT Nutmeg	8/12–1/13	6	4	24,479	1,914	12.8	1,020
SL AT	8/12–7/13	12	1	9,340	906	10.3	778
SL AFCB	8/12–7/13	12	1	36,339	2,380	15.3	3,028
TX Proterra	10/12–3/13	6	1	1,374	N/A	—	229

Bus use—Figure 5 shows the average monthly bus use for the fuel cell buses and their respective baseline buses. The target of 3,000 miles is included on the chart. Transit agencies continue to operate their fuel cell buses fewer miles than they operate their baseline buses; however, there is a general upward trend as some of the demonstrations are stepping up the amount of time the buses run per day and adding weekend service. This is particularly true for SunLine's AFCB, which is typically scheduled for all-day service 7 days per week. Because of this, the bus has average monthly miles that are slightly over the target.

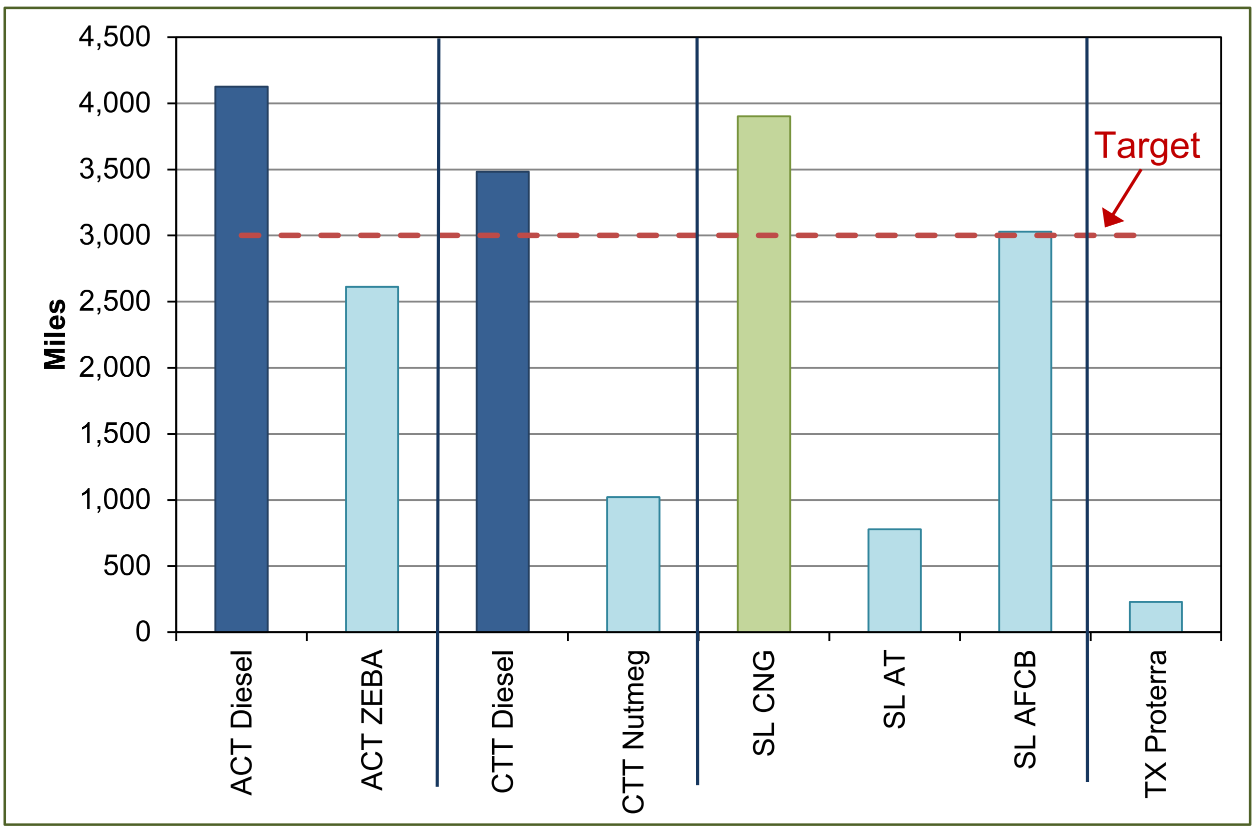

Figure 5. Average monthly miles per fuel cell and baseline buses

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 7 summarizes the availability of the fuel cell buses at each transit agency. Availability varies from site to site with a low of 31% up to a high of 81%. The average availability for the group is 69%. Figure 6 tracks the monthly availability for the FCEBs by project. The percent availability is shown as a separate line for each of the projects with the combined overall average for all the FCEBs in dark blue.

Table 7. Availability for the Fuel Cell Buses

ID	Period	Months	No. of Buses	Planned Days	Days Avail.	% Avail.
ACT ZEBA	3/13 - 7/13	5	12	1,486	1,209	81%
CTT Nutmeg	8/12–1/13	6	4	437	222	51%
SL AT	8/12–7/13	12	1	280	88	31%
SL AFCB	8/12–7/13	12	1	331	247	75%
TX Proterra	10/12–3/13	6	1	82	46	56%

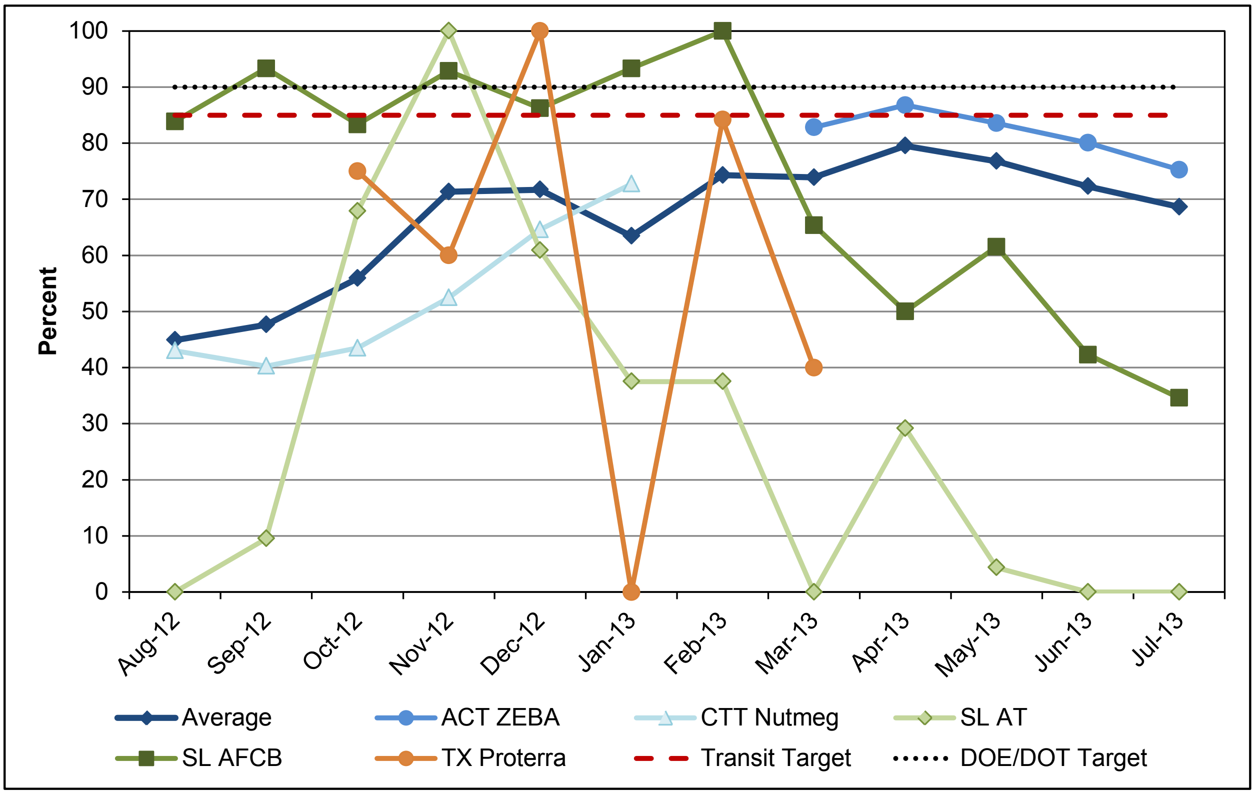

Figure 6. Monthly availability for the FCEBs

The SL AFCB (shown as a dark green line in the graph) has achieved one of the highest availability averages of the group, at or over the 85% target for 7 of the 12 months in the data period. In March 2013, the bus developed a coolant leak that proved difficult to locate. This problem, eventually traced to the radiator, caused the availability to drop during the end of the data period.

The SunLine AT bus (light green line in the figure) availability has been much lower than what was reported previously. The primary issue has been with the traction batteries overheating, but there were also issues with the fuel cell and the bus's camera system.

The ACT ZEBA (medium blue line in the graph) FCEBs were out of service during the beginning of the data period while the hydrogen station was down. Once the buses went into service, the availability showed an increase over what was reported in the previous report. The buses at CTTRANSIT (light blue line) are the same design as the ZEBA buses. The availability during the period began low but increased over time. One of the four buses was moved to Flint, Michigan, and has been in service there for the entire data period. When the planned demonstration ended in early 2013, ClearEdge Power ended service for the three remaining buses at CTTRANSIT. ClearEdge Power has made a business decision to focus on the stationary power market and will transfer the ownership of the buses to other parties. Once contractual agreements are complete, the buses are expected to enter service in other fleets.

The Proterra bus in Texas had several issues during its planned demonstration that caused extended downtime. The primary issues have been with the hybrid propulsion system and the fuel cell. Considering this bus is the first prototype from Proterra and incorporates a number of new technology components, the experience is typical of many advanced systems. The bus availability for December calculates to 100%; however it was only scheduled for eight days during the month.

Figure 7 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 five demonstration projects. The stacked bars show the total number of days the buses were unavailable each month by primary system category. The most common issue affecting the availability for the buses was general bus maintenance (52%), followed by traction batteries (21%), fuel cell system (20%), and hybrid system (7%).

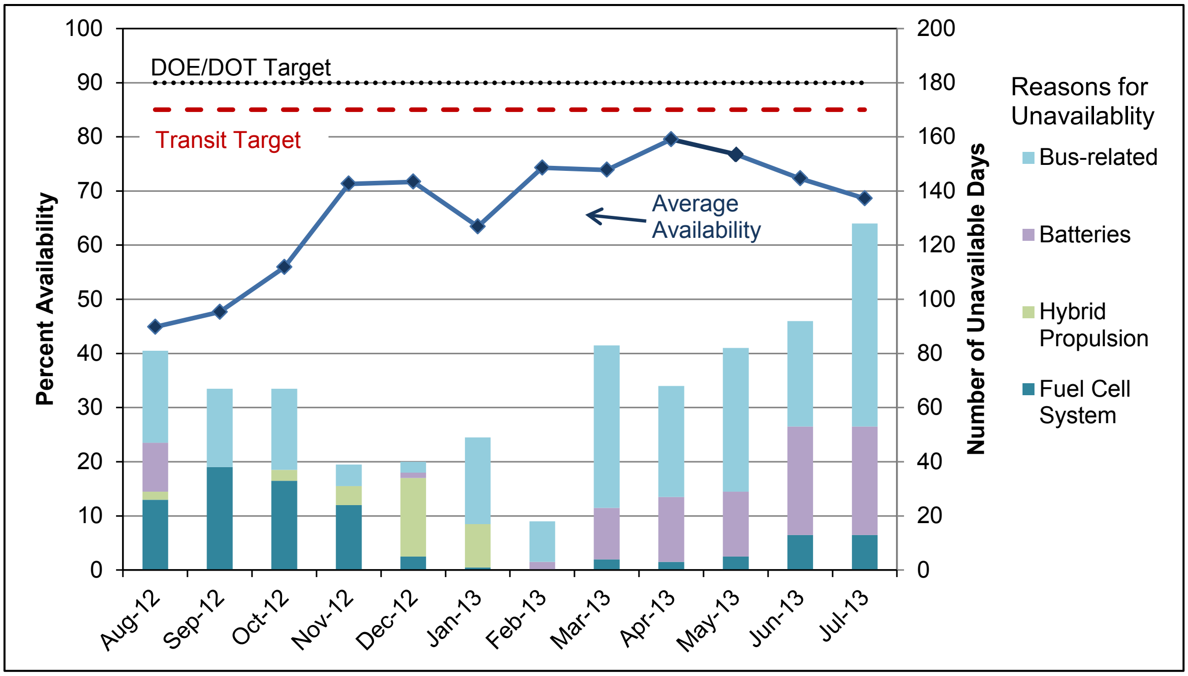

Figure 7. Average monthly availability and number of unavailability days by category

Fuel economy—Table 8 shows the average fuel economy in miles per diesel gallon equivalent (mi/DGE) for each type of FCEB compared to the conventional baseline bus technology at the same site. The Proterra bus had no conventional comparison during its demonstration period. Figure 8 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 8. Average Fuel Economy Comparisons between the FCEBs and Baseline Buses

ID	Miles per kg or GGE	Miles per DGE	Difference from Baseline
ACT ZEBA	6.49	7.34	1.91x
ACT diesel	–	3.85	–
CTT Nutmeg	6.29	7.10	1.82x
CTT diesel	–	3.89	–
SL AT	5.15	5.82	1.87x
SL AFCB	6.38	7.20	2.31x
SL CNG	2.79	3.12	–
TX Proterra	5.88	6.65	–

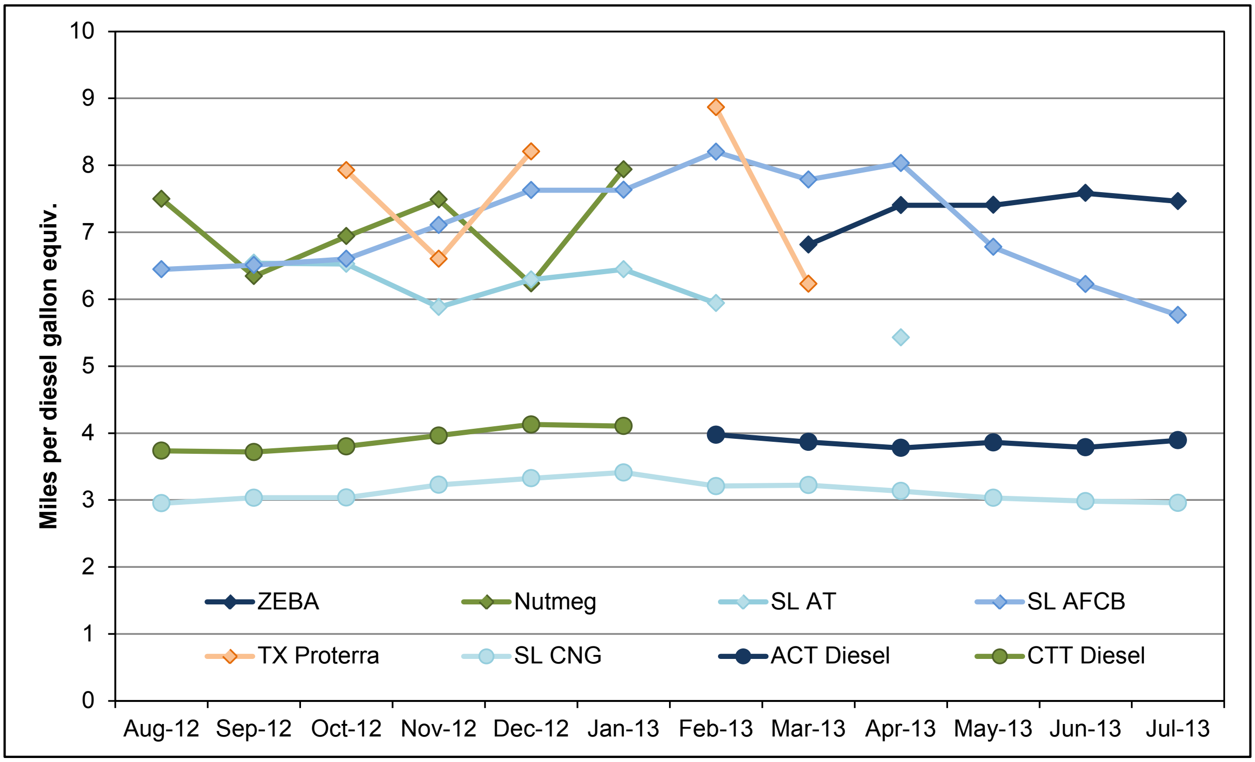

Figure 8. Fuel economy for fuel cell and baseline buses

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 2.3 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 9 shows miles between roadcalls (MBRC) for bus 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 DOE/FTA target for bus MBRC (4,000), and the orange hashed line is the target for fuel-cell-system-related MBRC (20,000). A secondary target of 10,000 MBRC is marked with a red hashed line. This is not one of the DOE/FTA targets; however, it is a general target for the transit industry. 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.

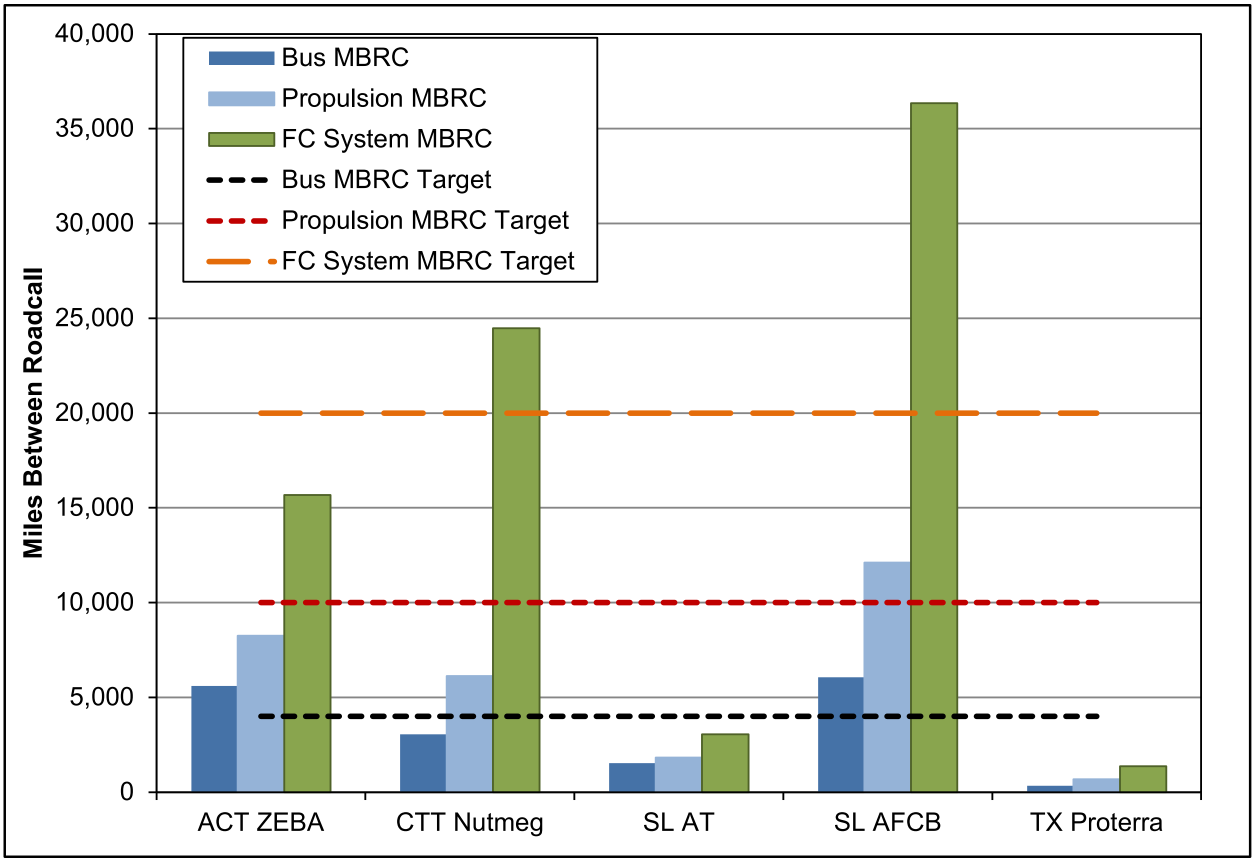

Figure 9. MBRC rates for fuel cell buses compared to the targets

Hydrogen fueling—NREL tracks total hydrogen use for FCEBs at all of the sites. Figure 10 shows the total hydrogen dispensed over time for the three primary sites since the current buses went into service through July 2013. During the data period from August 2012 through July 2013, the FCEBs at the three sites were fueled 1,835 times with a total of 35,754 kg of hydrogen. The average fill amount for these fuel cell dominant FCEBs was 19.5 kg per fill.

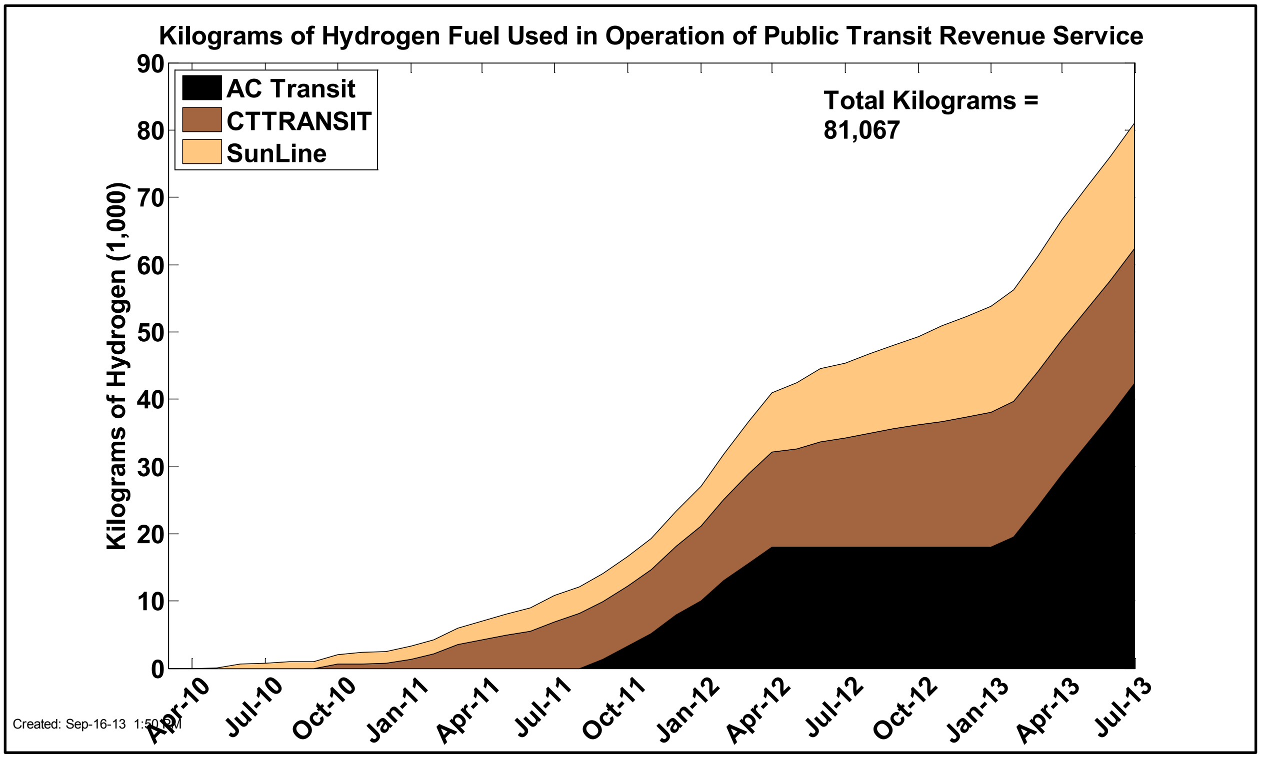

Figure 10. Hydrogen dispensed for the FCEBs through July 2013

Current Status of FCEB Introductions: Summary of Achievements and Challenges

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

In 2012, DOE and FTA established performance, cost, and durability targets for FCEBs in a Fuel Cell Technologies Program Record.[6] Interim targets were set for 2016 along with ultimate targets that FCEBs would need to meet to compete with current commercial technology buses. Table 9 shows a selection of these technical targets for FCEBs.

Table 9. DOE/FTA Performance, Cost, and Durability Targets for FCEBs[a]

	Units	2016 Target	Ultimate Target
Bus lifetime	years/miles	12/500,000	12/500,000
Power plant lifetime[b]	hours	18,000	25,000
Bus availability	%	85	90
Fuel fills	per day	1 (< 10 min)	1 (< 10 min)
Bus cost[c]	$	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[d]	$/mile	0.75	0.40
Range	miles	300	300
Fuel economy	miles per gallon diesel equivalent	8	8

[a] The cost targets for sub-systems (power plant and hydrogen storage) are not included.
[b] The power plant is defined as the fuel cell system and the battery system.
[c] Cost is 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.
[d] Excludes mid-life overhaul of power plant.

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. An 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

[6] Fuel Cell Technologies Program Record # 12012, September 12, 2012, http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf.

FCPP surpassing 12,000 hours without repair or cell replacement. Manufacturers have continued to make significant progress toward meeting the target over the last year. As of July 2013, that FCPP has surpassed 13,000 hours. Figure 11 tracks the accumulation of hours on each FCPP since the current buses went into service through July 2013. The buses included in this data summary have only been in service for three 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 first-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 second-generation FCEBs to continue to validate the systems in service. The third high-hour FCPP was transferred from another first-generation bus that had been in service at another location. The jumps in hours toward the beginning of the graph show when these systems were transferred into the current buses. All three of these high-hour systems continue to operate. The FCPP hours for the Proterra bus are not shown on the graph because the hours were not available during the data collection.

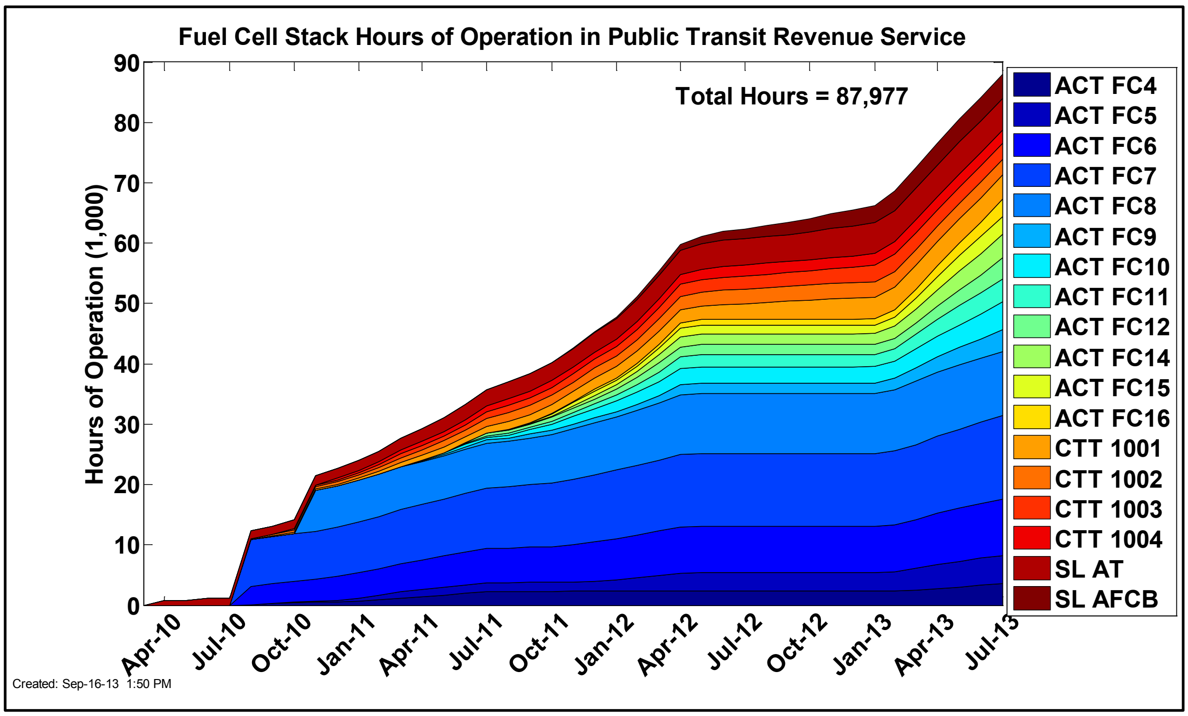

Figure 11. Accumulation of hours on the FCEBs through July 2013

Bus availability—As shown in the data summary section, the average bus availability for the five FCEB demonstrations ranges from a low of 31% to a high of 81%, with the overall average at 69%. Although this is much lower than the target, it is not unexpected for technology at this stage of development. Despite the lower availability numbers for two of the projects, the average shows an increase since the last report when the overall average was 57%. The reasons for unavailability continue to be most often attributed to bus-related or battery issues rather than to the fuel cell system. The manufacturers continue to work through issues with the integration and communication software between new systems and have shown progress in addressing the problems causing downtime. As the manufacturers identify and solve the issues, the availability is expected to increase.

Roadcall frequency—The DOE/FTA 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 fareboxes, 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 12 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 the cumulative MBRC through July 2013 was 2,728 for bus MBRC; 3,999 for propulsion MBRC; and 11,043 for FC system MBRC. Although the FC system MBRC dropped during the last year, the bus and propulsion system MBRC both show a slow increase.

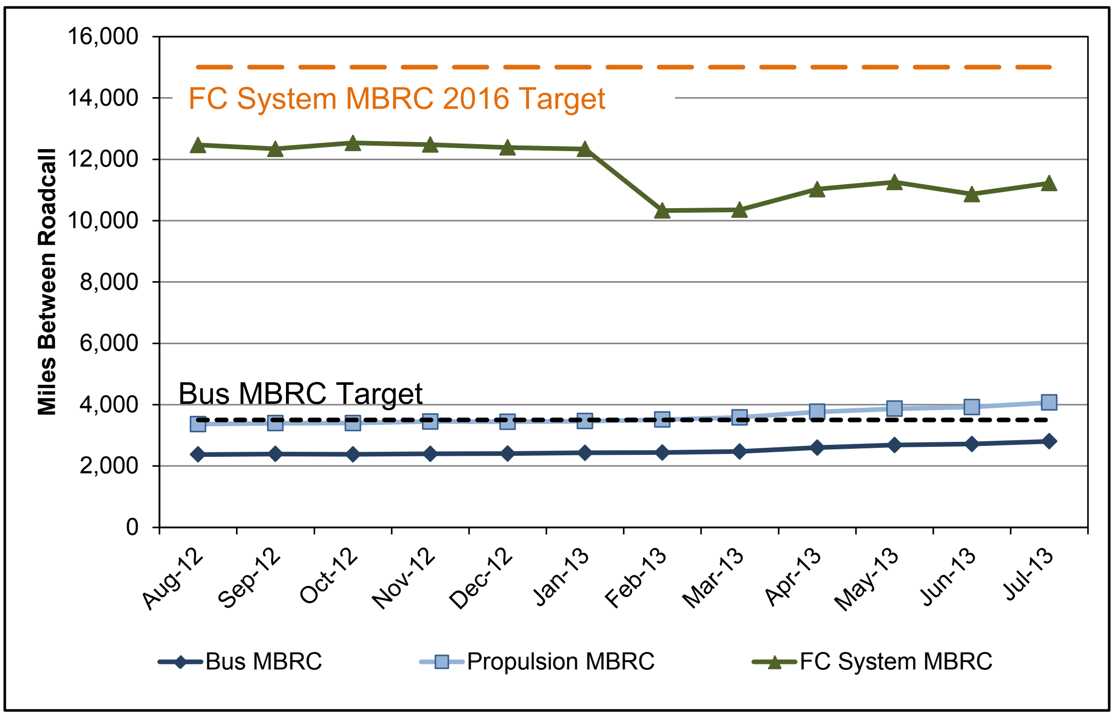

Figure 12. Cumulative MBRC for the FCEBs

Range and fuel economy—Table 10 lists the fuel economy and hydrogen capacity for the FCEBs in all five demonstrations. Fuel economy for the 40-ft FCEBs ranged from 5.15 mi/kg up to 6.49 mi/kg for an average of 6.08 mi/kg. The estimated range is calculated based on the fuel economy numbers and useful fuel of 95% of the tanks capacity resulting in an estimated average range for the group of 250 miles. As it is the only battery dominant system, the fuel economy for the Proterra bus is not included in the 40-foot bus average. To achieve the full range potential of this bus, the transit agency is expected to plug in the bus each night to top off the batteries. During the demonstration in Austin, the bus was not plugged in; therefore the fuel economy listed is based solely on the hydrogen consumed and not necessarily representative of the bus capabilities.

Table 10. Fuel Economy and Range for the FCEBs

ID	Period	Fuel Economy (mi/kg)	Hydrogen Capacity (kg)	Range (miles)
ACT ZEBA	3/13–7/13	6.49	40	247
CTT Nutmeg	8/12–1/13	6.29	40	239
SL AT	8/12–7/13	5.15	43	211
SL AFCB	8/12–7/13	6.38	50	303
Average for 40-ft bus		**6.08**		**250**
TX Proterra	10/12–3/13	5.88	29	162

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 ongoing challenges as well as lessons learned from recent issues that occurred over the last year.

Successful reintroduction of the ZEBA fleet—In the last report, NREL summarized an incident that took place at AC Transit's Emeryville hydrogen station. In early May 2012, a mechanical failure of a pressure relief device valve on one of the high pressure storage tubes resulted in venting and ignition of pressurized hydrogen through the vent stacks. A team of investigators reviewed the incident and made recommendations on actions to improve the station as well as the emergency shut-down procedures and communications plans for potential future safety incidents. The station was repaired, upgraded, and re-commissioned by the end of January 2013. During the 9-month period that the station was down, the FCEBs were parked at the depot. AC Transit staff was able to move some of the buses around the yard for maintenance as long as they had fuel; however, they had no way to fill the buses once the hydrogen in the tanks was depleted. Once the station was back online, the agency began the start-up procedure to get the 12-bus fleet operational. This situation had never been experienced during a demonstration and the partners did not know how well the buses would operate after a long period of inactivity. The agency reports that the start-up procedure went extremely well and that anticipated problems did not occur. The primary result of the buses sitting idle was that the 12-volt batteries on the buses were all depleted and had to be replaced. Once the batteries were replaced, maintenance staff conducted a re-wet procedure to force water up into the fuel cells and conducted a thorough inspection of all the bus systems. The buses were then started, fueled, and run through a series of operational tests. There were no apparent problems with the buses as a result of the downtime. The agency actually took advantage of the downtime to complete several upgrades on the buses and to repair one bus that had been out of service for an extended period waiting for parts. Since that time, the agency reports that the buses have performed extremely well and that the availability has increased.

Integration/optimization of components—Manufacturers continue to work on issues with systems integration and optimization, which is still one of the major challenges for FCEBs. The FCEB design in operation at AC Transit and CTTRANSIT has had several software changes to address issues with the hybrid system and energy storage. Some of the early issues were intermittent, which made troubleshooting difficult.

Changing market players—The current economic climate has resulted in changing players within the FCEB market. Over the years, several companies have left the market through restructuring or bankruptcy. This makes conducting long-term demonstrations a challenge when the partners no longer provide technical support or produce parts needed for repair. During the last year, United Technologies made a business decision to sell its fuel cell division, UTC Power. Because UTC Power was one of the major players in the bus market, this had ramifications for several demonstrations. ClearEdge Power, a relatively small company in the fuel cell market, purchased UTC Power, which included the production capability for transit bus power plants as well as the stationary power business. After completing the acquisition, ClearEdge Power announced its intent to focus on the stationary power business and to sell the transit bus power plant portion of the company.

This has caused some uncertainty in the FCEB market as well as for several NFCBP projects. UTC Power had been awarded several FTA grants under the program to develop and demonstrate fuel cell technology in transit buses. The company's exit from the market left these projects incomplete. A California technology company, US Hybrid, has stepped in to take on the UTC Power projects and complete the development of the next-generation FCPP for buses. US Hybrid was founded in 1999 and specializes in design and manufacture of integrated power conversion components for electric propulsion systems in medium- and heavy-duty vehicles. The company has been involved in several component development projects funded through the NFCBP and is familiar with the goals of the program.

Bus build process—For FCEBs to be fully commercialized, the fuel cell hybrid propulsion system needs to be an option offered by the bus OEM in response to increased market demand, as is the case with current diesel hybrid systems. Hybrid buses are currently offered by most OEMs, which order and install the propulsion system at the bus manufacturing plant. The hybrid system integrator's role is as a supplier of propulsion and electric power systems that enable the capability offered by the OEM. For most of the current FCEB demonstrations, the integrator, fuel cell supplier, or transit agency has taken the lead role in developing the bus. This role needs to transition to the bus OEM for the technology to be fully adopted. The current market for FCEBs is small and has not led any bus OEMs to take on this lead role. SunLine's order for two AFCBs under the FTA Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) Program is taking steps to make this transition. The first bus glider will be shipped to BAE Systems for integration of the propulsion system. BAE Systems will work with ElDorado staff to complete the installation. The second bus will be entirely built at the ElDorado factory with support of BAE Systems. This step needs to be taken by more bus OEMs for the product to be commercialized.

Operational costs after warranty—For most FCEB demonstration projects, the buses are still covered under some level of warranty support from the manufacturers. Although agencies have increased staff to begin transitioning to in-house maintenance, most parts costs are still covered under warranty. With the help of government grants, transit agencies have been successful in negotiating extended warranties for the FCEBs. To help with future planning, transit agencies need to understand what future costs will be as the technology moves into early deployment.

What's Next

In this report, we have included data from four 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, FTA, and CARB. The addition of new FCEB 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 20-bus BC Transit FCEB fleet in Whistler, Canada
- 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).
- An EV America/Ballard bus in Birmingham, Alabama.

Additional buses that may begin operation and be available for the next report are the following:

- Additional AFCBs in four locations:
    - Chicago Transit Authority in Chicago, Illinois (1)
    - SunLine Transit Agency in Thousand Palms, California (2)
    - Massachusetts Bay Transit Authority in Boston, Massachusetts (1)
    - CTTRANSIT in Hartford, Connecticut (1)
- Proterra next-generation battery dominant FCEB at Capital Metro in Austin, Texas

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.

General

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Appendix: Summary Statistics

Table A-1. 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.

AC Transit ZEBA Demonstration Summary

Table A-2. AC Transit Data Summary

	ACT ZEBA All Data	ACT ZEBA Past Year	ACT Diesel All Data	ACT Diesel Past Year
Data period	9/11–7/13	3/13–7/13	9/11–7/13	3/13–7/13
Number of buses	12	12	3	3
Number of months	15	5	15	5
Total miles	323,151	156,789	61,886	61,886
Total FC hours	38,006	18,251	–	–
Average speed (mph)	8.5	8.6	–	–
Average miles per month	1,795	2,613	3,718	4,126
Number of scheduled days	3,706	1,486	1,236	442
Number of days available	2,471	1,209	979	339
Availability	67%	81%	79%	77%
Fuel economy (mi/kg)	6.64	6.49	–	–
Fuel economy (mi/DGE)	7.50	7.34	3.93	3.83
Bus MBRC	2,993	5,600	2,632	2,695
Propulsion-only MBRC	4,552	8,252	4,935	4,492
FC system-only MBRC	11,145	15,679	–	–
Total hydrogen used (kg)	42,953	22,811	–	–
SI Units				
Total kilometers	520,061	252,328	99,596	99,596
Average speed (kph)	13.7	13.8	–	–
Average km per month	2,889	4,205	2,213	6,640
Fuel consumption (kg/100 km)	9.36	9.57	–	–
Fuel consumption (liter/100 km)	27.66	30.28	60.14	61.69
Bus km between roadcalls (KBRC)	4,816	9,012	4,236	4,338
Propulsion-only KBRC	7,326	13,280	7,942	7,230
FC system-only KBRC	17,936	25,233	–	–

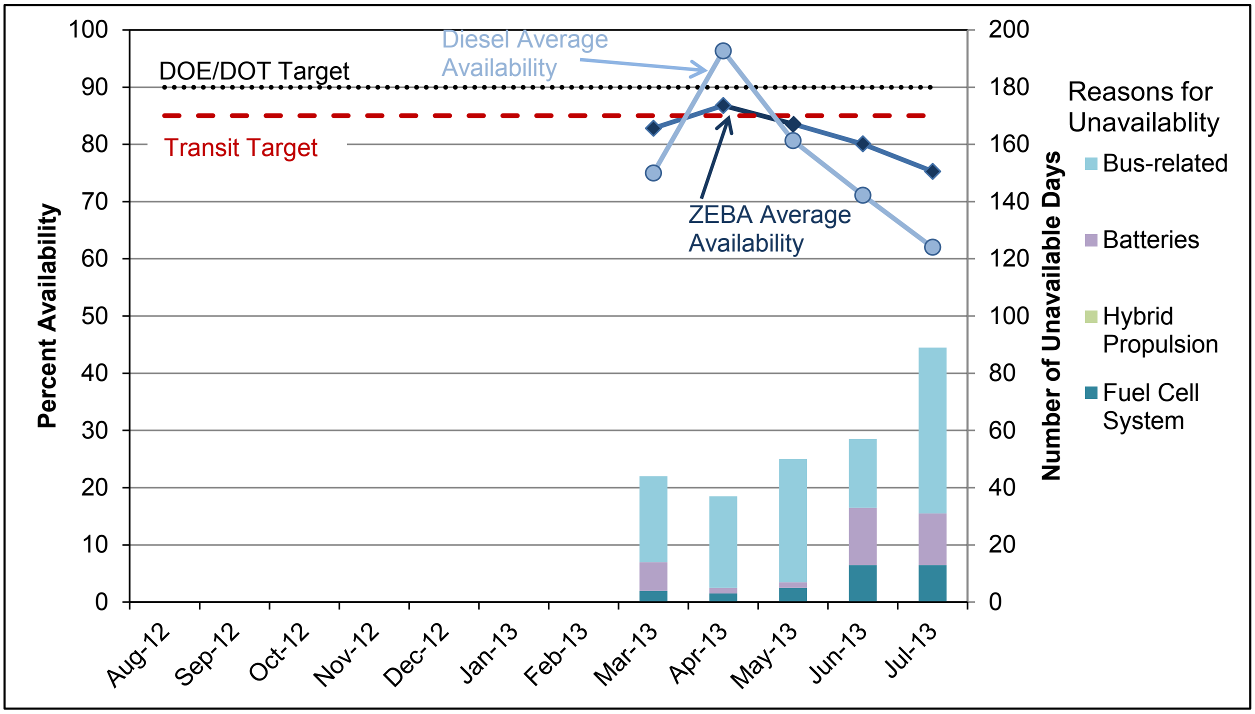

Figure A-1. Monthly availability and number of unavailability days for the ACT ZEBA buses

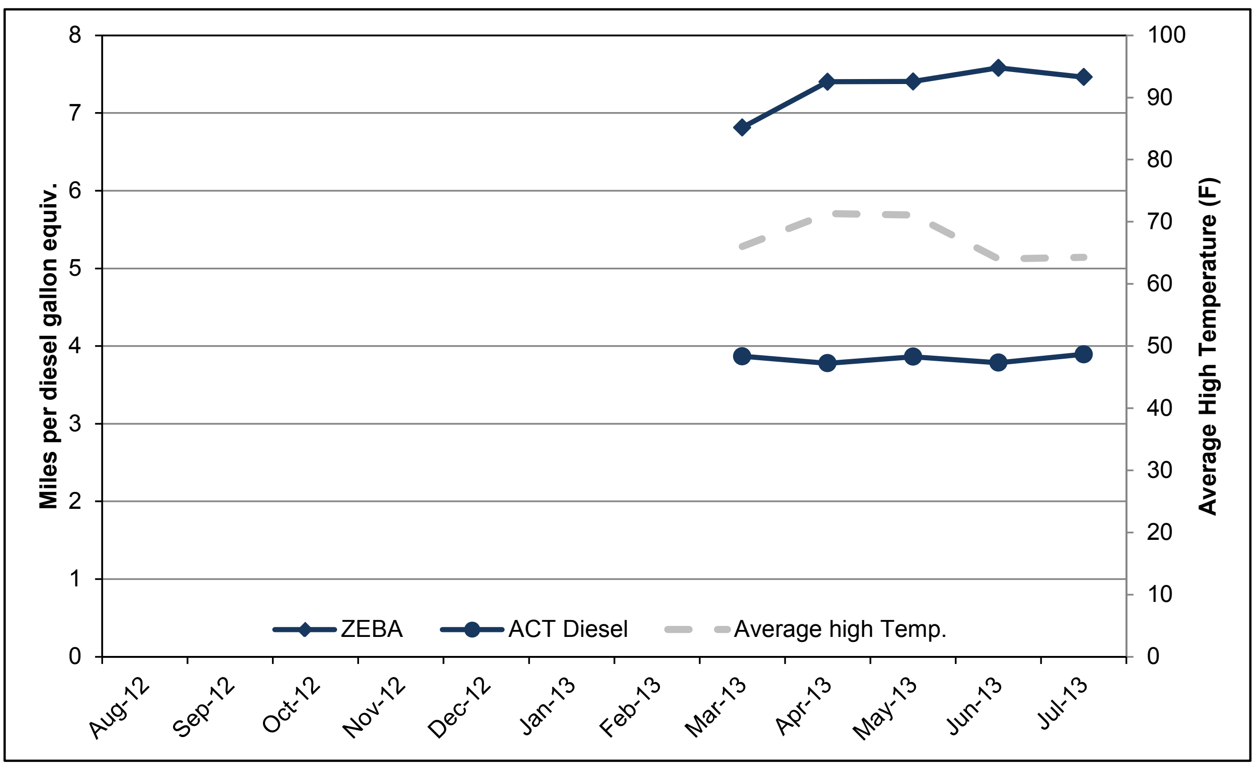

Figure A-2. Monthly fuel economy for the ACT ZEBA and diesel buses

CTTRANSIT Nutmeg Demonstration Summary

Table A-3. CTTRANSIT[a] Data Summary

	CTT Nutmeg All Data	CTT Nutmeg Past Year	CTT Diesel All Data	CTT Diesel Past Year
Data period	10/10–1/13	8/12–1/13	10/10–1/13	8/12–1/13
Number of buses	4	4	3	3
Number of months	28	6	28	6
Total miles	133,735	24,479	276,965	62,676
Total FC hours	9,949	1,914	–	–
Average speed (mph)	13.4	12.8	–	–
Average miles per month	1,311	1,020	3,297	3,482
Number of scheduled days	2,135	437	–	–
Number of days available	1,112	222	–	–
Availability	52%	51%	–	–
Fuel economy (mi/kg)	6.67	6.29	–	–
Fuel economy (mi/DGE)	7.53	7.10	3.89	3.89
Bus MBRC	2,502	3,060	5,028	5,108
Propulsion-only MBRC	3,424	6,120	7,588	7,826
FC system-only MBRC	16,262	24,479	–	–
Total hydrogen used (kg)	20,057	3,895	–	–
SI Units				
Total kilometers	215,226	39,395	445,732	100,867
Average speed (kph)	21.6	20.6	–	–
Average km per month	1,922	1,641	5,306	5,604
Fuel consumption (kg/100 km)	9.32	9.89	–	–
Fuel consumption (liter/100 km)	31.21	33.12	60.86	60.76
Bus km between roadcalls (KBRC)	4,026	4,924	8,091	8,220
Propulsion-only KBRC	5,510	9,849	12,212	12,595
FC system-only KBRC	26,171	39,395	–	–

[a] Data include FCEB operation in Flint, Michigan.

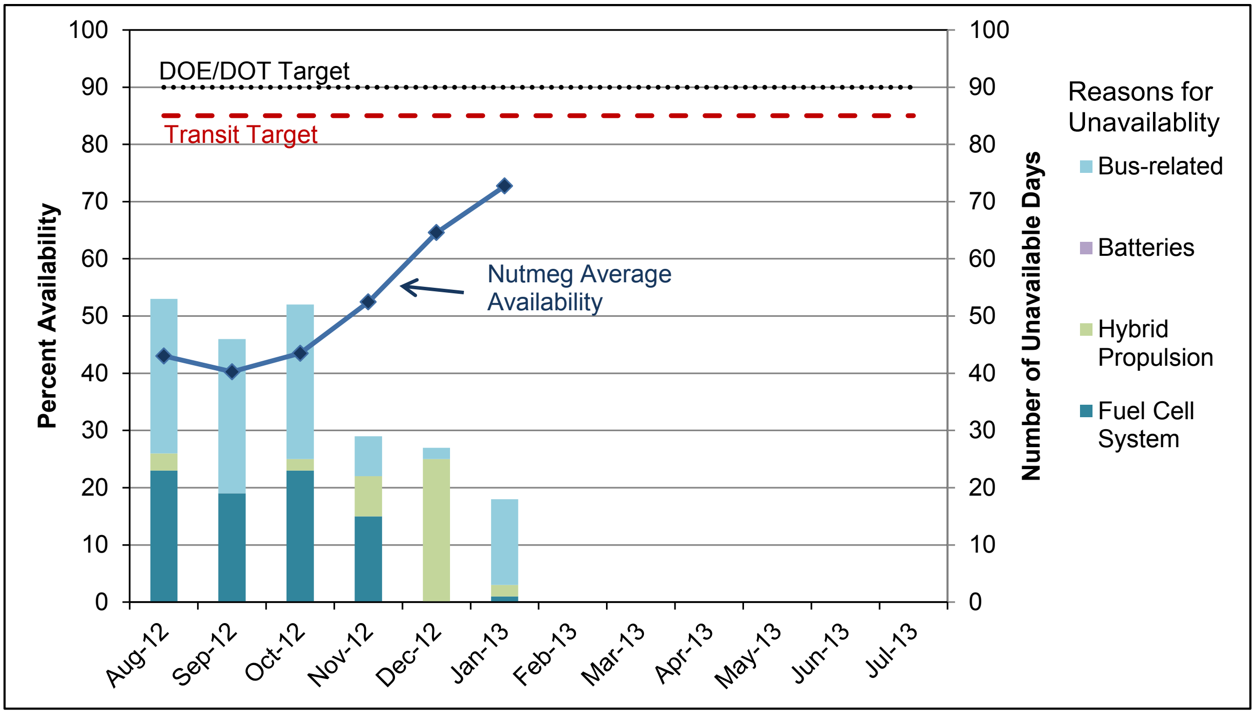

Figure A-3. Monthly availability and number of unavailability days for the CTT Nutmeg buses

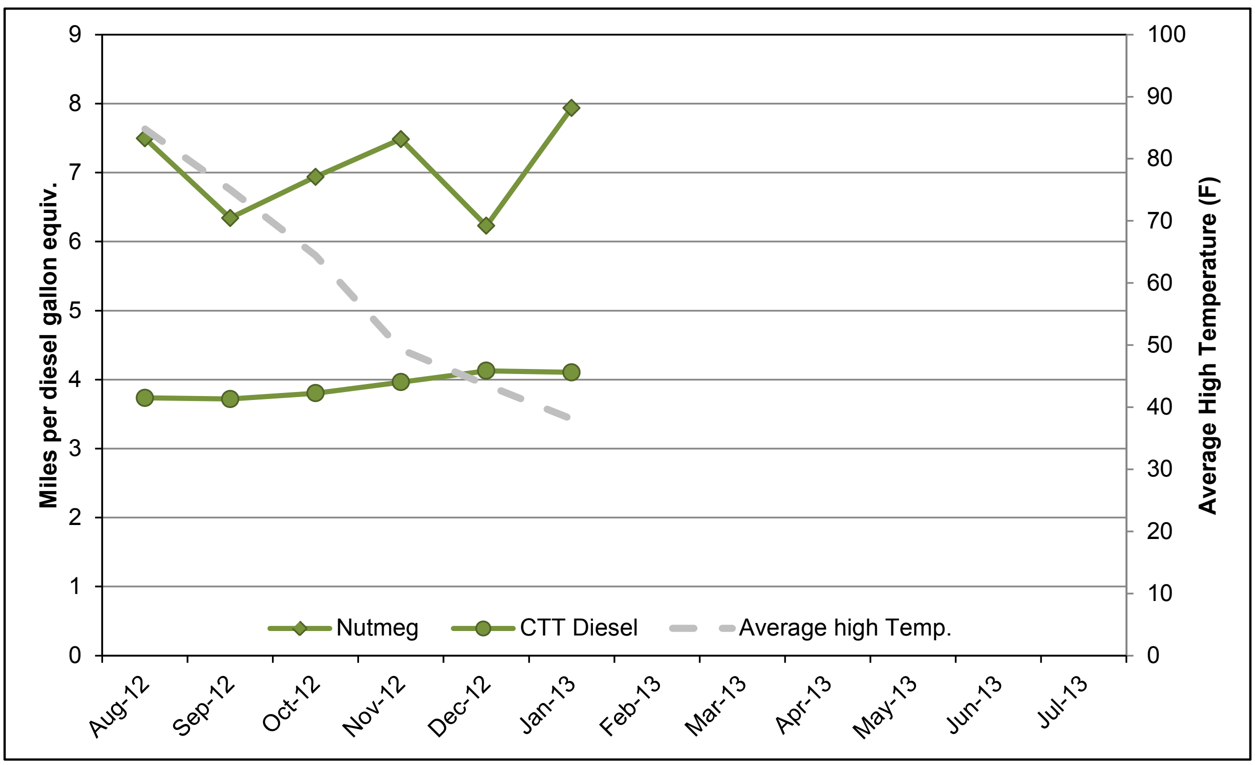

Figure A-4. Monthly fuel economy for the CTT Nutmeg and diesel buses

SunLine AT and AFCB Demonstration Summary

Table A-4. SunLine Data Summary

	SL AT All Data	SL AT Past Year	SL AFCB All Data	SL AFCB Past Year	SL CNG All Data	SL CNG Past Year
Data period	5/10–7/13	8/12–7/13	3/12–7/13	8/12–7/13	5/10–7/13	8/12–7/13
Number of buses	1	1	1	1	5	5
Number of months	39	12	17	12	39	12
Total miles	52,749	9,340	54,066	36,339	841,350	234,064
Total FC hours	4,557	906	3,496	2,380	–	–
Average speed (mph)	11.6	10.3	15.5	15.3	–	–
Average miles per month	1,353	778	3,180	3,028	4,315	3,901
Number of scheduled days	935	280	537	331	2,202	1,526
Number of days available	535	88	394	247	1,717	1,188
Availability	56%	31%	76%	75%	84%	78%
Fuel economy (mi/kg or GGE)	5.52	5.15	6.50	6.38	2.90	2.79
Fuel economy (mi/DGE)	6.23	5.82	7.34	7.20	3.24	3.12
Bus MBRC	2,504	1,529	4,159	6,057	10,786	5,087
Propulsion-only MBRC	2,768	1,835	7,724	12,113	28,043	21,272
FC system-only MBRC	5,843	3,059	18,022	36,339	–	–
Total hydrogen used (kg)	9,525	1,804	8,318	5,700	–	–
SI Units						
Total kilometers	84,891	15,031	87,011	58,482	1,354,022	376,689
Average speed (kph)	18.6	16.6	24.9	24.6	–	–
Average km per month	2,177	1,253	5,118	4,873	6,944	6,278
Fuel consumption (kg/100 km)	11.26	12.06	9.56	9.75	–	–
Fuel consumption (liter/100 km)	37.58	40.19	32.02	32.64	73.08	75.88
Bus km between roadcalls (KBRC)	4,030	2,461	6,693	9,747	17,358	8,186
Propulsion-only KBRC	4,454	2,953	12,430	19,494	45,130	34,234
FC system-only KBRC	9,403	4,922	29,004	58,482	–	–

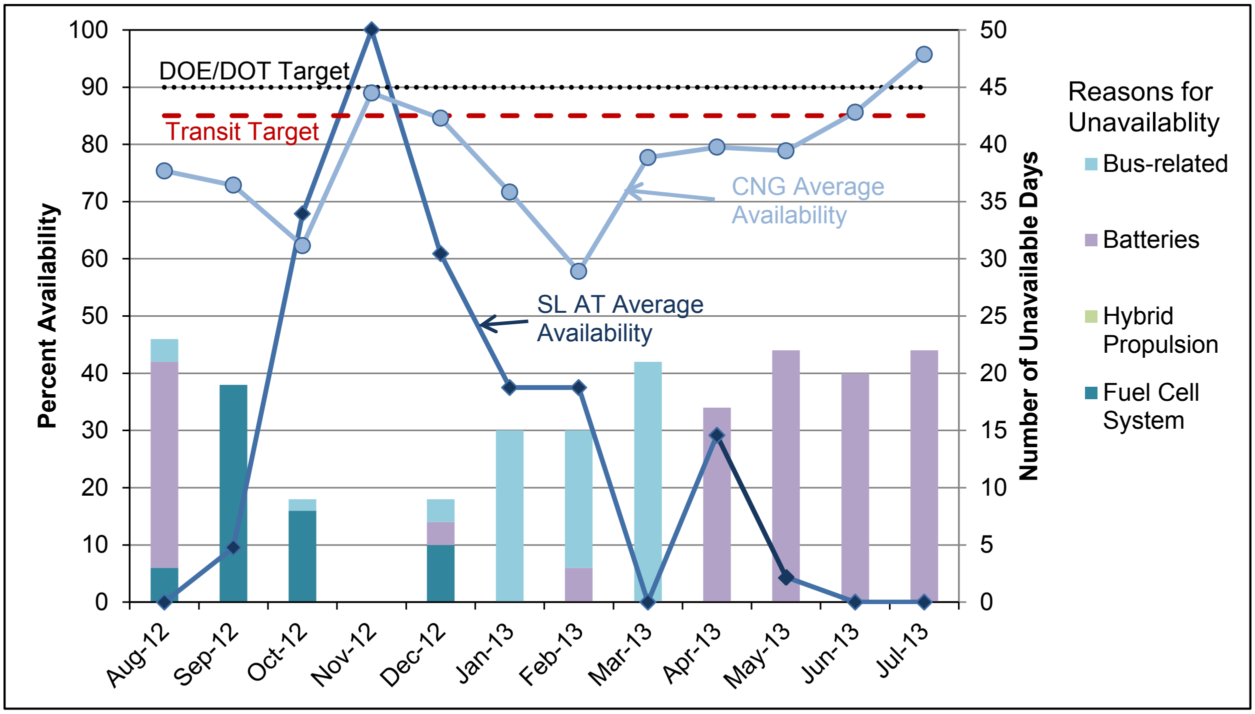

Figure A-5. Monthly availability and number of unavailability days for the SunLine AT FCEB

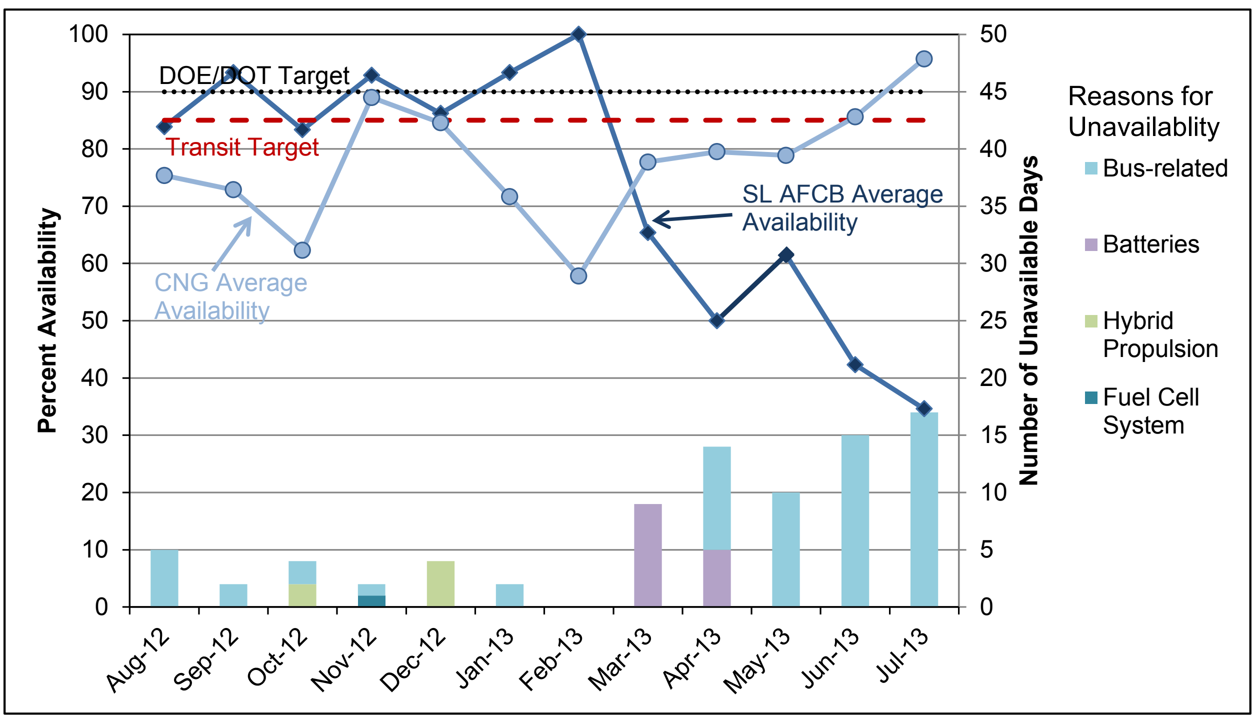

Figure A-6. Monthly availability and number of unavailability days for the SunLine AFCB

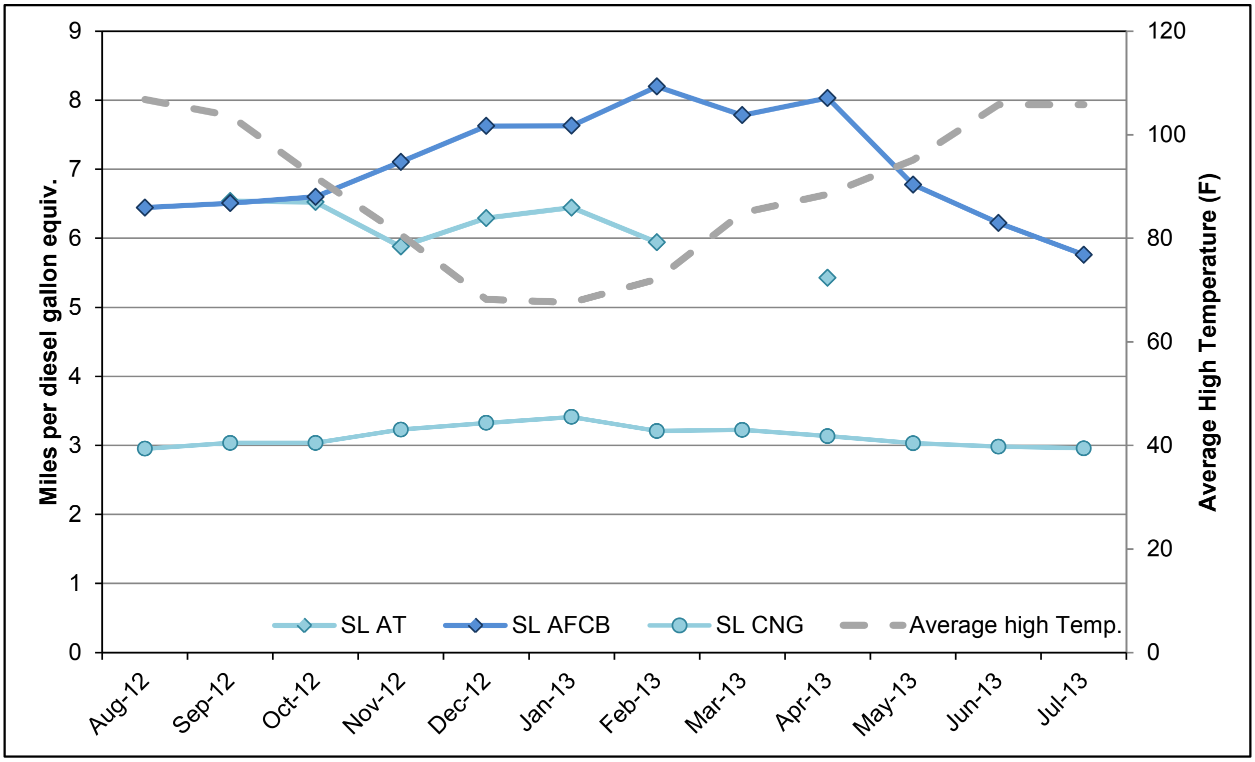

Figure A-7. Monthly fuel economy for the SunLine FCEB and CNG buses

TX Proterra Demonstration Summary

Table A-5. TX Proterra Data Summary

	TX Proterra
Data period	10/12–3/13
Number of buses	1
Number of months	6
Total miles	1,374
Total FC hours	N/A
Average speed (mph)	N/A
Average miles per month	229
Number of scheduled days	82
Number of days available	46
Availability	56%
Fuel economy (mi/kg or GGE)	5.88
Fuel economy (mi/DGE)	6.65
Bus MBRC	344
Propulsion-only MBRC	687
FC system-only MBRC	1,374
Total hydrogen used (kg)	233.5
SI Units	**SI Units**
Total kilometers	2,211
Average speed (kph)	N/A
Average km per month	369
Fuel consumption (kg/100 km)	10.56
Fuel consumption (liter/100 km)	35.37
Bus km between roadcalls (KBRC)	553
Propulsion-only KBRC	1,106
FC system-only KBRC	2,211

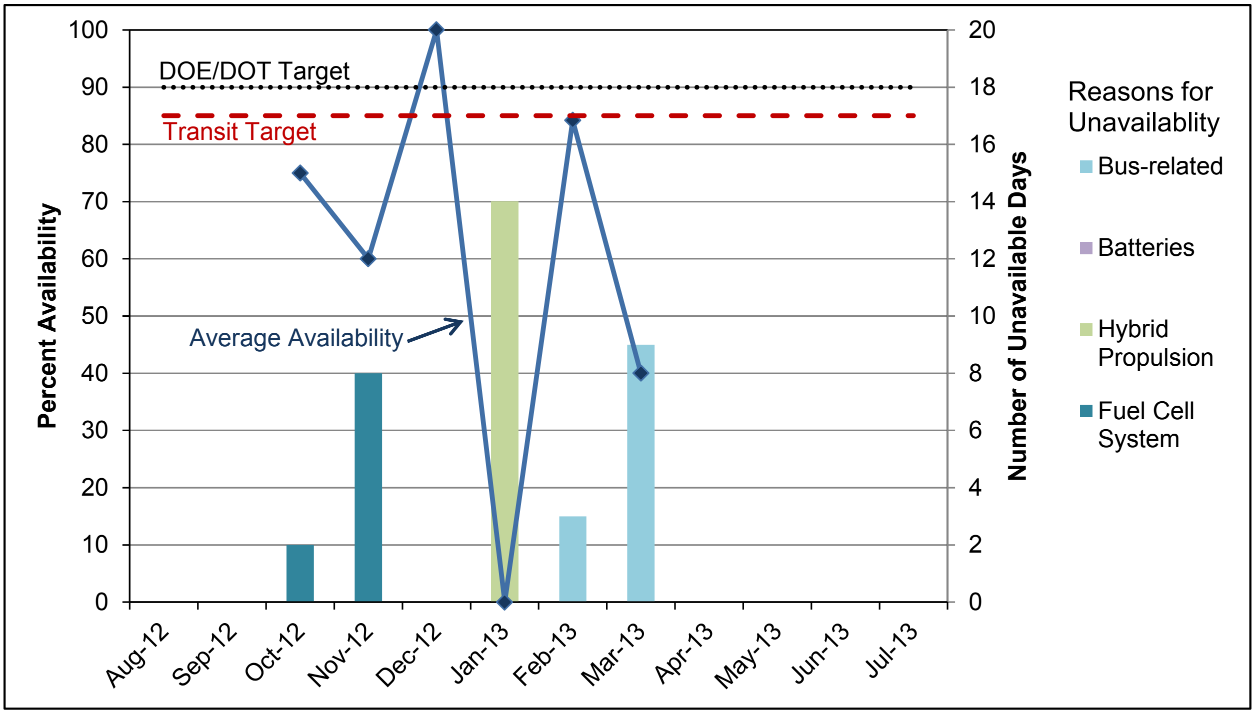

Figure A-8. Monthly availability and number of unavailability days for the Proterra bus