December 2008

Fuel Cell School Buses

Report to Congress

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Preface

This Department of Energy report addresses Section 743(c) of Public Law No. 109-58, also known as the Energy Policy Act of 2005 (EPACT 2005). Section 743 of EPACT 2005 calls for a fuel cell school bus development and demonstration program; subsection 743(c) requires a Report to Congress on this activity, which is presented in the pages that follow.

> EPACT 2005
>
> **SEC. 743. FUEL CELL SCHOOL BUSES** (page 234)
> (a) ESTABLISHMENT.—The Secretary shall establish a program for entering into cooperative agreements—
> (1) with private sector fuel cell bus developers for the development of fuel cell-powered school buses; and
> (2) subsequently, with not less than 2 units of local government using natural gas-powered school buses and such private sector fuel cell bus developers to demonstrate the use of fuel cell-powered school buses.
>
> (b) COST SHARING.—The non-Federal contribution for activities funded under this section shall be not less than—
> (1) 20 percent for fuel infrastructure development activities;
> and
> (2) 50 percent for demonstration activities and for development activities not described in paragraph (1).
>
> (c) REPORTS TO CONGRESS.—Not later than 3 years after the date of enactment of this Act, the Secretary shall transmit to Congress a report that—
> (1) evaluates the process of converting natural gas infrastructure to accommodate fuel cell-powered school buses; and
> (2) assesses the results of the development and demonstration program under this section.
>
> (42 U.S.C. 16093)

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Executive Summary

This document was produced in response to the requirements of Section 743 of the Energy Policy Act of 2005 for a Report to Congress describing the results of a fuel cell school bus development and demonstration program and an assessment of the process for converting natural gas infrastructure to accommodate hydrogen fuel cell school buses (42 U.S.C. 16093(c)).

The Department of Energy (DOE) Hydrogen Program has examined the potential for a fuel cell school bus development and demonstration program. As discussed in this report:

- Cost and durability remain critical barriers to transportation fuel cell technology readiness, and the school bus market is particularly sensitive to these issues.
- A robust fuel cell transit bus program already exists and can provide important lessons learned toward the future development and use of fuel cell school buses. The compressed natural gas (CNG) bus market followed a similar development path—initial efforts focused on CNG transit buses, and school bus developers and users were able to benefit from key lessons learned before adopting CNG technology.

Using existing natural gas infrastructure, distributed (on-site) hydrogen production via natural gas reforming can be a cost-effective pathway for initial hydrogen fuel cell vehicle deployment. In 2006, an independent panel verified that DOE met its hydrogen cost goal of $3.00 per gallon gasoline equivalent, or gge, (delivered, untaxed) for distributed natural gas reforming.[1] Analysis also suggests that using natural gas for initial, near-term hydrogen fuel cell vehicle deployments will not significantly affect overall natural gas demand in the United States.[2] Converting an existing natural gas fueling station to include hydrogen fueling capability depends heavily on the individual site and must consider differences in fuel properties, dispensing and supply conditions, and codes and standards, but it is technically feasible. A 2004 report completed by TIAX, LLC for the California Energy Commission suggests that new CNG station designs should consider future hydrogen fueling capability.[3]

In addition to distributed hydrogen production at the point of use, a robust hydrogen fuel cell bus market that expands beyond initial demonstrations will require additional infrastructure to allow for hydrogen delivery from central and semi-central hydrogen production facilities. Significant challenges exist, however, in the conversion of natural gas pipelines for hydrogen delivery. For example, hydrogen can permeate and embrittle some of the steels used in the existing natural gas pipeline infrastructure, and the polyvinyl chloride (PVC) piping used for natural gas distribution/service lines is not suitable for the required higher pressure hydrogen delivery. There are also natural gas demand considerations—current natural gas demand is high and spare pipeline capacity would be limited during peak demand periods.

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[1] National Renewable Energy Laboratory, *Distributed Hydrogen Production from Natural Gas Independent Review* (October 2006), page 4. http://www.hydrogen.energy.gov/pdfs/40382.pdf, accessed May 2008.

[2] H. Vidas, Energy and Environmental Analysis, Inc., "Initial Look at Potential Natural Gas Infrastructure Constraints Related to Transition to Hydrogen Transportation Fuels," (September 2006), Prepared for the U.S. Department of Energy.

[3] California Energy Commission/Consultant Report, *Requirements for Combining Natural Gas and Hydrogen Fueling* (February 2004), page 5-2.

Although DOE is not directly pursuing a fuel cell school bus program at this time, it supports several activities that will affect the development of a future market for fuel cell school buses. DOE's Hydrogen Program (the Program) includes fuel cell research and development (R&D) activities, which are focused on reducing the cost and improving the durability of fuel cells, two critical barriers to commercialization. Great progress has been made, but additional work is needed to ensure technology readiness. DOE-funded research has contributed to reducing the projected, high-volume manufacturing cost of automotive fuel cell systems from $275/kW in 2002 to $73/kW in 2008[4], but further R&D will be needed to achieve the target cost of $30/kW by 2015.

Through the DOE Hydrogen Learning Demonstration, part of the Program's technology validation activity, DOE is collecting data on fuel cell vehicle and hydrogen infrastructure performance in real-world environments. To date, the Learning Demonstration has included 92 fuel cell vehicles and 15 hydrogen fueling stations that have provided data on fuel efficiency, fuel economy, driving range, fuel cell durability, hydrogen quality, refueling rates, infrastructure safety, and other metrics that feed back into R&D activities and help DOE communicate technology status to the public and Congress.

DOE and the National Renewable Energy Laboratory (NREL) are also working closely with the Department of Transportation's Federal Transit Administration (FTA) to evaluate fuel cell technologies in transit applications—specifically, to document technical results and lessons learned from user demonstration experiences, as well as identify and understand remaining challenges to commercialization and deployment. In September 2007, NREL published results from fuel cell transit bus demonstrations at SunLine Transit Agency, Alameda-Contra Cost Transit District, and Santa Clara Valley Transportation Authority. Key findings are summarized in Table ES 1.

Attribute	Fuel Cell Technology	Conventional Diesel Technology
Vehicle Fuel Economy	2 times higher than conventional buses	3 – 4 miles per gallon (diesel)
Reliability (measured in "miles between road call," or MBRC)	919 – 1,600 MRBC	10,000 MBRC
Availability	58-77%	85%
Capital Cost	$2 – $3 million	$328,000
Fuel Cost	$8.90 to $18.80 per diesel gallon equivalent	$4.72/gallon*

Source: L. Eudy, et al., *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status* (September 2007), NREL/TP-560-41967, http://www.nrel.gov/hydrogen/pdfs/41967.pdf, accessed May 2008.
* Energy Information Administration, Weekly On-Highway Diesel Prices, 07/07/08, http://tonto.eia.doe.gov/oog/info/wohdp/diesel.asp, accessed July 2008.

Table ES 1. *Comparison of Fuel Cell Transit Buses and Conventional Buses*

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[4] U.S. Department of Energy Hydrogen Program, Records #5005 and #8019. (The costs of $275/kW and $73/kW are based on 2002 and 2008 dollars, respectively. The 2015 target of $30/kW is based on 2002 dollars.)

Through its National Fuel Cell Bus Program (NFCBP) announced in 2006, FTA has partnered with transit agencies in different cities across the country to demonstrate the latest fuel cell bus technology. In an effort to advance technology development, FTA set rigorous performance objectives, including targets for cost and durability for fuel cell systems in transit buses, under the NFCBP. The fuel cell buses developed under this program will begin rolling out in late 2008 and early 2009. DOE is supporting data collection and evaluation and will work with FTA to publish results that regularly communicate technology status to the transit industry and others. The NFCBP (and other similar fuel cell transit bus programs) will provide valuable lessons learned and insight into the technology needs for future demonstration and deployment efforts, including programs for fuel cell school buses.

1. Introduction

Section 743 of the Energy Policy Act of 2005 instructs the Secretary of Energy to establish a program for entering into cooperative agreements with private sector fuel cell bus developers for the development of fuel cell-powered school buses and to demonstrate the use of these buses with at least two local government entities that are already using natural gas school buses (42 U.S.C. 16093). This report addresses the requirements of Section 743 by describing Department of Energy (DOE) Hydrogen Program fuel cell research, development, and demonstration (RD&D) activities, the status of technologies required for fuel cell school buses, existing fuel cell transit bus demonstration activities, and how they can influence related efforts for school buses. The report also describes issues related to converting existing natural gas infrastructure to accommodate hydrogen fuel cell vehicles.

Hydrogen is an energy carrier, meaning it can store and deliver energy in a useable form. It can be produced using abundant and domestic energy resources including fossil, nuclear, and renewables. Fuel cells use hydrogen to create electricity, with only heat and water as byproducts. They are scalable and can be used for a variety of applications, and they offer quiet operation with few moving parts. When fuel cells are used to power a vehicle, the only output from the tailpipe is water; there are no greenhouse gas or criteria emissions. Fuel cell vehicles also promise more than two times the efficiency of traditional combustion technologies[5]—for vehicles, this can mean a more than 50 percent reduction in fuel consumption compared to a conventional vehicle with a gasoline engine.[6] In addition, on a well-to-wheels basis, which accounts for the energy in fuel production and delivery, a fuel cell vehicle using hydrogen produced from natural gas would consume approximately 12% less energy than a gasoline hybrid-electric vehicle and approximately 43% less energy than a conventional gasoline internal combustion engine vehicle.[7]

In 2003, President George W. Bush announced the Hydrogen Fuel Initiative to accelerate the pace of research and development (R&D) of hydrogen fuel cell technologies. In support of the President's Hydrogen Fuel Initiative, the DOE Hydrogen Program focused its efforts on high-risk, critical technology barriers preventing widespread use of hydrogen as an energy carrier. Through cost-shared projects with partners, it conducts basic and applied research, technology development and learning demonstrations, underlying safety research, systems analysis, and outreach and education activities. Public and private partners include automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, standards development organizations, other Federal agencies, state government agencies, universities, national laboratories and other national and international stakeholder organizations.

Although the Program's scope is broad, covering transportation, stationary, and portable power applications, it maintains a particular emphasis on fuel cells for automotive applications to align with DOE's mission to strengthen national energy security. More than one-half of the petroleum consumed in the United States is imported, and that percentage is expected to grow to 60 percent by 2025.[8] The U.S.

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[5] Singh M., A. Vyas and E. Steiner, Argonne National Laboratory, *VISION Model: Description of Model Used to Estimate the Impact of Highway Technologies and Fuels on Energy Use and Carbon Emissions to 2050*, (December 2003), ANL/ESD/04-1, retrieved September 27, 2005, from http://www.transportation.anl.gov/pdfs/TA/299.pdf. The energy efficiency assumed for FCVs relative to conventional vehicles is 2.25 in 2018 and 2020, 2.5 in 2030 and 2040 and 3.0 beginning in 2050 with linear interpolation used for intervening years (assumes average new light duty vehicle fuel economy of 24.3 mpg for baseline vehicles).

[6] U.S. Department of Energy Program Record #8020.

[7] U.S. Department of Energy, *Hydrogen Posture Plan*, Appendix B, page B-2, (December 2006), provides the data, sources, and assumptions used in the calculations.

[8] U.S. Department of Energy, Energy Information Administration, *Annual Energy Outlook 2006: With Projections to*

transportation sector relies almost exclusively on petroleum, accounting for more than two-thirds of the oil used.[9] Each day, more than eight million barrels of oil are required to fuel the more than 225 million vehicles that constitute the U.S. light-duty transportation fleet.[10,11] The gap between U.S. oil production and transportation oil needs is projected to grow, and the increase in the number of light-duty vehicles will account for most of that growth. In addition to the increased use of biofuels and plug-in hybrid-electric vehicle (PHEV) technologies, using hydrogen as an energy carrier will allow the U.S. to diversify its energy supply with abundant, domestic resources and reduce our dependence on foreign oil.

The DOE Hydrogen Program structured its activities with the overall goal of achieving hydrogen fuel cell "technology readiness" in 2015. Among its key activities is a robust fuel cell R&D effort focused on meeting key technical targets related to cost and durability (as well as other performance factors), conducted in parallel with a technology validation and demonstration activity. By providing a reliable stream of data, technology validation helps to identify issues that can be addressed in the Program's R&D activities. Technology validation also provides the necessary real-world data that industry needs to make informed and accurate assessments of technology status as it approaches a decision whether or not to fully pursue commercialization. The data collected also helps the Federal government make informed decisions about R&D investments and policy that promotes the adoption of hydrogen and fuel cell technologies.

As stated in the 2003 *Fuel Cell Report to Congress,* Federal involvement in technology validation and demonstration should be balanced with ongoing near- and long-term R&D needs.[12] The Program's current demonstration activities reflect this philosophy and have been designed to strategically align with core R&D efforts. As this report shows, great care has been taken to ensure that funds available for demonstration activities are directed to provide maximum benefit to the Program and align with the DOE mission.

2. Fuel Cell Technology Status

2.1 FUEL CELL RESEARCH & DEVELOPMENT

A majority of the DOE Hydrogen Program's fuel cell R&D effort focuses on Polymer Electrolyte Membrane (PEM) fuel cells. With a relatively low operating temperature, quick start-up time, high power density and efficiency, and ability to rapidly vary output with changing power demands, PEM fuel cells are particularly well suited to automotive applications. Although some fuel cell transit bus demonstrations use Phosphoric Acid Fuel Cell (PAFC) technology, for the reasons cited above, most of the past and current fuel cell vehicle (light-duty vehicle and transit bus) demonstrations use PEM fuel cells.

Some fuel cells are commercially available today for certain niche markets, including material handling equipment, remote and backup stationary power, and prime power for critical power applications such as

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2030 (February 2006), page 8. http://www.eia.doe.gov/oiaf/aeo.pdf/0383(2006).pdf, accessed September 2006.

[9] Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 25* (2006), "Table 1.13 Consumption of Petroleum by End-Use Sector, 1973 – 2005," 1-17. http://cta.ornl.gov/data/tedb25/Edition25_Full_Doc.pdf, accessed August 2006.

[10] Ibid., "Table 2.5 Transportation Energy Use by Mode, 2002-2003," 2-7.

[11] Ibid., "Table 3.3 U.S. Automobiles and Trucks in Use, 1970 – 2003," 3-5.

[12] U.S. Department of Energy, *Fuel Cell Report to Congress* (February 2003), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb2003.pdf, accessed May 2008.

data centers (See Appendix for information about fuel cell early markets). Fuel cells for transportation, however, face several critical barriers. Two of the most critical barriers are cost and durability. To compete with today's internal combustion engines in vehicles, fuel cells must have comparable lifetimes—for automotive applications, this means a fuel cell system that can operate for approximately 5,000 hours (150,000 miles) with a widely varying duty cycle and thousands of stops and starts. Fuel cell cost must be comparable to the cost of internal combustion engines as well. DOE established a 2015 target of $30/kW for automotive fuel cell power systems. Key fuel cell technical targets are noted in the Table 1 below.

Characteristic	Units	2003 Status	2008 Status	2010	2015
Energy efficiency[b] @ 25% of rated power (*transportation fuel cell systems*)	%	59[c]	59[c]	60	60
Cost[d] (*transportation fuel cell systems*)	$/kW	275	73[e]	45	30
Durability with cycling (*transportation fuel cell stacks*)	hours	N/A	~2,000	5,000	5,000

Source: U.S. Department of Energy, *Hydrogen, Fuel Cells & Infrastructure Technologies Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005 - 2015* (October 2007), http://www.eere.energy.gov/hydrogenandfuelcells/mypp/, accessed June 2008.

[a] Targets exclude hydrogen storage, power electronics, and electric drive.

[b] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.

[c] These efficiency values, which affect fuel economy, are based on laboratory results. Fuel cells used in vehicles have been shown to have approximately double the efficiency of gasoline internal combustion engines. Results from the National Renewable Energy Laboratory's evaluation of data from DOT's National Fuel Cell Bus Program showed significant improvements in fuel economy: fuel cell buses achieved more than 70% improvement in fuel efficiency over diesel buses in one fleet and more than 150% improvement over compressed natural gas buses in another (see L. Eudy, Fuel Cell Bus Evaluation Results, January 2008, slides 12 and 20, www.nrel.gov/hydrogen/pdfs/42665.pdf).

[d] Based on 2002 dollars and cost projected to high-volume production (500,000 systems per year).

[e] Status is from 2008 Directed Technologies Institute (DTI) study and will be updated periodically.

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Table 1. *Status and technical Targets for 80-kW$_e$ (net) Transportation Fuel Cells Operating on Direct Hydrogen.*[a]

Great progress has been made since the start of the President's Hydrogen Fuel Initiative in 2003. Program-funded research has reduced automotive fuel cell costs from $275/kW in 2002 to $73/kW in 2008 (projected and assuming high volume production of 500,000 units per year). In addition to the *system-level* targets, DOE has also established *component-level* targets. A notable success at the component level is a major improvement in fuel cell durability, announced in June 2008. Through the use of ternary platinum alloys and with the help of mechanical stabilization techniques, durability for membrane electrode assemblies (MEAs) has improved from 2,000 hours in 2005 to more than 7,300 hours under cycling conditions, while at the same time reducing platinum group metal loading to 0.2 mg/cm^2. This exceeds the 2010 target of 5,000 hours and 0.3 mg/cm^2 platinum loading.[13]

While these advancements are significant, PEM fuel cell technology for light-duty fuel cell vehicles is not yet ready for the commercial market. Cost remains a major hurdle, and durability must be proven. Other areas of research focus on materials improvements, especially in the areas of catalysts, catalyst supports,

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[13] U.S. Department of Energy, 2008 Hydrogen Program Annual Merit Review Proceedings, http://www.hydrogen.energy.gov/annual_review08_proceedings.html (to be available July 2008)

and membranes, as well as the development of a better understanding of the effects of impurities and how materials properties affect the mass and electrical transport in the fuel cell. Water transport, which is critical for performance and for freeze-thaw issues, is also a challenge.

2.2 FUEL CELL VEHICLE TECHNOLOGY VALIDATION AND DEMONSTRATION

To fully assess and validate the results of its R&D efforts, the DOE Hydrogen Program includes a technology validation activity that supports fuel cell vehicle and infrastructure demonstrations, stationary power demonstrations, and projects that integrate renewable power generation and hydrogen production. Technology validation is an extension of R&D—by providing real-world operations data, it helps identify issues to be addressed by R&D activities, and it aids in accurately assessing technology status in integrated operating systems. The cornerstone of this effort is the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project (or "Learning Demonstration"). Launched in April 2004, the Learning Demonstration brings together DOE and four teams of automobile and energy company partners in a 50/50 cost-shared effort to operate fuel cell vehicles and hydrogen infrastructure in real-world environments. The teams are led by Chevron and Hyundai-Kia; Chrysler, Daimler, and BP; Ford and BP; and General Motors and Shell, with additional participation from hydrogen suppliers, fuel cell suppliers, utility or gas companies, fleet operators, system and component suppliers, small businesses, universities, and government entities.

To date, the Learning Demonstration has included 92 fuel cell vehicles and 15 hydrogen fueling stations, allowing DOE to gather data on fuel cell efficiency, fuel economy, driving range, fuel cell durability, vehicle safety, hydrogen quality, refueling rates, infrastructure safety, as well as many other metrics[14]. DOE publishes aggregate results in the form of composite data products. As of March 2008, DOE published 47 composite data products; project results are updated every six months as new information is added to the database.

Key project metrics and status are shown in Table 2. The reported data represents first-generation technology from 2003 to 2004. The lag time between technology development and demonstration reflects the time required to move new technology from the laboratory into full integration in a small fleet of vehicles. As a result, more recent advances in materials and component technology are not reflected here. Second-generation vehicles were introduced in the fourth quarter of 2007 and will continue to be introduced through the first quarter of 2009 (a total of 130 vehicles are planned for the project). This will allow progress made from first- to second-generation technology to be benchmarked and compared with Program targets.

	Status, as Reported (2008)[a]	**2015 Targets**
System Efficiency	53-58%	60%
Demonstrated Fuel Cell System Durability	1,200 hrs *(~36,000 miles)*[b]	5,000 hrs *(~150,000 miles)*
Vehicle Range	103–190 miles	300 miles

Source: K. Wipke, et al., Learning Demonstration Progress Report—Spring 2008, National Renewable Energy Laboratory, April 2008, www.nrel.gov/hydrogen/pdfs/42986.pdf, accessed May 27, 2008.
[a] Current status is from Generation 1 stack technology developed ~4-5 years ago. Second generation

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[14] K. Wipke, et al., *Learning Demonstration Progress Report – Spring 2008*, (April 2008), http://www.nrel.gov/hydrogen/pdfs/42986.pdf accessed May 2008.

stack technology is now on the road and providing data for results to be published in late 2008 and 2009.

[b] Some Learning Demonstration vehicle stacks have now demonstrated 1,200 hours real-world durability and the average projected time to a 10% voltage drop from the four teams is also just over 1,200 hours. The highest team projected time to a 10% voltage drop is 1,900 hours. See http://www.nrel.gov/hydrogen/docs/cdp/cdp_1.ppt (accessed May 2008) for details of actual and projected durability results.

Table 2. *Status and Targets for the Fuel Cell Vehicle Learning Demonstration*

3. Overview of Fuel Cell Transit Bus Activities

Although transit vehicles comprise less than two percent of the national total vehicle population, they are well suited to demonstrate advanced technologies and fuels because they are centrally located and fueled, government subsidized, professionally operated and maintained, operate on a fixed route and schedule, and highly visible among the public.

As shown in Table 3, government agencies worldwide have funded projects to develop, demonstrate, and evaluate fuel cell transit buses since the mid-1990s. The Department of Transportation's FTA has led U.S. efforts, beginning with a feasibility and proof-of-concept demonstration program with Georgetown University in 1988 and including demonstrations in Northern and Southern California, Connecticut, and Delaware. While FTA has taken the lead for the direct development of fuel cell buses, DOE and NREL work in partnership with FTA, as well as state agencies on data collection and evaluation, documenting technical results and lessons learned in an effort to better understand the challenges that remain to commercialization and deployment. DOE and NREL staff also participate on FTA's steering group to develop a new five-year Electric Drive Strategic Plan that identifies gaps and future focus areas for electric drive and fuel cell technologies. The plan is scheduled for release in early calendar year 2009.

Project Dates	Status	Project	Location	Description
1994-1995	Complete	Federal Transit Administration (FTA)/Georgetown University	Various	Three 30-ft fuel cell buses operating on methanol using 100 kW phosphoric acid fuel cell (PAFC) stacks from Fuji
1998	Complete	FTA/Georgetown	Various	One 40-ft fuel cell bus operating on methanol using 100 kW PAFC from UTC Power
1998-2000	Complete	Ballard Phase III	Chicago, IL, and Vancouver, Canada	Six 40-ft fuel cell buses using 205 kW polymer electrolyte membrane (PEM) fuel cell stacks from Ballard
2000-2001	Complete	Ballard Phase IV	Thousand Palms, CA	One test bus using 200 kW PEM fuel cell stack from Ballard
2000-	Complete	CityCell	Turin, Italy	One UTC Power 60 kW powerplant, hybrid bus, showcased in 2006 Winter Olympics
2000-	Complete	Citycell	Madrid,	One UTC Power 60 kW

Project Dates	Status	Project	Location	Description
2003			Spain	powerplant, hybrid bus
2001	Complete	FTA/Georgetown University	Various	One 40-ft fuel cell bus operating on methanol using 100 kW PEM fuel cell stack from Ballard
2002-2003	Complete	ISE/UTC Power ThunderPower	Thousand Palms and Oakland, CA	ThunderPower 30-ft fuel cell bus using 60 kW PEM fuel cell stack from UTC Power, ISE hybrid system
2003-2005	Complete	Clean Urban Transport for Europe (CUTE), Ecological City Transport System (ECTOS), Sustainable Transport Energy for Perth (STEP)	Europe, Iceland, and Australia	33 40-ft buses using Ballard PEM fuel cell stacks
2003-2006	In service	Hino/Toyota Fuel Cell Bus — Japan Hydrogen and Fuel Cell Demonstration Project	Japan	Eight 40-ft hybrid fuel cell buses with Toyota PEM fuel cell stacks
2004-2007	In service	Santa Clara Valley Transportation Authority	San Jose, CA	Three 40-ft fuel cell buses using Ballard fuel cell stacks
2004-2006	In service	United National Development Program-Global Environment Facility (UNDP-GEF) China	Beijing, China	Three 40-ft fuel cell buses using Ballard PEM fuel cell stacks
2004-	In service	SunLine Transit Agency	Thousand Palms, CA	One 40-ft fuel cell bus using UTC Power fuel cell stack, ISE hybrid system
2004-	In service	Hickam Air Force Base	Honolulu, HI	One battery dominant plug-in hybrid fuel cell bus with Hydrogenics PEM fuel cell and Enova hybrid system
2005-2007	In service	Alameda-Contra Costa Transit District	Oakland, CA	Three 40-ft fuel cell buses using UTC Power fuel cell stacks, ISE hybrid system
2006-2007	Complete (FCBs) In service (H2ICE)	HyFLEET CUTE	Europe, Iceland, China, and Australia	One-year extension of the demonstration of the Citaro/Ballard fuel cell buses and new demonstration of 14 hydrogen-fueled internal combustion engine buses (MAN)
2006	Complete	Natural Resources	Winnipeg,	One 40-ft hybrid fuel cell bus

Project Dates	Status	Project	Location	Description
		Canada (NRCan)/ Hydrogenics	Canada	using Hydrogenics PEM fuel cells
2006-	In service	Van Hool	Delijn, Belgium	One 43-ft hybrid using UTC Power 120 kW fuel cell, to be leased later to other European transit agencies
2007-	In service	CT Transit	Hartford, CT	One 40-ft hybrid fuel cell bus using UTC Power 120 kW fuel cell stacks, ISE hybrid system
2007-	In service	University of Delaware	Newark, DE	One 22-ft, battery dominant plug-in hybrid fuel cell bus using a Ballard fuel cell and Ebus hybrid system
2007-	In service	University of Texas	Austin, TX	One 22-ft, battery dominant plug-in hybrid fuel cell bus using a Ballard fuel cell and Ebus hybrid system
2007-	Design/Build	FTA National Fuel Cell Bus Program	Various locations in the United States	U.S. demonstration of fuel cell buses to advance technology commercialization; competitive solicitation to award $49 million over 4 years to selected projects
2007-	Design/Build	Georgetown University	Washington, DC	Development and demo of a 30-ft bus with a 60-kW automotive-sized PEM fuel cell powered by an on-board methanol reformer
2007-	Design/Build	California Air Resources Board, City of Burbank	Burbank, CA	Development of a battery dominant, 35-ft, plug-in hybrid fuel cell bus with Hydrogenics fuel cell in a Mobile Energy Solutions bus
2007-2014	Design/Build	British Columbia Transit, New Flyer, ISE, Ballard	Whistler, Vancouver, British Columbia, Canada	Operation of 20 hybrid fuel cell buses in British Columbia for the 2010 Olympics

Source: L. Eudy, et al., *Fuel Cell Buses in U.S. Transit: Summary of Experiences and Status*, (September 2007), http://www.nrel.gov/hydrogen/pdfs/41967.pdf, accessed May 2008.

Table 3. *Overview of Worldwide Fuel Cell Transit Bus Demonstrations*

3.1 ONGOING DEMONSTRATION PROGRAMS AND EVALUATIONS — NATIONAL FUEL CELL BUS PROGRAM

FTA's National Fuel Cell Bus Program (NFCBP) was established as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (Public Law No. 109-59; SAFETEA-LU), which authorizes $49 million in funding for 2006 through 2009 to help develop commercially viable fuel cell buses and technologies.[15] The NFCBP, a 50/50 cost-share program, seeks to dramatically improve the energy efficiency, emissions, performance, and cost-effectiveness of the 40-ft heavy-duty transit bus—the most prevalent vehicle used by U.S. transit agencies. Program objectives include:

- Develop and demonstrate fuel cell buses using innovative and improved fuel cell bus technologies.
- Develop and demonstrate innovative and improved components and technologies for fuel cell buses, including fuel cell technologies, energy storage, transit bus systems integration, and power electronics technologies.
- Advance different fuel cell technologies that may be viable for transit.
- Develop an understanding of the requirements for market introduction. This includes fuel supply, fueling infrastructure, supplier networks, maintenance, safety, insurance, education, performance, support, etc.
- Enhance the awareness of, and education about, fuel cell bus technologies.
- Collaborate in the development of design standards for fuel cell bus technologies.
- Compile and maintain information on the state of fuel cell bus technology development and needs.

FTA competitively selected the following nonprofit organizations to administer NFCBP projects: the Center for Transportation and the Environment (CTE), Northeast Advanced Vehicle Consortium (NAVC), and WestStart-CALSTART. As noted in Table 4, the selected projects include eight fuel cell bus demonstrations featuring multiple drive technologies and configurations, fuel cell power plants in various sizes, and several energy storage technologies. Project partners include multiple fuel cell manufacturers, drive system integrators, bus manufacturers, and fuel suppliers. In addition to the demonstration projects, two component technology projects and four supporting and outreach projects were also selected to be part of the overall program.

Site/Locations	Project/Title	Buses	Propulsion/ Power	Schedule
Alameda-Contra Costa Transit District (Oakland, CA)	Accelerated Fuel Cell Bus Testing	3	UTC Power/ISE Corporation (ISE)	4Q 2007 – 4Q 2008
SunLine Transit (Thousand Palms, CA)	All American Fuel Cell Bus Demonstration	1	UTC Power/ISE	4Q 2008 – 4Q 2010
CT Transit (Hartford, CT)	CT Hybrid Fuel Cell Bus Demo	4	UTC Power	4Q 2008 – 4Q 2010

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[15] FTA Bus Research and Testing website: http://www.fta.dot.gov/assistance/technology/research_4578.html, accessed May 2008.

Site/Locations	Project/Title	Buses	Propulsion/ Power	Schedule
Columbia, SC/2nd site TBD/CT Transit (New Haven, CT)	Dual Variable Output Fuel Cell Hybrid Bus	1	Hydrogenics/ Proterra	3Q 2008 – 4Q 2010
Logan Airport (Boston, MA)	MY Hydrogen Fuel Cell Powered Bus Fleet	1	Nuvera	3Q 2009 – 4Q 2010
New York	Lightweight Fuel Cell Bus Demonstration	1	General Electric/Plug Power	1Q 2009 – 4Q 2010
New York Power Authority (New York)	Hydroelectric Hydrogen Powered Fuel Cell bus Demonstration	2	Ballard/ISE	2Q 2009 – 4Q 2010
San Francisco Municipal Transportation Agency (San Francisco, CA)	Compound Fuel Cell Hybrid Bus Demonstration	1	Hydrogenics/ BAE Systems	1Q 2010 – 4Q 2010
Source: L. Eudy, et al., *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration - Appendix A: Summary of Hydrogen and Fuel Cell Transit Bus Demonstration Sites in the U.S.* (May 2008). http://www.nrel.gov/docs/fy08osti/42781-1.pdf, accessed May 2008.				

Table 4. *DOT/FTA National Fuel Cell Bus Program Demonstration Sites*

Through the NFCBP, FTA set the following performance objectives for advancing fuel cell bus technologies by 2012:

- Achieve a fuel cell bus vehicle cost of no greater than five times that of a commercial transit bus.
- Achieve four to six years or 20,000 to 30,000 hours of durability for the fuel cell propulsion system.[16]
- Achieve double the fuel efficiency of a commercial transit bus, to enhance energy security.
- Achieve fuel cell bus performance equal to, or better than, that of an equivalent commercial transit bus in terms of acceleration, gradability, range, braking distance, etc.
- Exceed the 2010 heavy-duty bus emissions standards.[17]
- Foster economic competitiveness in fuel cell bus technologies.
- Increase public acceptance for fuel cell bus technologies.

Building on its partnership with FTA, DOE and NREL are supporting data collection and evaluation, which is coordinated with related DOE activities and uses standard data collection and analysis protocol established for DOE heavy-duty vehicle evaluations.[18]

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[16] FTA requires 40-ft buses to operate 12 years or 500,000 miles (roughly equivalent to 20,000 – 30,000 hours) before it will provide transit agencies with funds for a new bus.

[17] Emissions standards available from the electronic Code of Federal Regulations (e-CFR): http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=7f9555134357c50771e8ed8631036064&rgn=div8&view=text&node=40:18.0.1.1.2.1.1.41&idno=40, accessed June 2008.

[18] *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the*

Results will be published at regular intervals to help accomplish the following:

- Measure the progress of fuel cell buses toward commercial readiness.
- Provide credible and consistent data collection and analysis for comparison.
- Enable the Federal government to understand the status and progress of the work and to continue funding necessary research and development.
- Ensure that FTA funds are used to push the technology forward.
- Provide information to the transit industry that will aid those making purchasing decisions on the technology.

3.2 STATUS OF THE TECHNOLOGY IN TRANSIT

Previous and ongoing fuel cell bus demonstrations have provided a significant amount of information about the performance of fuel cell buses relative to transit vehicles using conventional power technologies.

In September 2007, NREL published results from three transit agency fuel cell bus demonstrations that began in 2005.[19] The buses included in the evaluation are currently in the demonstration, test, and prototype phase of commercialization. Manufacturers are using in-service demonstrations to evaluate how the systems and components perform and verify the results of lab testing and modeling. The participating transit agencies have been active partners in the development process, aiding manufacturers as they improve the systems. Although much progress has been made, there are still major issues that require additional time, research, and resources before the technology can be considered for commercialization. The participating agencies and major findings from their fuel cell bus demonstrations are described below:

- Santa Clara Valley Transportation Authority (VTA) in San Jose, California, along with partner transit agency San Mateo County Transit District (SamTrans) in San Carlos, California[20]
- SunLine Transit Agency in Thousand Palms, California (in the Palm Springs area)[21]
- Alameda-Contra Costa Transit District (AC Transit) in Oakland, California, along with partner transit agency, Golden Gate Transit (GGT) in San Rafael, California[22]

a. Bus Use: Each agency reported successful fuel cell bus demonstration, accumulating more than 159,000 miles in service and more than 13,000 fuel cell hours.

Federal Transit Administration (May 2008), NREL/MP-560-42781, http://www.nrel.gov/docs/fy08osti/42781-1.pdf, accessed May 2008.

[19] L. Eudy, et al., *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status* (September 2007), NREL/TP-560-41967, http://www.nrel.gov/hydrogen/pdfs/41967.pdf, accessed May 2008.

[20] Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Evaluation Results (November 2006) NREL/TP-560-40615, http://www.osti.gov/bridge/servlets/purl/902527-sV3hav/902527.PDF, accessed May 2008.

[21] SunLine Transit Agency Hydrogen-Powered Transit Buses: Preliminary Evaluation Results (February 2007) NREL/TP-560-41001, and Evaluation Results Update, September 2007, NREL/TP-560-42080, http://www.nrel.gov/hydrogen/pdfs/42080.pdf, accessed May 2008.

[22] Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Preliminary Evaluation Results, February 2007, NREL/TP-560-41041, and Evaluation Results Update, October 2007, NREL/TP-560-42249, http://www.nrel.gov/hydrogen/pdfs/42249.pdf, accessed May 2008.

- VTA—three fuel cell buses accumulated 40,429 miles and 3,219 fuel cell system hours over 17 months.[23]
- SunLine—one fuel cell bus accumulated 50,931 miles and 3,918 fuel cell system hours in 27 months.[24]
- AC Transit—three fuel cell buses accumulated 68,098 miles and 6,586 fuel cell system hours in 21 months.[25]

Currently, these fuel cell buses are not operated at the same level as conventional technology buses, for various reasons. Some transit agencies allow the fuel cell buses to be in service only when appropriately trained maintenance staff are available. The agencies typically hold one bus as a spare, use it as added-service (rather than use it to replace a regularly scheduled bus), and use it for participation in public events. There have been some problems with the systems and components, including the fuel cell system and battery, which have led to unscheduled downtime. The level of fuel cell bus use has increased recently, however, as the agencies have become more comfortable with the buses and, along with manufacturer partners, they seek to push the technology to further identify problems and improve systems.

b. Fuel Economy: Fuel cell bus efficiency can be as high as two times that of conventional buses in the same service.[26] Results depend heavily on duty cycle, so a comparison to baseline buses is important. For example, the same bus design achieved a fuel economy of more than 7 miles per kg at one operating location, and around 6 miles per kg at another location. Data collected show a need for hybridization—the fuel economy for the non-hybrid system evaluated was 13 percent lower than the diesel baseline buses.

c. Reliability: Prototype hybrid fuel cell buses currently have a much lower reliability than conventional technology. For the transit industry, reliability is typically measured by distance between failure, or miles between road call (MBRC).[27] MBRC data for hybrid fuel cell propulsion systems range between 919 and 1,600 miles. These rates are generally a factor of ten lower than typical conventional technology buses, which are around 10,000 MBRC for propulsion-related systems.

d. Availability: The participating transit agencies reported an average fuel cell bus availability ranging between 58 percent and 77 percent. Typical conventional buses average 85 percent availability.

***e. Capital Cost*:** The capital cost of a fuel cell bus is an order of magnitude higher than the capital cost of a conventional bus. Reported costs are decreasing, and some manufacturers claim that on a full lifecycle cost basis, fuel cell buses may become competitive sooner rather than later when rising diesel fuel prices are considered.[28] Detailed analysis of lifecycle cost is needed, and further technology development is

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[23] Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Evaluation Results (November 2006) NREL/TP-560-40615, http://www.osti.gov/bridge/servlets/purl/902527-sV3hav/902527.PDF, accessed May 2008.

[24] SunLine Transit Agency, Hydrogen-Powered Transit Buses: Third Evaluation Report, June 2008, NREL/TP-560-43741-1 (report body) and NREL/TP-560-43741-2 (Appendices).

[25] Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Third Evaluation Report, July 2008, NREL/TP-560-43545-1 (report body) and NREL/TP-560-43545-2 (Appendices).

[26] This statement refers to vehicle efficiency. On a well-to-wheels basis, which accounts for the energy in fuel production and delivery, a fuel cell vehicle using hydrogen produced from natural gas would consume approximately 12% less energy than a gasoline hybrid-electric vehicle and approximately 43% less energy than a conventional gasoline internal combustion engine vehicle (see reference #7 on page 4 of this report).

[27] Road call or revenue vehicle system failure (as it is named in the National Transit Database) is defined as a failure of an in-service bus that causes the bus to be replaced en route or causes a significant delay in schedule.

[28] J. Murray, “Fuel Cell Buses in the Fast Lane to Maturity,” *BusinessGreen* (May 13, 2008).

required to bring the purchase price down to a level compatible with conventional technologies. Reported costs for these prototype buses participating in the demonstration are approximately $2 million to $3 million per bus. For comparison, a typical diesel bus costs $328,000, a compressed natural gas (CNG) bus costs approximately $395,000, and a current-generation hybrid-electric bus is approximately $483,000.

f. Maintenance Cost: Current data on maintenance costs do not reflect the true cost to the transit agency, because the demonstration buses are under warranty. For these demonstrations, manufacturers have on-site staff conduct the majority of the work on the propulsion system. These costs are not usually available to the evaluators, partly because of the sensitive nature of the data during this stage of technology development. As transit staff assume more of the maintenance work, these costs are expected to rise sharply. The cost for parts will also increase when the warranties expire and the agencies are responsible for costs of the fuel cell parts.

g. Hydrogen Fueling Experience**:** The demonstration fleets reported a total of 41,804 kg of hydrogen safely dispensed into the buses during the demonstration period. To operate in transit service, fuel cell buses require much larger quantities of hydrogen than that of light-duty fuel cell vehicles—current-generation buses can store approximately 50 kg on board the bus. The agencies reported average fill amounts ranging from 16.5 to 30 kg per fill and average fueling rates ranging from 0.89 to 2 kg per minute.

h. Hydrogen Cost*:* Hydrogen has been supplied to the three demonstration sites either by an on-site natural gas reformer or a liquid hydrogen storage system in which the liquid hydrogen was delivered. The currently reported cost for hydrogen ranges from $8.00 to over $17.00 per kg (or $8.90 to $18.80 per diesel gallon equivalent).[29] The higher price estimate was due primarily to excess boil-off[30] and loss of hydrogen from the liquid hydrogen station.

3.3 MANUFACTURERS INVOLVED IN U.S. FUEL CELL BUS PROJECTS

Existing commercial technologies for transit buses are diesel and CNG engines. Hybrid buses recently completed the early production stage of development and are now entering the market in significant numbers. The current generation fuel cell buses are purpose-built as opposed to assembly line-built, in part because U.S. orders to date have been small. For the early projects, the bus chassis was ordered from the manufacturer as a glider (no propulsion system) and the hybrid integrator/fuel cell manufacturer then installed the fuel cell propulsion system. More recent projects are collaborative efforts between the bus and fuel cell system manufacturers.

Many of the manufacturers that produce standard technology buses have been involved in early fuel cell bus demonstrations and should be capable of manufacturing larger quantities of fuel cell buses as the technology matures and costs are reduced. For this to be possible, however, the bus manufacturers will need to be able to purchase the hybrid and fuel cell systems for installation on the manufacturing line.

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http://www.businessgreen.com/2216475, accessed May 2008.

[29] Calculation assumes hydrogen heat content of 116,000 Btu/kg and diesel heat content of 128,500 Btu/gal (data obtained from the Hydrogen Analysis Resource Center, http://www.hydrogen.energy.gov/resource_center.html).

[30] Liquid hydrogen has to be stored at temperatures of -253ºC or lower. Boil-off occurs when its temperature rises above this level and some of the hydrogen "boils" (converts from liquid to gas). This gaseous hydrogen, usually a very small amount, is vented to the atmosphere, where it disperses harmlessly.

Current Fuel Cell Manufacturers Providing Bus Systems:

- Ballard (Burnaby, British Columbia)
- Hydrogenics (Mississauga, Ontario)
- Nuvera (Billerica, Massachusetts)
- UTC Power (South Windsor, Connecticut)

Hybrid Integrators for Fuel Cell Buses:

- BAE Systems—fuel cell auxiliary power unit in current diesel hybrid (Rockville, Maryland)
- Enova (Torrance, California)
- ISE Corporation (Poway, California)
- General Electric—designing a new lightweight bus under FTA's NFCBP (Fairfield, Connecticut)

Bus Chassis Manufacturers Involved in Fuel Cell Bus Projects:

- Ebus—including system integration (Downey, California)
- Daimler (Orion)—fuel cell auxiliary power unit integrated into current hybrid design by BAE Systems (Oriskany, New York)
- Gillig—past project, complete (Hayward, California)
- Proterra—including system integration (Golden, Colorado)
- New Flyer—current system integrated by ISE (Winnipeg, Manitoba)
- Van Hool—original system integrated by ISE, new model integrated in-house (Lier Koningshooikt, Belgium)

3.4 INDUSTRY NEEDS FOR SUCCESSFUL FUEL CELL BUS DEMONSTRATION

Although fuel cell bus technology has come a long way since the early demonstrations of the mid 1990s, the technology is not yet at the optimization stage. For fuel cell transit bus development and implementation to move ahead to deployment and commercialization, the industry must overcome several critical challenges. Cost reduction is a top priority; this includes reducing the capital cost of the fuel cell system and vehicle, as well as the cost to install infrastructure, deliver fuel, and operate and maintain both vehicles and infrastructure. Fuel cell system durability also must improve—and be proven—for fuel cell transit buses to compete with buses that use conventional technologies. Significant work is required to ensure that fuel cell buses can operate in normal service with the same, or better, performance and reliability as today's conventional technology buses.

Education and training are also important. This includes the technicians who service the vehicles and the drivers who operate them, as well as other agency personnel who are not likely to be familiar with hydrogen as a fuel or form of energy. Additionally, continued data collection, analysis, and reporting—fed back to the R&D community—are important to technology development. Targeted research, especially in the areas of energy storage, hydrogen production and availability, electric accessories development, overall system weight reductions, and detection sensor reliability, is important to advancing the technology from prototype demonstration to commercialization and deployment. Third-party evaluations, standardized protocols, and dissemination of evaluation data are also critical to helping other transit agencies, as well as policy makers at all levels, understand the potential benefits of, challenges to, and opportunities for fuel cell buses.

4. Lessons Learned from Deployment of Natural Gas School Buses

DOE's Office of Energy Efficiency and Renewable Energy (EERE) has long supported alternative fuel and advanced technology vehicle deployment. Established by the Energy Policy Act of 1992 (Public Law No. 102-486), Clean Cities, a voluntary, public-private partnership program within EERE's Vehicle Technologies Program, seeks to reduce petroleum use in the transportation sector through the increased use of alternative fuels and advanced vehicles, fuel blends, fuel economy, hybrid vehicles, and idle reduction technologies. The program now consists of nearly 90 locally based coalitions that include government and industry stakeholders, as well as fleet managers and other technology end users.

Since its inception, Clean Cities has focused on niche market fleets, including school buses. Through Clean Cities, DOE has awarded more than $4 million for natural gas school buses between 1999 and 2008. Cost share from awardees has increased the value of these projects to more than $21 million. Additionally, in 2001, Clean Cities awarded grants for technical training that included hydrogen and CNG training programs for transit employees, liquefied natural gas (LNG) heavy-duty training, CNG fire and safety training, and CNG tank inspection training.

The lessons learned from the deployment of alternative fuels (in the school bus market and others) can be used to help create strategies for hydrogen and fuel cell technology deployment. As with fuel cell buses, natural gas transit buses were deployed before natural gas school buses were considered. This approach was taken for several reasons, including:

- *Funding:* The FTA funds at least 80 percent of nearly every transit bus purchase (cleaner technologies often qualify for additional Federal funding), making the additional costs of advanced technologies an easier burden to bear for bus owners. FTA does not fund school buses. Although there are a variety of funding sources for schools to purchase cleaner technology buses and replace old ones, this funding is not guaranteed. This makes investment in new technologies much more difficult for school bus owners.
- *Replacement Schedule:* FTA requires a 40-foot transit bus to be operated for 12 years or 500,000 miles (or just over 41,000 miles per year) before it will provide replacement funds. Although the potential school bus market is larger than the transit market, school buses are typically used for 15 years or more.[31]
- *Operational Characteristics:* High usage is needed to gather the extensive data required to validate new technologies. Accelerated data collection efforts are important to provide timely information to the R&D community that seeks to improve future generations of the technology. Transit buses accumulate mileage much faster than school buses. Transit buses are typically used two full shifts per day, up to seven days per week (average 2,500 miles per month or 30,000 miles per year).[32] By contrast, school buses are used twice a day during school days only (as shown in Table 5, the 505,000 school buses in the U.S. travel 5.8 billion miles for an average use of 11,400 miles per year, or roughly that of an average passenger car).

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[31] 2007 Transit Vehicles Database, American Public Transportation Association, available through the website; www.apta.com, accessed May 2008.

[32] 2006 National Transit Summaries and Trends, National Transit Database, FTA, http://www.ntdprogram.gov/ntdprogram/pubs/NTST/2006/2006_NTST.pdf, accessed May 2008.

Fleet Characteristics	
Total fleet	505,000 buses
Children transported	25.4 million
Annual fleet mileage	5.8 billion miles
Average individual bus mileage per year	11,400 miles
Fuel of Choice	
Diesel	94%
Gasoline	5%
Alternative fuels	1%
There are approximately 4,150 alternative fuel school buses in the nation (about 1,650 buses fueled primarily by propane and 1,360 fueled by natural gas)	
Source: School Bus Pollution Report Card 2006: Grading the States, Union of Concerned Scientists (May 2006), http://www.ucsusa.org/clean_vehicles/big_rig_cleanup/clean-school-bus-pollution.html, accessed May 2008.	

Table 5. *The U.S. School Bus Fleet, 2006*

As fuel cell systems become more cost-competitive and fuel cell bus technology is validated, fuel cells may become an attractive option for school buses, particularly for public health reasons. School buses are the safest way for children to get to school, with a fatality rate that is nearly six times lower than that of passenger vehicles.[33] Thirty-seven percent of U.S. school buses are more than a decade old. Thus, these vehicles conform to significantly less stringent emission standards than the current 2007-2010 regulations and are not equipped with many safety features that more modern buses have as standard. With water as its only tailpipe emission, a fuel cell school bus would offer a clean transportation option for school systems, particularly those in urban areas where air pollution is a problem.

Given these issues, school bus operators are increasingly receptive to new technologies, but their willingness to demonstrate and deploy advanced technologies and alternative fuels must be balanced with strict financial and operational considerations.

5. Lessons Learned from Deploying Alternative Fuels

Experience with the deployment of alternative fuel vehicles, including CNG transit and school buses, offers valuable lessons learned for the commercialization and deployment of hydrogen fuel cell vehicles.[34]

- As with CNG, the "Chicken and Egg" issue is very real; it is likely that infrastructure and vehicles will need to be developed simultaneously.

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[33] U.S. Environmental Protection Agency, http://www.epa.gov/OMS/schoolbus/index.htm, accessed May 2008.

[34] B. McNutt and D. Rodgers, *The Hydrogen Energy Transition Moving Toward the Post Petroleum Age in Transportation, Chapter 12 - Lessons Learned from 15 Years of Alternative Fuels Experience—1988 to 2003*, Pages 165-179, http://www.science-direct.com/science/book/9780126568813, accessed May 2008.

- Deployment of CNG transit and school buses benefited from government policies, subsidies, incentives, tax credits, etc., that assisted with the incremental cost of vehicles and with building infrastructure.
- Achieving low operating costs is a key goal for fleets.
- The technology must cost the same as or less than existing technology, and it must offer the same or better performance. Also, fleets often make decisions based on lifecycle costs.
- Energy density must be considered when marketing alternative fuels. Cost, as well as more frequent refueling trips, are a concern for fleets and consumers.
- Station owners base decisions on profit margins and levels of risk.
- Unregulated and unsubsidized private sector investment in refueling infrastructure has been very limited. Historically, building infrastructure in anticipation of market development has rarely happened.
- Fleets have not demonstrated a willingness to purchase technology if it is inconvenient (for example: inadequate fueling infrastructure, maintenance or safety issues, range issues, and inconsistent product development or availability).
- Conventional fuels and technology have been shown to be very difficult to replace; both have the advantage of enormous, long-term financial investment and broad mass acceptance.
- Fleets are not likely to purchase technology with obvious social or environmental benefits unless there is a significant cost or performance improvement.
- Focusing solely on fleets and niche markets has not led to a consumer-based market.
- Education and outreach to consumers, manufacturers, fuel providers, regulators, automotive technicians, etc., takes time and persistence.
- Non-traditional benefits have, in instances, greatly increased acceptance and sales, for example, HOV access for hybrids.
- Unbiased data on all available fuels and technologies is critical.
- Building an alternative fuel market takes many years, if not decades.
- Bridging the gap between available CNG technologies and market demand involved technical, financial, and policy assistance.

6. Natural Gas Infrastructure Use for Hydrogen

The U.S. currently produces about nine million tons of hydrogen per year.[35] Most of this hydrogen is used in industrial processes such as petroleum refining, petrochemical manufacturing, glass purification, and in fertilizers. Only a small fraction is used as an energy carrier, most notably by the National Aeronautics and Space Administration (NASA). Nearly 95 percent of the hydrogen produced in the U.S. today is made at large central plants in a process called steam methane reforming, in which high-temperature steam (700 - 1000°C) is used to produce hydrogen from a methane source such as natural gas.[36] Hydrogen can also be produced by steam methane reforming in a distributed manner, either at or very near the point of end use. Distributed production requires less capital investment and less delivery infrastructure so it is considered a viable approach for expanding the use of hydrogen in the near term.

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[35] National Academy of Sciences/National Research Council, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, page 17. (Feb 2004), http://books.nap.edu/openbook.php?isbn=0309091632, accessed May 2008.

[36] National Academy of Sciences/National Research Council, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (Feb 2004), http://books.nap.edu/openbook.php?isbn=0309091632, accessed May 2008.

Today there are approximately 630 miles of hydrogen pipelines in the U.S., located along the Gulf Coast and in California and Illinois, primarily near large refineries.[37] In comparison, there are more than a million miles of natural gas pipelines across the country. With an extensive infrastructure and relatively mature natural gas-to-hydrogen production technology, and given the general similarities between these gaseous fuels, government and industry stakeholders have been examining issues related to using natural gas infrastructure to accommodate hydrogen for fuel cell vehicles. An overview of these key issues is provided below.

6.1 COST

A primary objective of DOE's hydrogen production R&D activity is reducing cost. In 2005, the program announced a hydrogen cost goal of $2.00-3.00/gge (delivered, untaxed, 2005 dollars, by 2015), independent of the pathway used to produce and deliver hydrogen. The methodology used to develop the goal accounts for the energy efficiency of gasoline hybrid-electric vehicles and fuel cell vehicles on a cost-per-mile basis. This was derived using National Academy of Sciences fuel-efficiency improvement factors and the Energy Information Administration "High A" gasoline price projection for 2015 (in the High A case, the U.S. economy is more vulnerable to limited oil supplies from foreign sources due to the increasing world and U.S. oil demand, resulting in higher oil prices).[38]

In 2006, an independent review panel assessed the progress of distributed natural gas reforming R&D toward achieving the DOE hydrogen cost goal.[39] The panel reviewed available information about the technologies needed for forecourt (on-site) hydrogen production of 1,500 kg per day by natural gas reforming (1,500 kg of hydrogen is required to fuel 300 light-duty hydrogen fuel cell vehicles at 5 kg per fill). Panel members also conducted discussions with interested parties representing government, vendor companies, and utilities. Based on the information available, and assuming 500 new forecourt stations per year, the panel concluded the following:

- The hydrogen production technology presented is scaleable to 1,500 kg/day through a combination of scaling up existing designs and using multiple units.
- The cost estimates provided by DOE and various vendors are realistic and in line with the experience of the panel.
- It is reasonable to conclude the technologies to produce hydrogen from natural gas (reforming, hydrogen clean-up, compression, storage, and dispensing) will be mature and capable of licensing and certification resulting in short (less than three months) installation times (not including time for permitting).
- The skid-mounted-system approach (sheet metal-enclosed and fence-protected following a universal set of codes and standards as opposed to specific designs and approvals for each site) is rational given that such a design could be standardized, licensed, and certified by all the appropriate agencies, following on the safety experience gained through hydrogen handling and storage in fuel cell vehicles.
- The consumption volume of the mature hydrogen fueling industry could result in near-industrial natural gas and industrial electricity prices for most new forecourts.

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[37] *FreedomCAR and Fuel Partnership Hydrogen Delivery Technology Roadmap* (February 2007) http://www1.eere.energy.gov/hydrogenandfuelcells/delivery/pdfs/delivery_roadmap0207.pdf.

[38] U.S. Department of Energy Program Record #5013.

[39] National Renewable Energy Laboratory, *Distributed Hydrogen Production from Natural Gas – Independent Review*(October 2006), http://www.hydrogen.energy.gov/pdfs/40382.pdf, accessed May 2008

The panel used existing DOE-developed analyses as a starting point for the assessment. The above conclusions, panel experience, and input from various parties were used to evaluate, adjust, and develop the panel-defined baseline analysis. The baseline analysis, which used industrial rates for natural gas and electricity, resulted in a hydrogen total cost of $3.00 per gge. The panel performed sensitivity studies to fully understand the effects of several key parameters and associated uncertainties, and it projected a hydrogen total cost range of $2.75-3.50 per gge, confirming that DOE had met its cost goal for the distributed natural gas reforming pathway.[40] It is important to note that although the panel confirmed the $3.00 cost goal had been met, the assessment assumed on-site production of hydrogen at 1,500 kg per day. Initial technology introduction will likely not require this volume of fuel, so the cost could be higher than $3.00 per gge.

6.2 USING NATURAL GAS PIPELINE INFRASTRUCTURE FOR HYDROGEN DELIVERY

Converting natural gas pipelines to hydrogen pipelines as an approach to hydrogen delivery would present several problems:

- Current natural gas demand is high: The current U.S. natural gas pipeline infrastructure is heavily utilized and spare capacity may not exist at all times of the year.[41] Using natural gas pipelines for hydrogen would require additional natural gas pipeline to meet current demand.
- Hydrogen can permeate and embrittle certain materials: Today's natural gas pipeline infrastructure is composed of a variety of low-carbon steels. High pressure hydrogen transmission lines use only a particular grade of lower carbon steel known to work well with hydrogen.
    - Large, high pressure (~1,000 psi) natural gas transmission pipelines are made of a variety of low-carbon steels. *Older* lines are typically made of lower-strength low-carbon steels that are more ductile, resistant to third-party damage, and potentially better for delivering hydrogen. *Newer* natural gas transmission pipelines, however, are made of higher-strength low-carbon steels that are more susceptible to hydrogen embrittlement.
    - Low pressure (less than 200 psi) natural gas distribution and service lines are low-carbon steel or plastic PVC piping (most service lines are now using PVC).[42] Hydrogen can embrittle these steels; the PVC piping is not strong enough for the desired high pressure hydrogen service and has a high hydrogen leak rate.

- Hydrogen vehicles currently require high pressure storage: Current demonstration fuel cell vehicles store hydrogen gas on board at 350 bar (5,000 psi)—some newer light-duty vehicles store hydrogen gas at 700 bar (10,000 psi). To minimize compression needs for hydrogen storage at a fueling station, ideal distribution line pressure is 20 to 100 bar (333 – 1,500 psi), which is significantly higher than the typical pressures of current natural gas service pipelines that operate at less than 1 bar. Current U.S. hydrogen transmission pipelines operate at constant line pressures in the range of 20 to 80 bar (300 – 1,200 psi).
- Natural gas compressors may not be suitable for hydrogen: Both natural gas and hydrogen gas must be compressed for transport via pipeline. The centrifugal compressors used for

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[40] Ibid.

[41] *FreedomCAR and Fuels Partnership Delivery Tech Team Roadmap*, (November 2005), page 9, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/delivery_tech_team_roadmap.pdf, accessed May 2008.

[42] 2006 DOE Hydrogen Program Annual Progress Report, III.C.2, *Hydrogen Regional Infrastructures Program in Pennsylvania, Existing Natural Gas Pipeline Materials and Associated Operation Characteristics*, Concurrent Technologies Corporation; http://www.hydrogen.energy.gov/pdfs/progress06/iii_e_1_eslin.pdf , accessed May 2008.

natural gas are not suitable for hydrogen. With a low molecular weight, hydrogen causes seal design problems including contamination, vibration, and rotor dynamics issues. To achieve high pressures, hydrogen centrifugal compressors would require more stages operating at higher rotational speeds, special seals, tolerance standards, and new materials that will not embrittle in the presence of hydrogen. Alternatively, more expensive reciprocating compressors are used. DOE supports research for the development of centrifugal hydrogen compressors. DOE is also investigating electrochemical compressors that use PEM fuel cell technology, will have essentially no moving parts, and will be less susceptible to hydrogen embrittlement.

- Geologic storage of hydrogen is not fully understood: The U.S. natural gas pipeline delivery infrastructure relies heavily on bulk geologic storage. Many geologic sites have the potential to store hydrogen, however, it is an area needing further investigation.

It may be possible to use existing natural gas pipeline infrastructure to transport a blend of natural gas and hydrogen, and separate and purify the hydrogen at the point of end use. The blend could contain no more than 10 to 20 percent hydrogen, in order to meet heating value and other natural gas appliance requirements. Natural gas infrastructure capacity, materials of construction, and other issues discussed above for pure hydrogen would come into play, though possibly to a lesser extent, with such a mixture. Most importantly, analysis has shown that it would be prohibitively expensive to separate and purify the hydrogen for use in fuel cells for transportation without a major breakthrough in separation technology.[43]

Although there are problems with using existing natural gas pipelines for hydrogen delivery, a *hydrogen* pipeline infrastructure would be the most cost-effective option for delivery from central production facilities. DOE's hydrogen delivery R&D effort includes research to better understand hydrogen embrittlement and the potential for using lower-cost composite pipelines, research to develop improved compression technology specific to hydrogen, and research to fully understand the potential for geologic hydrogen storage. Among the challenges for developing a hydrogen pipeline infrastructure is pressure. The current hydrogen pipeline infrastructure operates at nearly constant pressures to avoid failures due to embrittlement. When the number of end users increases, the pressure will fluctuate and lead to possible fatigue failures. The Program is investigating new materials, including composites and new steels, to address this challenge.

Another promising approach for hydrogen delivery is to use pipelines for transport from the plant to the city gate, from which it could be distributed to fueling sites in gaseous tube trailers. With technology under development that could increase the hydrogen-carrying capacity of tube trailers, this option could avoid the disruptive construction and safety concerns of urban hydrogen distribution pipelines and could allow for a cost approaching that of a pure pipeline system (which is essentially how gasoline is delivered today).

6.3 CONVERTING NATURAL GAS FUELING STATIONS TO ACCOMMODATE HYDROGEN

In February 2004, the California Energy Commission (CEC) published a report prepared by TIAX, LLC, examining requirements for combining natural gas and hydrogen fueling. The study concludes that "in some, but not nearly all cases, it is feasible to convert an existing CNG fueling station to hydrogen." It also suggests that when planning new stations, "in most cases it is feasible to design the station so that it can dispense both CNG and hydrogen, or so that it can be converted from CNG to hydrogen at some time

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[43] 2006 DOE Hydrogen Program Annual Progress Report, III.C.2 *Hydrogen Delivery Infrastructure Options Analysis*, Nexant Inc., http://www.hydrogen.energy.gov/pdfs/progress06/iii_c_2_chen.pdf, accessed May 2008.

in the future."[44]

As the report notes, the feasibility of converting a CNG station to hydrogen or adding a hydrogen fueling capability to an existing CNG station depends heavily on the individual site. Differences in fuel properties, dispensing requirements, supply, equipment specifications, and codes and standards affect both the technical feasibility as well as the economics of co-locating CNG and hydrogen fueling. Key issues are:

- Fuel properties: CNG and hydrogen are both gaseous fuels with several properties in common (e.g., both are lighter than air and non-toxic). Many of their properties are different, however, and require different safety systems at the fueling site to prevent an unintended release or mitigate the effects of a release.
    - Odorants: Hydrogen has no odor. CNG is also odorless, but industry adds a sulfur-containing odorant so people can detect the gas. Currently, however, odorants cannot be used with hydrogen, as there is no known odorant light enough to move at the same speed as hydrogen, at the same dispersion rate. Current odorants also contaminate fuel cells.
    - Flammability range and ignition energy: Hydrogen's flammability range is very wide compared to CNG and other fuels, and it has a lower ignition energy than CNG. Under optimal combustion conditions (at a 29 percent hydrogen-to-air volume ratio), the energy required to initiate hydrogen combustion is much lower than that required for CNG.
- Dispensing conditions: CNG is usually dispensed at 3,600 psi, whereas hydrogen is typically dispensed at 5,000 psi, and, as noted earlier, newer demonstration vehicles use 10,000 psi storage.
- Supply conditions: With the exception of liquefied/compressed natural gas (L/CNG), CNG is supplied at various pipeline pressures. Hydrogen is also supplied at different pressures that depend on the method of delivery (tube trailer, liquid hydrogen tank, reformer, or electrolyzer).
- Codes and standards: Codes and standards for CNG fueling stations are well established, but hydrogen-specific codes and standards remain under development. Hydrogen fueling stations require different set-back distances, for example, which can complicate layouts for converting stations to offer hydrogen.

Although there are challenges to converting CNG fueling stations to accommodate hydrogen, the report suggests that new CNG station planning consider future interests in hydrogen fueling capability:

> "As a minimum, the site utilities and civil work should be planned to accommodate future hydrogen equipment (e.g., electric service and high-pressure piping), and the site layout should accommodate code-compliant installation of this equipment."[45]

6.4 POTENTIAL EFFECTS ON OVERALL NATURAL GAS DEMAND

Although fuel cell technology readiness—primarily issues related to cost and durability—will affect the timing of fuel cell school bus deployment, DOE analyzed the effects of fuel cell school bus deployment on overall U.S. natural gas demand, should buses deployed in the future require hydrogen produced from natural gas. The impact is described in the section below.

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[44] California Energy Commission/Consultant Report, *Requirements for Combining Natural Gas and Hydrogen Fueling* (February 2004), page 5-1.

[45] California Energy Commission/Consultant Report, *Requirements for Combining Natural Gas and Hydrogen Fueling* (February 2004), page 5-2.

Analysis Scenarios

The analysis considered three scenarios to determine the impact of fuel cell school buses on U.S. natural gas infrastructure, assuming the buses fuel with hydrogen produced by distributed reforming of natural gas. The scenarios are based on the year 2000 school bus fleet that included 458,000 school buses, as noted in the 2001 report, *Analysis of U.S. School Bus Populations and Alternative Fuel Potential*, which examined scenarios for converting school buses to other alternative fuels.[46]

- Scenario 1: This option would achieve approximately 4 percent market penetration of 458,000 school bus fleet in eight years. At this penetration, the school bus fleet would include 17,000 fuel cell buses.
- Scenario 2: This option would achieve approximately 6 percent market penetration of the 458,000 school bus fleet in eight years. At this penetration, the school bus fleet would have 27,000 fuel cell buses.
- Scenario 3: This option examines the hydrogen required if the entire school bus fleet of 458,000 buses is converted to use hydrogen fuel cells.

Calculations and Results

To determine the hydrogen required and resulting natural gas demand, this analysis assumes each fuel cell school bus travels 8,950 miles annually and achieves a fuel economy of 10 miles per gallon equivalent of hydrogen (with fuel cell systems enabling a 50 to 70 percent improvement over conventional buses that achieve a fuel economy of 7 miles per gallon). Results are summarized in Table 6 below.

Deployment Scenario	Market penetration/ number of buses	Annual hydrogen requirement (kg)	Annual natural gas requirement (standard cubic feet/year)	Annual natural gas demand increase
Scenario 1	4% or 17,000 buses	15 million	2.5 billion	0.01%
Scenario 2	6% or 27,000 buses	24 million	4.1 billion	0.02%
Scenario 3	100% or 450,000 buses	410 million	69 billion	0.3%

Table 6. *Effects of Deployment of Fuel Cell Buses Using Hydrogen Produced by Distributed Natural Gas Reforming on Overall U.S. Natural Gas Demand*

The increase in natural gas demand for the scenarios described above would not significantly impact the natural gas infrastructure, as indicated by a separate analysis performed by Energy, Environmental Analysis, Inc (EEA).[47] EEA examined the impact of various market penetration scenarios on overall U.S. natural gas demand, assuming the hydrogen required is produced using natural gas. EEA determined that a 15 percent market penetration by 2025 (11.7 million light-duty fuel cell vehicles) would require approximately 440 billion standard cubic feet/year of natural gas. This is approximately two percent of U.S. annual natural gas demand, and therefore would have minimal impact on the national gas infrastructure.

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[46] M. Laughlin, *Analysis of U.S. School Bus Populations and Alternative Fuel Potential*, ANTARES Group, Inc. (April 2004), DOE/GO-102004-1871, http://www.nrel.gov/docs/fy04osti/35765.pdf, accessed May 2008.

[47] H. Vidas, Energy & Environmental Analysis, Inc., *Initial Look at Potential Natural Gas Infrastructure Constraints Related to the Transition to Hydrogen Transportation Fuels*, prepared for Fred Joseck, U.S. Department of Energy, September 13, 2006.

7. Conclusion

Fuel cells offer great promise. They use hydrogen that can be produced using a variety of abundant and domestic energy resources, which contributes to national energy security goals. When hydrogen fuel cells are used to power a vehicle, the only output from the tailpipe is water—there are no greenhouse gas or criteria emissions from the vehicle that contribute to climate change or affect air quality. Fuel cell vehicles also can achieve more than two times the efficiency of traditional combustion technologies, which can translate to fuel consumption reductions of more than 50 percent compared to a conventional vehicle with a gasoline internal combustion engine. In addition, on a well-to-wheels basis, which accounts for the energy in fuel production and delivery, a fuel cell vehicle using hydrogen produced from natural gas would consume approximately 12% less energy than a gasoline hybrid-electric vehicle and approximately 43% less energy than a conventional gasoline internal combustion engine vehicle.

Although there are a number of fuel cell products available today for select niche applications (e.g., material handling equipment, stationary backup power, prime power for critical power needs such as data centers, and portable power), fuel cells for transportation face several critical barriers to commercialization (see Appendix for additional early market information). Reducing cost and improving durability are among the most significant challenges. DOE research has made significant progress over the last several years. As an example, automotive fuel cell costs have dropped from $275/kW in 2002 to $73/kW in 2008 (projected cost that assumes high volume production of 500,000 units per year). Additional R&D is needed for fuel cells, however, to compete with conventional technologies, particularly for transportation applications.

Ongoing transit bus demonstrations that provide data on vehicle operation, maintenance, and cost indicate that progress is being made toward practical and more affordable fuel cell buses, but significant challenges to commercialization remain. For example, information collected from the transit bus demonstration efforts shows that the buses in these activities traveled over 150,000 miles and achieved efficiencies of up to twice that of conventional buses. However, the buses have capital costs that are an order of magnitude more expensive and reliability levels are about a tenth of conventional buses.

School bus operators are increasingly receptive to new technologies that can provide a clean and safe option for transporting the Nation's children to and from school. With water as the only tailpipe emission, fuel cell buses may offer an attractive option, but school bus operators must balance their willingness to demonstrate new technology with strict financial and operational considerations, especially in times of increasingly tight budgets at the state and local level. Many school districts do not have the resources to serve as demonstration sites for technology at the considerable expenditure of time and money that these projects require. The customers they serve seek reliable transport for their children at the most efficient possible expenditure of tax dollars, and advanced technology demonstrations do not always fit with these priorities.

The transit industry, however, is well suited to early technology demonstration, in part because of the significant (up to 80%) capital cost subsidy provided by FTA—funding that is applicable to the initial purchase of advanced technology vehicles as well as conventional vehicles. Additionally, unlike school districts, many transit agencies have bus fleets of sufficient size to meet daily ridership needs with a portion of the fleet, so having a demonstration fuel cell bus that is available only for special events or limited service is less of an issue.

Demonstration and deployment efforts for other alternative fuels have focused initially on the transit bus market before attempting to influence the school bus market. Natural gas vehicle demonstrations began with transit buses and then expanded to the school bus market when engine, refueling, and gas storage technologies advanced to the point where it was sufficiently cost-effective for school bus operators to invest in technology adoption. FTA provided more than $185 million in support for compressed natural gas buses from 1988 to 1990. Compressed natural gas is now the most common alternative fuel in transit buses, and the natural gas school bus market has expanded to the point of more than 4,000 natural gas buses operating throughout the U.S.[48] Hydrogen fuel cells for buses could follow a similar path of development, demonstration, and deployment. FTA developed an electric drive strategic plan to identify gaps and focus future activities in electric drive and fuel cell bus technology. Under the NFCBP, FTA set performance goals for fuel cell bus technology, including vehicle cost of no greater than five times that of a commercial transit bus, durability for the fuel cell propulsion system of 20,000 to 30,000 hours, and fuel efficiency performance double that of a commercial transit bus by the year 2012. These goals will keep efforts focused on overcoming critical cost and durability barriers, and the program's data collection and evaluation component will provide key lessons learned with particular respect to fuel cell bus operation that will help to assure the successful implementation of a future fuel cell school bus program.

Distributed natural gas reforming (on-site production at the point of end use) can be a cost-effective pathway for near-term hydrogen fuel cell vehicle deployment. An extensive natural gas delivery infrastructure already exists and natural gas-to-hydrogen production technology is relatively mature. DOE research achieved its hydrogen cost goal of $3.00 per gge for distributed natural gas reforming. CNG refueling stations can be modified to accommodate hydrogen dispensing, but there are challenges. Differences in fuel properties, dispensing requirements, supply, equipment specifications, and codes and standards affect both the technical feasibility as well as the economics of co-locating CNG and hydrogen fueling.

Robust hydrogen fuel cell vehicle deployment efforts over the longer term will require a more extensive hydrogen pipeline infrastructure to deliver hydrogen from central and semi-central production facilities to points of end use. Although more than a million miles of natural gas pipeline operate today, natural gas transmission and distribution pipelines are not suitable for hydrogen transport. This is due primarily to materials compatibility problems. For example, hydrogen can permeate and embrittle many of the steels used for natural gas pipeline. Other issues include differences in compression requirements as well as overall pipeline infrastructure capacity.

After evaluating fuel cell technology readiness status, carefully reviewing the progress of fuel cell transit bus development activities, and with an understanding of school bus owner and operator requirements for cost and performance, DOE elected not to implement a fuel cell school bus development and demonstration program at this time. There may be a potential for a fuel cell school bus program in the 2012 to 2015 timeframe to align with timelines for achieving fuel cell transit bus performance objectives and fuel cell technology readiness targets. Continued DOE support of FTA efforts under the NFCBP, in parallel with fuel cell R&D efforts, is intended to push the technology forward, address key barriers, and provide valuable lessons learned for a future school bus market. This path, which has shown great success for other alternative fuel technologies such as natural gas, has the potential to provide cost-effective and timely benefits for future fuel cell vehicle users.

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[48] Union of Concerned Scientists, *School Bus Pollution Report Card 2006*, page 30, http://www.ucsusa.org/assets/documents/clean_vehicles/pollution-report-card-2006.pdf, accessed May 2008.

Appendix: Early Markets for Hydrogen and Fuel Cells

DOE's efforts to bring fuel cell technology to the commercial marketplace extend beyond R&D and technology validation to include market transformation activities. Through partnerships with other Federal agencies, state and local government entities, and the private sector, DOE seeks to facilitate technology adoption in early markets to create economies of scale that can reduce cost and lay groundwork for a domestic supplier base. Early adoption can also raise public awareness and inform a broad array of investors and potential users of technology status and the performance characteristics of various fuel cell systems. DOE's market transformation strategy includes performing analysis of hydrogen and fuel cell markets, developing hydrogen and fuel cell manufacturing technologies, building partnerships with government and private-sector entities, and developing and disseminating educational materials and training to key target audiences with a role in early technology adoption.

The U.S. Fuel Cell Council maintains a list of more than 40 commercially available fuel cell products—several of which are on the General Services Administration (GSA) Schedule for purchase by Federal agencies.[49]

In an April 2007 report commissioned by DOE, Battelle Memorial Institute evaluated and identified key early markets for PEM fuel cells.[50] Forklifts and related material-handling equipment at high-throughput distribution centers were identified as an important near-term market, based on the need for lower emissions, longer runtimes, and continuous performance as compared with conventional hydrocarbon or battery powered forklifts. Analysis shows that PEM fuel cells can provide value over incumbent technologies for indoor applications by offering longer runtimes than batteries, thus increasing productivity and reducing operation and maintenance costs. The market for forklifts was $3.2 billion in 2003 and is projected to grow to $5.2 billion in 2013. Current and projected market share of battery-powered forklifts is approximately 58 percent of the total forklift market. While lead-acid batteries are a known technology and are fairly reliable, there are concerns with operation and maintenance, issues with power loss as the batteries discharge, and downtime during battery change-outs or recharging. Compared to battery-powered forklifts, demonstrations show that fuel cells offer longer runtime, faster return to service, and no decrease in power capability during the operating shift. Compared to internal combustion engine powered forklifts, fuel cell forklifts offer zero emissions and quieter operation. From a lifecycle cost perspective, PEM fuel cell powered forklifts require significantly less investment (calculated as net present value of costs) than battery powered forklifts under conditions of near-continuous use. While fuel cell powered forklifts require more initial capital investment than battery-powered forklifts, they require less investment in operation and maintenance over their lifetime.

The emergency response market also represents a promising early niche for PEM fuel cells as a backup power source at radio tower sites. Many states are considering mandating backup power at call centers and radio tower sites. Various user requirements, such as system size, reliability and ease of use, fit well with the performance of PEM fuel cells relative to alternatives. PEM fuel cells offer many advantages over incumbent technologies. Compared to batteries, fuel cells offer a longer continuous run-time; compared to generators, fuel cells have lower maintenance requirements since they have fewer parts, they can be monitored remotely, reducing actual maintenance time, and they have lower emissions. Financial

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[49] U.S. Fuel Cell Council, *Commercially Available Fuel Cell Product List*, http://www.usfcc.com/resources/outreachproducts.html, accessed May 2008.

[50] Battelle Memorial Institute, *Identification and Characterization of Near-Term Direct Hydrogen Proton Membrane Fuel Cell Markets* (April 1007), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf, accessed May, 2008.

incentives, demonstration projects, and fuel availability will be critical for fuel cells to compete effectively with current backup power technologies for radio towers. Adoption of hydrogen and fuel cell technologies across Federal and state governments in these areas will act to stimulate the much larger industry markets. For example, the Federal Aviation Administration (FAA) has approximately 15,000 radio tower sites across the U.S. that require backup power. Fuel cell penetration into this market could ultimately lead to penetration into the much larger telecommunications industry, which includes approximately 250,000 telecommunication towers.

Key early markets for non-PEM fuel cells include portable power and applications with critical power needs, such as data centers. Direct methanol fuel cells (DMFCs), for example, are well-suited for consumer electronic devices, which have low power requirements and infrastructure needs that are less stringent that those for transportation. To enable early market entry of fuel cells for portable power, DOE's Hydrogen Program is working in collaboration with industry to develop and field test DMFC prototypes for consumer electronics. These systems must be cost-effective, reliable, and durable to meet the demands of power needs for applications such as cell phones and lap top computers. Commercialization of DMFC applications will help establish a domestic supplier base for critical manufactured components, such as membrane electrode assemblies, that are vital for PEM fuel cell market introduction. The Hydrogen Program is also coordinating its activities with the Department of Defense, which supports the development of portable power systems for military applications including field battery recharging and auxiliary power, which may be significant, early DMFC markets.

Combined heat and power (CHP) fuel cell systems can provide energy efficient, high quality, and reliable electricity with significantly reduced greenhouse gas emissions compared to other commercially available on-site power generation technologies. A large and rapidly growing early market segment for stationary fuel cells in the 300kW to 500kW range (as individual units or in series) includes facilities with critical loads supporting information technology computing operations called data centers, as well as security, financial, business, and healthcare operations, and vital national communication networks. Supporting this potential demand, a study by the Edison Electric Institute projects that by the end of 2009, both the U.S. and Canada will fall below the recommended generation margins that are necessary to ensure a reliable supply of grid delivered electricity.[51] Underscoring the timely nature of the match between CHP fuel cell systems and the early market opportunity for critical load power generation, when the Northeast Blackout of 2003 resulted in the loss of 61,900 MW of electric load servicing more than 50 million people and is estimated to have cost the economy between $7 and $10 billion,[52] the New York City Central Park Police Station, running on a series of fuel cells installed in 1999, did not know that the rest of the city had gone dark until it started receiving calls for assistance. As part of its market transformation efforts, the Hydrogen Program is working to identify early deployment opportunities, educate potential users with critical power needs about fuel cells, and build partnerships between fuel cell manufacturers and early adopters.

DOE's hydrogen and fuel cell market transformation activity seeks to move technologies from the laboratory to the hands of users in key early applications to ultimately achieve the economies of scale needed for price reductions, thereby enabling widespread use of fuel cells in more cost-sensitive applications, such as transportation. This experience will also seed an eventual fuel cell school bus market and enable it to grow more quickly than it may have done otherwise.

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[51] Edison Electric Institute, *Critical Issues Facing Federal Customers and the Electric Industry; A Call to Partnering*, November 2007.

[52] U.S.-Canada Power System Outage Task Force, *Causes of the August 14th Blackout: Interim Report*, November 2003, and ICF Consulting, *The Economic Cost of the Blackout: An Issue Paper on the Northeastern Blackout*, August 2003.