Fuel Cell Transit Buses

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Introduction

This report summarizes the current status of the fuel cell bus technology, primarily in the U. S. and North America, but it also includes a brief review of fuel cell bus projects in other countries.

Overview

Fuel cell-powered buses continue to be demonstrated in transit service at various locations in the U. S. and elsewhere. To promote consistency in performance requirements, the U. S. Departments of Energy and Transportation (DOE, DOT) issued a joint request for information (RFI) in May 2011 to seek input from industry stakeholders and the research community on what should be the targets for performance, durability, and cost for transit buses powered by fuel cells, and for the fuel cells in those transit buses. The DOE engages in fuel cell RD&D for a variety of stationary, portable power, and transportation applications; the DOT has established a National Fuel Cell Bus Program (NFCBP) under the Federal Transit Administration (FTA) to promote the advancement of fuel cell electric buses.

Based on the responses to the RFI, DOE and DOT have developed the bus and fuel cell power plant targets shown in Table 1. The 2011 status of fuel cell transit buses being demonstrated is shown in the last column of Table 1. The sections below provide more information on the current status of the various parameters in Table 1.

In mid-2011, there were 25 fuel cell transit buses in operation in the U. S. that included 18 Van Hool buses with UTC Power fuel cells, 1 New Flyer bus with a Ballard fuel cell, 2 Proterra plug-in hybrids with Hydrogenics fuel cells, 3 Ebus plug-in hybrids with Ballard fuel cells, and 1 Daimler/BAE diesel hybrid with a Hydrogenics fuel cell auxiliary power unit (APU). Table 2 shows some of these buses. Seven additional buses are planned to be added to the transit bus demonstration fleet as part of FTA's NFCBP. These buses will use Ballard and Nuvera fuel cells in combination with advanced lithium-ion batteries for energy storage and regenerative braking.

From the U. S. demonstrations, it has been observed that with the next generation of buses entering service, planned service times are increasing (to 19 h/day, 7 days/week), reliability is improving (one FC system has operated for >10,000 h, with two more with >6,500 and >5,500 h) with the MBRC for FC systems being >10,000 for most buses (see Fig. 1). Also, as shown in Fig. 2, fuel economies for the fuel cell buses are consistently better than the baseline buses (diesel buses operated over the same or similar routes). With average fills of 22.5 kg H_2 for FC dominant and 11 kg H_2 for battery dominant buses, more than 101,000 kg of H_2 have been dispensed successfully without any fueling incidents. Challenges remain, however, for the full commercialization of fuel cell buses, primarily in achieving the durability and cost targets.

Table 1. Proposed DOE/DOT targets for fuel cell-powered transit buses in the U. S.

Parameter	Units	Target Value	2011 Status
Bus Lifetime	years / hours	12 / 50,000[a]	TBD
Power Plant Lifetime	years / hours	6 / 25,000[b]	6 / 10,000
Bus Availability	%	90[c]	70
Fuel Fills	per day	1 (<5 min)[d]	1
Bus Cost	$	600,000[e]	2,000,000
Power Plant Cost	$	200,000[e]	1,000,000
Road Call Frequency (All / Power Plant)	MBRC	4,000 / 10,000	1,900 / 2,400
Operating Time	hours per day / days per week	20 / 7	19 / 7
Operating Cost	$/mile	0.38[f]	0.47
Range	miles	300	>300
Fuel Economy	mpgde[g]	8	6.5

[a]Based on RFI responses
[b]Assuming one power plant rebuild during the vehicle's lifetime
[c]For comparison, value for diesel buses is 85%, with 95% achievable by 2020
[d]With an upper bound of 10 min
[e]Cost needed to be competitive with alternatives
[f] Including routine maintenance, but excluding fuel and mid-life overhaul
[g]mpgde: miles per gallon diesel equivalent (lower heating value basis)

Table 2. Some of the fuel cell buses currently in transit service in the U. S.

	Van Hool bus with UTC Power fuel cell
	New Flyer/Bluways bus with Ballard fuel cell
	Proterra bus with Hydrogenics fuel cell (plug-in, battery dominant)

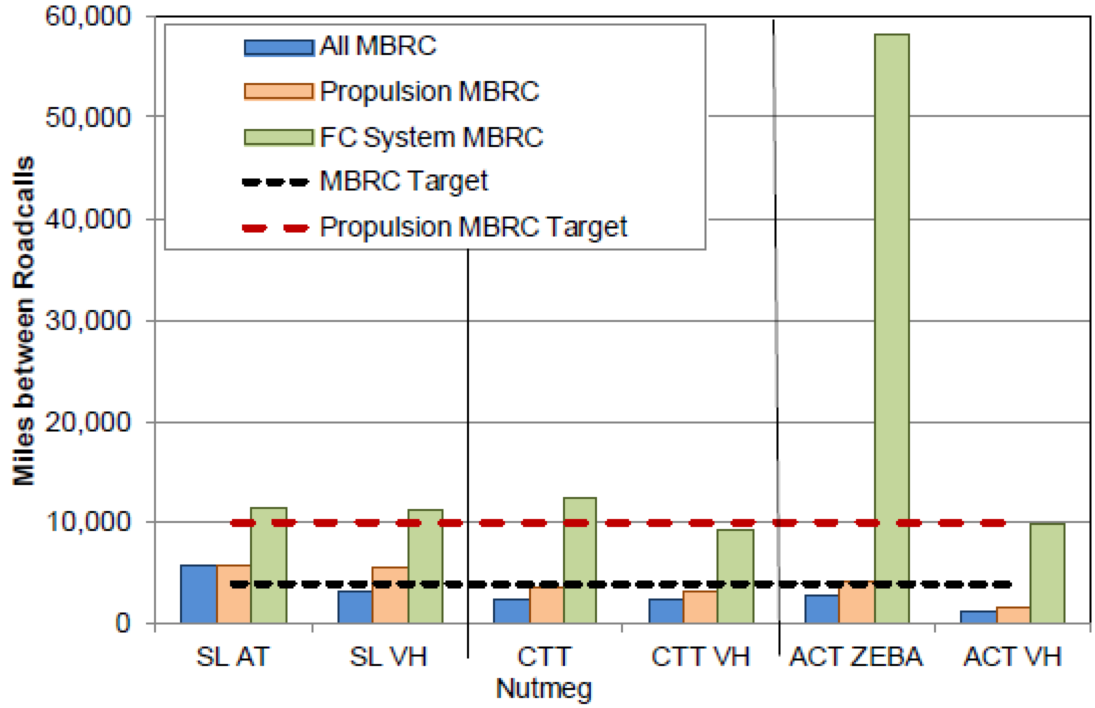

Fig. 1. Miles between road calls (MBRC) experience for fuel cell and baseline buses in the U. S. transit fuel cell fleet (see Abbreviations and Acronyms section for nomenclature).

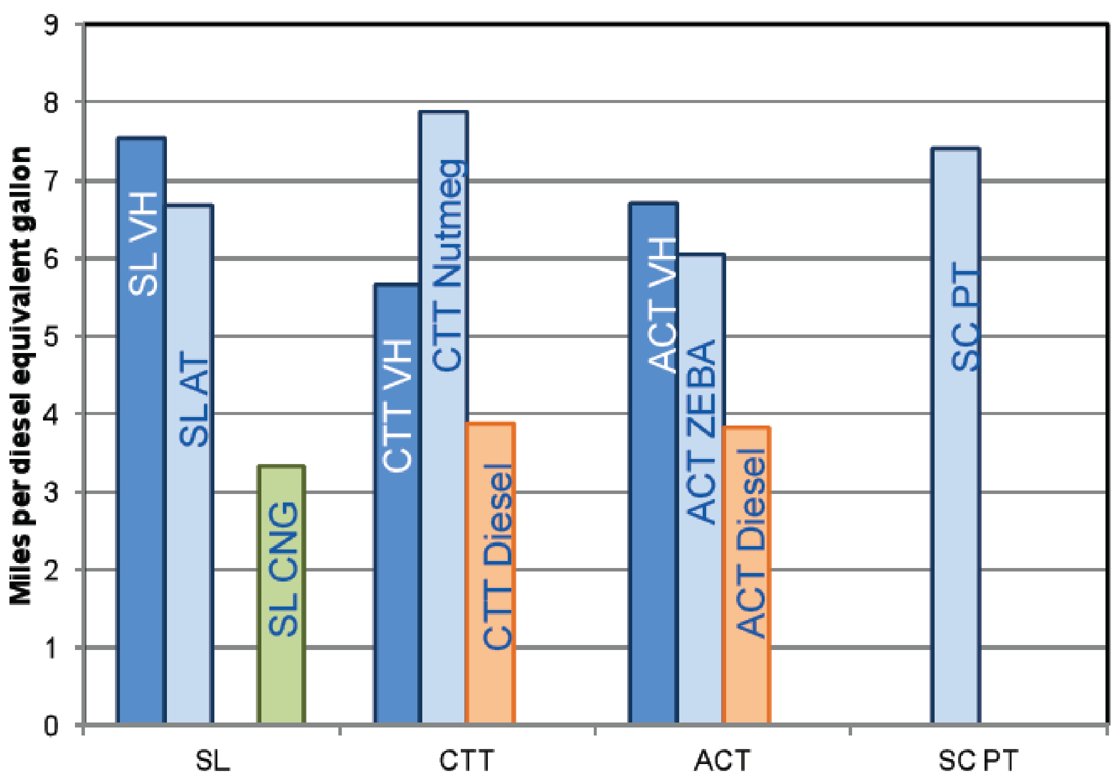

Fig. 2. In the U. S. demonstrations, the fuel cell transit buses have consistently achieved higher fuel economies than the corresponding diesel or CNG baseline buses (see Abbreviations and Acronyms section for nomenclature).

Outside the U. S., BC Transit in Vancouver, British Columbia, Canada, is acquiring the 20 fuel cell bus fleet (and its associated fueling systems) that has been providing transit service in the resort municipality of Whistler, Canada, since the February 2010 Winter Olympic and Paralympic Games. This fleet with Ballard fuel cells has already logged a combined 1,300,000 km, with a minimum of 43,600 km and a maximum of 72,000 km per bus. On some of the mountainous routes in Whistler, the fuel cell buses were unable to maintain highway speeds ($\geq$80 km/h) on >6% grades of one kilometer or longer, with the result that they could not be used on three of the Whistler routes. Performance of the fuel cell buses on the other Whistler routes was very positive, however, with strong driver and user support.

Some of the ongoing and planned Ballard fuel cell bus projects outside North America include 8 buses for Transport for London's CHIC Programme (75-kW FC with ultracapacitors, 2010–2014), 1 bus for EMTU, Sao Paulo, Brazil (150-kW FC, 2010–2012), and 5 buses for Ruter#, Oslo, Norway (150-kW FC, 2011–2016).

In Europe's CHIC (Clean Hydrogen In European Cities) Project, 26 buses will be put into daily passenger service in five locations: Aargau (Switzerland), Bolzano/Bozen (Italy), London (UK), Milan (Italy), and Oslo (Norway). Staged introduction and build-up of the bus fleets and the supporting H_2 fueling stations will facilitate a smooth integration of the fuel cell buses into Europe's public transport system, leading to full commercialization of these buses starting in 2015:

- Phase 0: Hamburg, Cologne, Berlin, Whistler (Canada); a total of 37 fuel cell buses.
- Phase 1: Aargau, Bolzano/Bozen, Milan, London, Oslo; a minimum of 26 fuel cell buses.
- Phase 2: 14 regions in France, Spain, UK, Germany, the Netherlands, Belgium, Italy, Finland, Sweden, Czech Republic, Slovenia, Hungary, and Poland.

In China, a fleet of more than 50 fuel cell buses shuttled athletes and government officials to various venues of the Asian Games in Guangzhou City during November and December 2010. At the 2008 Olympic Games, 2 fuel cell buses transported athletes in Beijing.

In Japan, 3 Toyota-Hino fuel cell buses shuttle passengers between the terminal and the airplanes on the tarmac at Nagoya, Japan's Centrair Airport. In September 2005, 8 Toyota-Hino fuel cell buses were deployed as shuttles at the Aichi Expo.

In Korea, a Hyundai fuel cell bus has operated since 2006 in routine service in metropolitan Seoul and Jeju Island. Hyundai has a contract with Seoul to start supplying multiple fuel cell buses starting in 2013.

Status of Technology

Technology

Fuel cells for transit buses are being developed by many developers, who, working with system integrators and bus manufacturers, are supporting a variety of fuel cell transit bus operations at several different locations around the world. Some technical highlights of these fuel cell systems and the transit buses are given below.

- The Ballard FCvelocity®-HD6 delivers 150 kW (or 75 kW) gross power with a system weight of 400 kg and offers a 12,000-h, 5-year warranty. The system includes air

humidification, H_2 recirculation, condenser for water management, and CAN and power supply connections.
- The Ballard HD-6+ available in 2014 will offer 24,000-h durability and 15–20% cost reduction, and HD-7 available in 2015 and later will offer 36,000-h durability and 35–40% cost reduction (which will be needed to meet the FC bus target of $750,000/bus).
- The UTC Power PureMotion™ fuel cell power system delivers 120 kW net with an efficiency of >46% at the rated power. This ambient pressure system has a transient ramp up capability of 24 kW/s.
- The Hydrogenics HyPM® HD 16 fuel cell system (used in the Proterra battery-dominant fuel cell buses)delivers 16 kW at a peak net efficiency of 53%, with a transient capability of idle to peak power in less than 5 s. Hydrogenics has also developed 30-, 90-, and 180-kW systems for buses and other heavy-duty applications.
- For the earlier generation fuel cell buses used in Whistler, Canada, transit service in 2010 and 2011, preventive maintenance requirements were manpower intensive, averaging 2.4 h/1000 km (compared to 0.8 h/1000 km for diesel buses). The batteries in the hybrid power systems needed to be balanced once a month, with up to 8 h of down time, which had a significant impact on bus scheduling.

Efficiency

All fuel cell transit buses have shown higher fuel economies than the corresponding diesel and CNG baseline buses in similar service. The fuel economies are highly dependent on the site's topography and transit duty cycles.

- The projected well-to-wheels efficiencies of various fuel/technology pathways are:
  - Battery EV: 40% from natural gas, 22% from coal
  - Diesel ICE: 26%
  - Fuel cell with H_2 from reformed natural gas: 24%
  - Compressed natural gas ICE: 22%
  - Fuel cell with H_2 from electrolysis: 6%–11% (non-renewable electricity)
- The 12-bus AC Transit HyRoad fuel cell bus project (San Francisco Bay Area) has a target fuel economy of 2 X diesel, and has achieved 1.7 X diesel. Improvements in bus performance have been helped by a 5,000-lb weight reduction in the vehicle and its sub-systems.
- The UTC Power's PureMotion® fuel cell system-based bus fleets have shown 6.5 to 8.0 mpgde in California and 6.0 to 10.0 mpgde in Connecticut, nearly double the fuel economy of corresponding diesel-hybrid buses.
- The Proterra battery-intensive fuel cell hybrid has fuel cell efficiencies of 55% peak and 50% average. The DC-DC converter efficiencies are 94% peak and 90% average, and the complete fuel cell APU is 45% efficient. Combined with >80% efficient drive train (battery 98.5%, traction motor 85%) and 85% efficient hotel loads, the overall system has an efficiency >55% with the 32-kW Hydrogenics fuel cells.
- The fuel cell buses with Ballard fuel cells used in Whistler, Canada, for the 2010 winter Olympics had an average fuel consumption of 13.27 kg/100 km in 2010, and 14.3 kg/100 km in 2011 (with the added weight of 8 H_2 storage tanks for increased range versus 6 tanks during 2010).
- With over 48,000 miles accumulated through mid-September 2011, the CHIC program in London, UK, has observed the day-to-day fuel efficiency for the fleet varying between 8 and 10 kg H_2/100 km, which represents more than a factor of 2 improvement since the

CUTE project, and it is also better than the target of 11–13 kg H_2/100 km that was set at the start of the CHIC project.

- In February and March 2008, over 24 days that logged 3,880 miles, the Golden Gate Transit fuel cell bus averaged 8.57 miles/kg H_2 (11.7 kg H_2/100 km) with no road failures; in July 2009, the Marin County Fair fuel cell shuttle bus logged 862 miles with an estimated fuel economy of 7.37 mile/kg H_2 (13.6 kg H_2/100 km).

Maturity (Performance, Durability, and Availability)

Since 2005, fuel cell transit buses have undergone significant evolution in fuel cell technology, bus integration, weight reductions, and performance enhancements. Given below are examples of the continuing maturation of this technology.

- With 12 buses delivered, the AC Transit HyRoad Project in the San Francisco Bay area is showing availability of >90%, and fuel cell stack lifetimes of >10,400 hours and climbing.
- Comment from a 30-year veteran Golden Gate Transit bus driver, after driving the latest Van Hool bus, "They're like Disneyland in the real world."
- Fuel cell buses have been and are being demonstrated in a wide range of climatic conditions, varying from the very hot desert climate of Palm Desert, CA, to the very cold and snowy Chicago, IL (ElDorado buses with 150-kW HD-6 and HD-6+ Ballard fuel cells).
- With fleet experience of over 670,000 miles, the 18-bus UTC Power fuel cell bus fleet is currently in revenue service in California and Connecticut. There have been no fuel cell-related causes for bus unavailability for over 12 months. The overall fuel cell power system availability has exceeded 95% and over 15,000 MBRC. With the new generation of PureMotion® 120 fleet, the MBRC for the fuel cell system is approaching 60,000.
- For the 20-bus fleet in service in Whistler, Canada, in the first year of operations (February 2010 to February 2011), the average daily roll-out availability was 72%, with an all-day availability of 65%, both of which improved slightly during the second year (January to August 2011) to 76% and 68%, respectively. The availability was limited by component failures (control boards, auxiliary heaters) rather than any issues with the fuel cell stack. Operating experience from April 2010 to September 2011 showed brief periods of 100% availability, but also brief dips to 45% availability for the fleet as a whole.

Cost

The results of a cost analysis by BAE Systems are given in Table 3, which shows the approximate premium cost of current fuel cell alternatives over the baseline $325,000 for a conventional diesel bus. Market development and viability studies by BAE Systems show the inverse relationship between fuel cell transit bus cost and the number of buses manufactured, over a project time scale, as shown in Fig. 3. Cost estimates by Ballard, Fig. 4, show a gradual reduction in fuel cell bus capital costs over the years and technology advancements. The corresponding fuel costs are shown in Fig. 5.

Table 3. Cost metrics for fuel cell and alternative transit bus architectures

Architecture	FC Bus Premium over $325 K Diesel Bus
Propulsion Fuel Cell	$1,475,000
Battery EV	$575,000
FC APU [Diesel (CNG)]	$375,000 ($425,000)
Hybrid / EA [Diesel (CNG)][a]	$225,000 ($275,000)
Conventional / EA [Diesel (CNG)]	$50,000 ($100,000)
CNG Conventional	$50,000

[a] Electric accessories

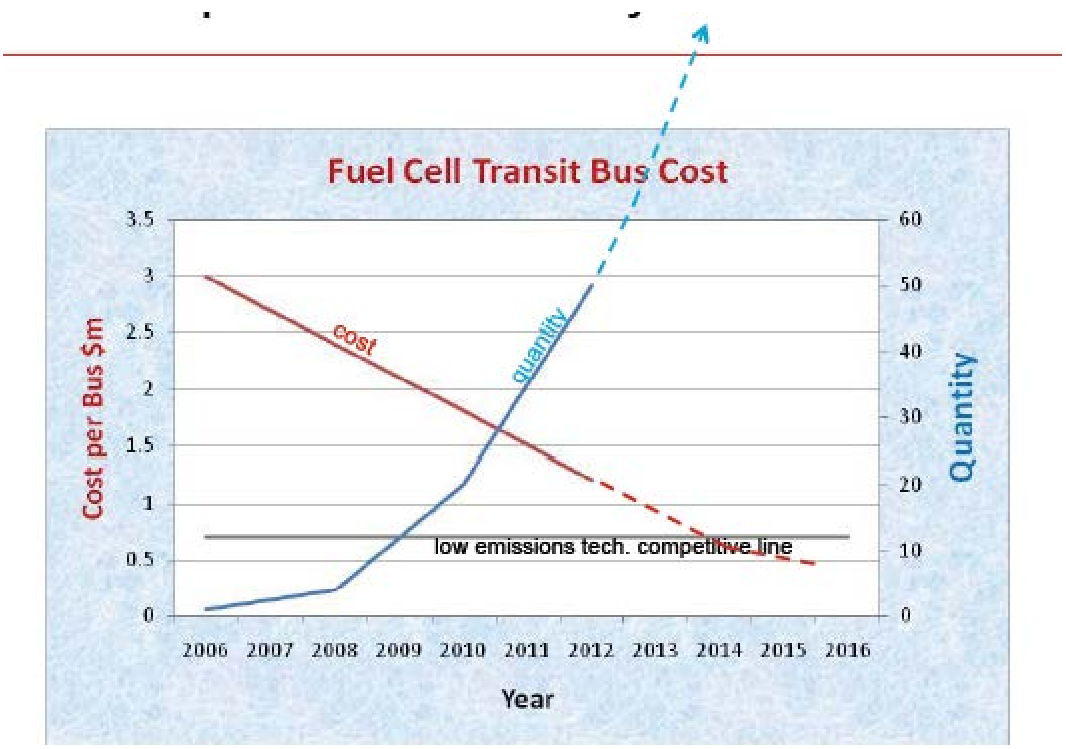

Fig. 3. Fuel cell transit bus cost versus number of buses over time (BAE Systems). Multiple fleets of >100 fuel cell buses will be needed to drive costs to a competitive range. The costs shown are drive-away costs, and they do not include operating and maintenance costs. Current cost, at 20-bus fleets, is approximately $1,200,000/fuel cell bus.

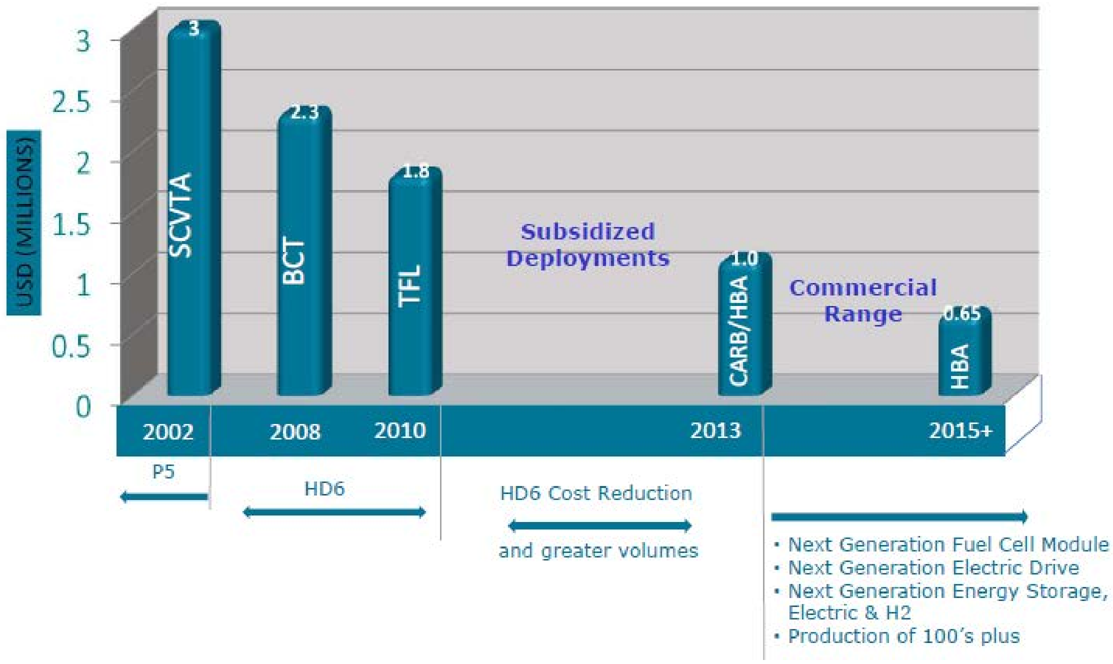

Fig. 4. Capital costs of Ballard fuel cell transit buses over the past decade, and future projections (and improvements needed to meet these projections). Commercial volumes of manufacture are projected to lower costs to $650,000/fuel cell bus.

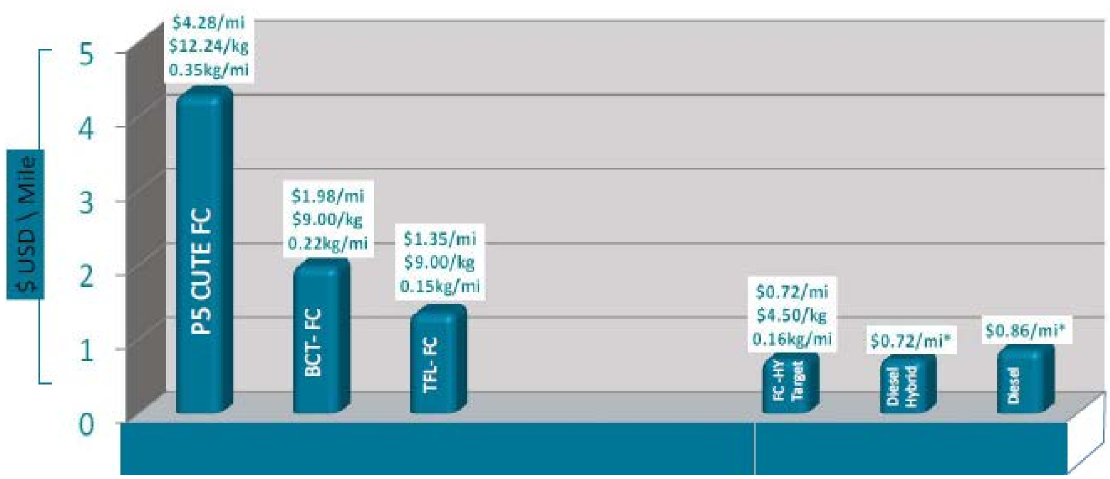

Fig. 5. Fuel costs for fuel cell and diesel/diesel-hybrid transit buses. To become competitive with conventional transit buses will require improvements in fuel cell efficiency and hybridization strategies, and a considerable reduction in the cost of H_2.

Other projections of fuel cell and fuel cell transit bus costs include the following:

- The ElDorado bus with the Ballard HD-6+ fuel cell will demonstrate advanced durability, power density, and fuel efficiency with a state-of-the-art automotive fuel cell stack, and a commercialization target cost of $1 million through design for volume manufacturing.
- The UTC Power bus fleet target is $200–350/kW for the fuel cell power system (stack, BOP, power control system) when manufactured in volumes of thousands per year, based on durability of >18,000 h (in transit service, with its associated load cycling) and 0.3 mg_{Pt}/cm^2 total PGM loading.

Fuels and Infrastructure

From January 2006 to July 2011, the U. S. fuel cell transit buses have been fueled with more than 100,000 kg of H_2 with no fueling safety incidents. Fueling amounts at the major transit sites include:

- AC Transit: 61,321 kg
- CT Transit: 18,217 kg (April 2007 to July 2011)
- SunLine Transit: 21,482 kg

The average fill amount is about 22.5 kg per fueling, with a fill time of about 16 min for fuel cell dominant power plants. For battery dominant power plants, the average fill is about 11 kg.

All of the major industrial gas suppliers have participated in one or more of the fuel cell transit bus demonstration projects. These gas suppliers include Air Liquide, Air Products and Chemicals, Inc. (APCI), and Linde. Fig. 6 shows the Oakland, CA, fueling station of AC Transit, where the H_2 is provided by Linde. The AC Transit fueling stations also use H_2 generated by solar-powered (photovoltaic) electrolysis and biogas.

Fig. 6. The Oakland, CA, fueling station of AC Transit capable of dispensing 360 kg/day.

Air Liquide has provided H_2 for the Project Driveway stations in New York and California, mass transit stations in Whistler, Canada, and Oslo, Norway, and for several materials handling fork-lift truck applications. Hydrogen supply alternatives include liquid trailer, 200–500-bar tube trailer, and on-site production by SMR or electrolysis. Compression technologies for dispensing include liquid pump and vaporization (1000 kg/day), liquid vaporization and gas compression to 1000 bar, by gas booster for up to 10 kg/day or by membrane compressor for 100–1000 kg/day.

For transit bus fleets smaller than 25 buses, Air Liquide's analysis indicates that delivered gas is the cheapest option; for larger fleets, SMR may be recommended.

Air Liquide's Vancouver Whistler project for the 20-bus fleet represents one of the world's largest fueling stations. It is capable of fueling 12–15 buses/day at a fill rate of 5 kg/min, with no limitation on successive fills of up to 50 kg in about 10 min. Hydrogen is obtained by SMR, liquefied, and shipped by liquid H_2 tanker; local back-up is provided by electrolysis. At the fueling station, liquid H_2 is stored in two vertical 20,000-gal tanks, each holding 5,300 kg (10 tons); this stored amount represents 10–12 days of usage at the maximum consumption rate. Equipment integrity is monitored by leak-test instrumentation, gas sensors, and flame detectors. All systems are wired with Emergency Stop push buttons. All construction is consistent with NFPA 52, 55, and 2. All equipment conforms to ASME/DOT codes and requirements, electrical equipment is UL listed, and the fuel dispensers are labeled by Intertek.

Air Products has been involved in H_2 energy projects since 1993, with an accumulated experience base of more than 130 H_2 station projects in 19 countries and over 350,000 fuelings/year. For a 200-bus fleet requiring 25 kg/fueling, the challenge would be to dispense 5,000 kg in 6 h, corresponding to an average fill rate of 13.9 kg/min. Industrial customers, by comparison, are more varied: refinery, 283,000 kg/day, 24/7 demand; large liquid H_2 customer, 5,000 kg/day, 24/7 demand; forklift site, 75–200 kg/day, 1 kg/fueling in 3–5 min, 25–100 fuelings/day; Space Shuttle, 130,000 kg/launch (program terminated).

Air Products has developed a dual-phase H_2 tanker by modifying a liquid H_2 tanker to deliver both liquid and gaseous H_2 at up to 7,200 psi. This tanker can supply fuel to a liquid H_2 tank, off-board bulk H_2 storage, a mobile fueler, or tube trailers. This tanker has been deployed in the U. S. and Europe and offers the opportunity to optimize fuel supply logistics and improve fueling economics. For example, for the CHIC project for Transport for London, the 500-kg gaseous H_2 storage is refilled using the dual-phase tanker; most of the refueling equipment is on-board the tanker, leaving little to maintain on the ground. This fueling station is unmanned and monitored remotely.

Linde covers the entire H_2 value chain, including large-scale production, on-site supply and storage, compression/transfer, and dispensing. They have conducted over 10,000 fuelings to-date:

- Up to 100 kg/day for the CUTE project in Amsterdam, the Netherlands; Porto, Portugal; Barcelona, Spain; Perth, Australia; and London, UK;
- 56 kg/h in Shanghai, China, for Shell;
- Up to 140 kg/day for CEP, Berlin, Germany;
- 30 kg/h for the Nuclear Research Institute, Prague, the Czech Republic;
- 5 kg/min at AC Transit's Emeryville and Oakland, CA, stations;
- 70 kg/h for CEP/Vattenfall in Hamburg, Germany; and
- Up to 200 kg/h for Shell in Berlin.

Linde has deployed three different types of H_2 compression technologies for dispensing the fuel to light-duty vehicles and transit buses:

1. Dry Runner: lubricant-free piston compressor, 5–11 kg/h, 350/700 bar.
2. Ionic: ionic liquid as a piston for compression (near isothermal operation), 12–35 kg/h, 420–900 bar.
3. Cryo Pump: high throughput liquid H_2 pump, up to 120 kg/h, 350/700 bar.

Fueling station requirements vary by the project and depend on the location, size of the fuel cell bus fleet, and projections for growth at the site and in the region. Examples of fueling station designs are:

- Proterra fuel cell bus: 66 kg storage capacity with 120 kg/day maximum dispensing amount; 7,000 psi off-board storage pressure for 5,000 psi on-board storage system; remote operation and monitoring capability, non-communication-based fast-fill dispensing; and designed for expansion to on-site H_2 generation capability.
- The Emeryville, CA, hydrogen fueling station of AC Transit, part of the HyRoad Project that opened in the second half of 2011, offers transit fueling inside the fence, and public fueling outside the fence. Some of the H_2 is obtained by electrolysis of water using solar photovoltaic energy.

Projections

Fuel cell and fuel cell bus technology is proving out, with steady increases in maintainability and reliability. Costs are still a challenge, however, and simply increasing the number of buses and power systems may not be enough to drive the costs down to the target values. "Value Engineering" must be applied to reduce cost and weight, and increase the level of integration of the fuel cell subsystem and the balance-of-plant. Higher vehicle-level integration will also be needed, that includes the fuel system, cooling system, safety systems, and power electronics. According to one developer, the goals of this integration should be to eliminate 50% of the subsystems and 75% of the common parts used in building the buses.

Acknowledgements

The information in this report has been obtained from a variety of published and internet sources. The major such sources are listed in the bibliography, below. If this report or excerpts from it are to be published, or any of its content is to be cited in a public manner, it will be necessary for the author of such a public presentation to obtain copyright clearances from the specific source(s) contained within the bibliography.

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Abbreviations and Acronyms

ACT VH	AC Transit Van Hool buses with UTC Power fuel cells
ACT ZEBA	AC Transit Zero Emission Bay Area Van Hool buses with UTC Power fuel cells
APCI	Air Products and Chemicals, Inc.
APU	Auxiliary power unit
ASME	American Society of Mechanical Engineers International
BC	British Columbia, Canada
BCT	British Columbia Transit (Canada)
BEV	Battery electric vehicle
CARB	California Air Resources Board
CHIC	Clean Hydrogen in European Cities Project (www.chic-project.eu)
CNG	Compressed natural gas
CTA	Chicago Transit Authority
CTT Nutmeg	Connecticut Transit Nutmeg Project Van Hool buses with UTC Power fuel cells
CTT VH	Connecticut Transit Van Hool buses with UTC Power fuel cells
CUTE	Clean Urban Transport for Europe Programme
DOE	U. S. Department of Energy
DOT	U. S. Department of Transportation
EMTU	Empresa Metropolitana de Transportes Urbanos (Sao Paulo, Brazil)
EV	Electric vehicle
FC	Fuel cell
FCB	Fuel cell bus
FCV	Fuel cell vehicle
FCPS	Fuel cell power system
FTA	Federal Transit Administration
GHG	Greenhouse gases (emissions expressed as CO_2-equivalent emissions)
HDV	Heavy-duty vehicle
ICE	Internal combustion engine
LDV	Light-duty vehicle
LH2	Liquid hydrogen
MBRC	Miles between road calls
mpgde	Miles per gallon diesel equivalent
NFCBP	National Fuel Cell Bus Program (U. S.)
NFPA	National Fire Protection Association (U. S.)
RFI	Request for Information
SC PT	South Carolina Proterra battery-dominant bus with Hydrogenics fuel cells
SCVTA	Santa Clara Valley Transit Agency (California)
SL AT	SunLine Transit New Flyer buses with Ballard fuel cells
SL CNG	SunLine Transit CNG buses (compressed natural gas)
SL VH	SunLine Transit Van Hool fuel cell buses with UTC Power fuel cells
SMR	Steam methane reforming (for producing hydrogen)
TBD	To be determined
TFL	Transport for London (UK)
UAB	University of Alabama, Birmingham
UL	Underwriters Laboratories
UTC	United Technologies Corporation