Journal of Power Sources 269 (2014) 975–993

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Review

Status of hydrogen fuel cell electric buses worldwide

Thanh Hua [a,*], Rajesh Ahluwalia [a], Leslie Eudy [b], Gregg Singer [c], Boris Jermer [d], Nick Asselin-Miller [e], Silvia Wessel [f], Timothy Patterson [g], Jason Marcinkoski [h]

[a] Argonne National Laboratory, Argonne, IL, USA
[b] National Renewable Energy Laboratory, Golden, CO, USA
[c] BC Transit, BC, Canada
[d] HyCologne, Germany
[e] Element Energy, Cambridge, United Kingdom
[f] Ballard, Burnaby, BC, Canada
[g] ClearEdge Power, Hartford, CT, USA
[h] U.S. Department of Energy, Washington DC, USA

HIGHLIGHTS

- Fuel cell electric buses worldwide: North America and Europe.
- Performance metrics: miles, availability, fuel economy, fuel cost, roadcalls, hydrogen refueling.
- Hydrogen refueling infrastructure.
- Fuel cell technology.
- Projections and targets for fuel cell electric buses.

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form
9 June 2014
Accepted 10 June 2014
Available online 31 July 2014

Keywords:
Fuel cell electric bus
Fuel cell technology
Hydrogen refueling
Hydrogen infrastructure
Public transportation

ABSTRACT

This review summarizes the background and recent status of the fuel cell electric bus (FCEB) demonstration projects in North America and Europe. Key performance metrics include accumulated miles, availability, fuel economy, fuel cost, roadcalls, and hydrogen fueling. The state-of-the-art technology used in today's fuel cell bus is highlighted. Existing hydrogen infrastructure for refueling is described. The article also presents the challenges encountered in these projects, the experiences learned, as well as current and future performance targets.

1. Introduction

For years, developed countries have made great strides toward improving air quality in densely populated metropolitan cities and advocated the need to use alternative energy sources to petroleum as the pathway toward reducing transportation-related air pollution. Heavy-duty vehicles, especially electric busses powered by hydrogen fuel cells will be an important element in any plan to achieve the targets for air quality and pollution reduction.

There are numerous operational, environmental and economic benefits of fuel cell electric buses (FCEBs) over traditional diesel or diesel hybrid busses. FCEBs are more fuel efficient [1] as shown in Fig. 1. These buses operate with no local emissions, reduced noise, and a substantial reduction in greenhouse gas emissions on a well-to-wheel basis without some of the performance, range and route flexibility issues seen in other zero emission technologies [2]. Use of fuel cells for transit reduces dependence on petroleum and adverse effects of price fluctuations. For these reasons, FCEBs are progressing towards commercialization and the number of FC bus and FC manufacturers are increasing steadily (Fig. 2). With about 100

* Corresponding author. Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA. Tel.: +1 (630) 252 7753.
E-mail address: hua@anl.gov (T. Hua).

http://dx.doi.org/10.1016/j.jpowsour.2014.06.055
0378-7753/

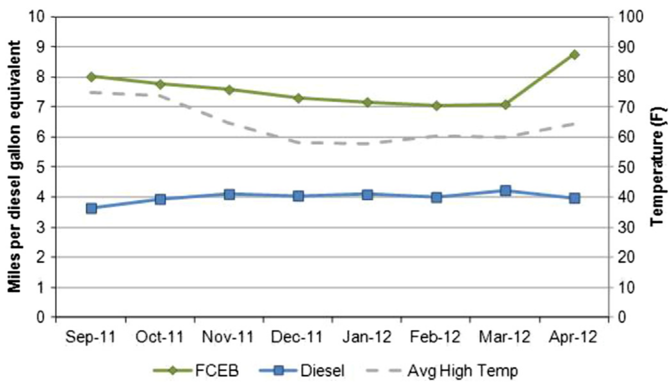


Fig. 1. Average fuel economy for the fuel cell and diesel buses [1].

buses on the road in demonstration projects across the globe, FCEBs are approaching government and transit agency targets in technical performance, durability and reliability. There remain, however, a few barriers to reaching full commercialization of FCEBs. The major barriers include durability of the fuel cell power systems, the relatively high initial capital cost of fuel cell buses, and the availability and cost of hydrogen. These barriers will be overcome with continuing improvement in fuel cell technology, high volume manufacturing, and establishment of large refueling facilities (1000 kg day^{-1}). Table 1 [3] summarizes current active FCEBs in the world. The majority of them are located in North America and Europe. Collectively, they have accumulated over 3 million miles of successful operation.

In the United States, the Federal Transit Administration established the national Fuel Cell Bus program in 2006 to advance the commercialization of FCEBs. The program has provided nearly $90 million since 2006 to promote the development and testing of cleaner, greener sources of fuel for the transit industry. As of August 2013, there are 18 active FCEBs in demonstrations at six locations [4]. Fourteen of the 18 busses are in the state of California. This review summarizes data collected for the data period from August 2012 to July 2013 from five different FCEB demonstrations at four transit agencies. These include 12 Van Hool buses with ClearEdge.

Power (formerly UTC Power) fuel cells (ZEBA) at AC Transit, Oakland, CA; 4 Van Hool buses with ClearEdge Power fuel cells (Nutmeg) at CTTRANSIT, Hartford, CT; 1 New Flyer bus with Ballard fuel cell and 1 Eldorado bus with Ballard fuel cell at SunLine, Thousand Palms, CA; and 1 Proterra bus with Hydrogenics fuel cell at Capital Metro, TX.

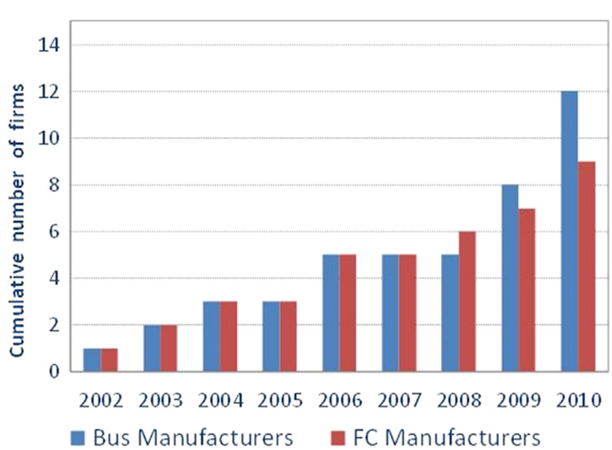


Fig. 2. Number of competitors in the fuel cell bus market [2].

In Europe, the HyFLEET-CUTE demonstration project with 30 full size Daimler buses in 10 cities accumulated 1.3 million miles between 2003 and 2010 [5]. These buses were battery dominant with 12 kW Hydrogenics fuel cells. Building on the HyFLEET-CUTE success, the European fuel cell bus CHIC (Clean Hydrogen in European Cities [6]) demonstration projects currently has 26 FCEBs in Phase 1 operating in 5 countries: 5 Daimler buses with AFCC fuel cells in Switzerland, 5 Van Hool buses with Ballard fuel cells in Norway, 8 Wrightbus buses with Ballard fuel cells in the United Kingdom, and 8 Daimler busses with AFCC fuel cells in Italy. This fleet will run from 2011 to 2017 with the aim to achieve a number of performance targets which will ease the integration of the technology into today's public transport standards. The CHIC projects are supported and funded by the Joint Technology Inititatives' (JTI) Fuel Cell and Hydrogen Joint Undertaking (FCH-JU) and a set of industry partners.

Additionally, the High V.LO City project [7] in Europe is deploying 14 FCEBs (all Van Hool busses) in 3 countries: Italy, Scotland and Belgium. HyTransit is another program sanctioned by EU, under which Van Hool and Ballard will supply 6 fuel cell buses to City of Aberdeen, Scotland, similar in design to High V.LO City buses. These projects aim to create a network of successful fuel cell bus operation sites, so called Clean Hydrogen Bus Centres of Excellence (CHBCE), linking High V.LO-City sites with similar fuel cell bus demonstrations in Europe. Both the High V.LO City and HyTransit projects are supported through the EU's JTI program.

In Canada, BC Transit has operated a fleet of 20 New Flyer buses with Ballard fuel cells that were deployed in time for the 2010 Winter Olympics. This fleet operates as the backbone of the transit service in the Resort Municipality of Whistler and has surpassed 1.9 million revenue miles [8]. It continues to be the largest fuel cell fleet to operate in a single location at one time. It also requires the largest hydrogen fueling station in the world to provide the fuel for the fleet with a dispensing capacity of 1000 kg day^{-1}. The hydrogen is shipped and stored in liquid form and dispensed into the demonstration fleet in a gaseous state.

In Japan, HINO (Toyota's bus subsidiary and the only fuel cell bus player) is operating 6 FCEBs with 90-kW Toyota fuel cells in various locations [9]. These buses were first deployed in 2005 as shuttles at the Aichi Expo. Although Toyota is one of the automakers most committed to light duty fuel cell vehicles, interest in the bus market is unclear.

In Korea, the situation is similar to Japan. Hyundai is the key fuel cell/OEM player. Hyundai is committed to commercial light duty fuel cell vehicles by 2014, but plans for buses are unclear. A Hyundai 40-ft bus with Hyundai 160 kW fuel cell has operated since 2006 in routine service in Seoul and Jeju island. Hyundai has a contract with Seoul to start supplying multiple FCEBs starting in 2013 [10].

In China, since 2005 FCEBs have been deployed for major events with global spotlight including 3 buses for the 2008 Summer Olympics and 6 for the 2010 Shanghai Expo [11]. In November and December 2010 a fleet of more than 50 fuel cell buses shuttled athletes and government officials to various venues of the Asian Games in Guangzhou City. These demo buses are no longer in service. In September 2013, Ballard announced a multi-year agreement to support Azure Hydrogen's fuel cell bus program for the Chinese market [12].

In Brazil and India, dozens of FCEBs with Ballard fuel cell are being planned for deployment within next few years [13,14].

This review article summarizes the performance data of FCEBs deployment globally, the status of fuel cell technology being used in FCEBs, the current hydrogen fueling infrastructure, and concludes with projections and targets for the next generation of FCEBs.

Table 1
Active fuel cell bus projects globally [3].

Site, country	Fleet size	Project/Operator	Start date	Manufacturer	
				Bus	Fuel cell
Bay Area, USA	12	AC Transit	2011	Van Hool	ClearEdge
Hartford, USA	4	CTTransit	2007	Van Hool	ClearEdge
Thousand Palms, USA	1	Sunline	2011	New Flyer	Ballard
Thousand Palms, USA	1	Sunline	2011	ElDorado	Ballard
Austin, USA	1	Capital Metro/UT	2012	Proterra	Hydrogenics
Burbank, USA	1	Burbank Bus	2010	Proterra	Hydrogenics
San Francisco, USA	1	SF Metro Transit	2010	Daimler	Hydrogenics
Newark, USA	2	U of Delaware	2007	Ebus	Ballard
New Haven, USA	1	GNHTD		Ebus	Ballard
Lewis-McChord, USA	1	Dept of Defense		Proterra	Hydrogenics
Barth, Germany	1	Osteebus	2006	Neoplan	Proton
Hamburg, Germany	4	CHIC, CEP	2011	Daimler	AFCC
Cologne, Germany	2	CHIC, HyCologne	2011	APTS	Ballard
London, UK	8	CHIC	2011	Wrightbus	Ballard
Oslo, Norway	5	CHIC	2012	Van Hool	Ballard
Aargau, Switzerland	5	CHIC	2011	Daimler	AFCC
Milan, Italy	3	CHIC	2011	Daimler	AFCC
Bolzano, Italy	5	CHIC	2013	Daimler	AFCC
San Remo, Italy	5	High V-LO City	2013	Van Hool	Ballard
Aberdeen, Scotland	10	High V-LO City	2014	Van Hool	Ballard
Aberdeen, Scotland	4	High V-LO City	2014	Van Hool	Ballard
Aberdeen, Scotland	6	HyTransit	2014	Van Hool	Ballard
Antwerp, Belgium	5	High V-LO City	2014	Van Hool	Ballard
Cologne	2	HyCologne	2014	Van Hool	Ballard
Hamburg	2	NOW, Hamburg	2014	Solaris	Ballard
BC, Canada	20	BC Transit	2010	New Flyer	Ballard
Gladbeck, Germany	1	NA	2010	Rampini	Hydrogenics
Amsterdam, NL	2	GVB	2011	APTS	Ballard
Neratovice, Czech	1	TriHyBus	2009	Skoda Irisbus	Proton
Centrair airport, Japan	2	CSS	2006	Toyota	Toyota
Haneda airport, Japan	2	Airport Transit	2010	Toyota	Toyota
Toyota City, Japan	1	Meitetsu	2010	Toyota	Toyota

2. Fuel cell bus activities in the United States

A timeline of FCEB development in the United States is shown in Fig. 3. In 2006, the Federal Transit Administration (FTA) established the National Fuel Cell Bus Program (NFCBP) to advance the research and demonstrations of FCEBs. This multi-year, cost-shared program has provided more than $180 million (including 50% cost share) for various research projects, FCEB demonstrations, component development projects and outreach projects. The projects are managed through three nonprofit consortia — CALSTART (Pasedena, California), the Center for Transportation and the Environment (CTE, Atlanta), and the Northeast Advanced Vehicle Consortium (NAVC, Boston). The National Renewable Energy Laboratory (NREL) was funded as a third-party evaluator to assess the viability of the buses demonstrated under the program.

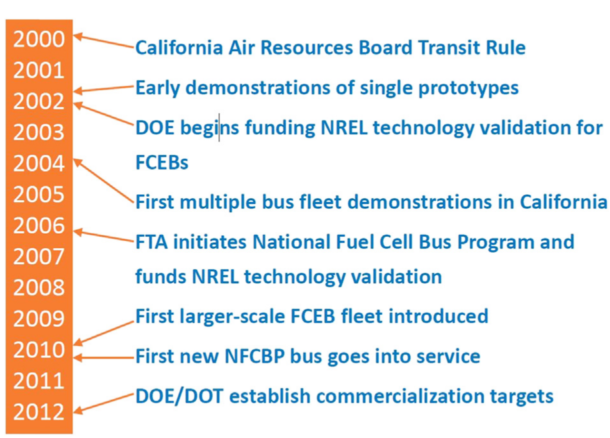


Fig. 3. Timeline in the development of FCEB in the United States.

In addition to the projects currently underway and listed in Table 1, seven more FCEBs will be deployed over the next year. Beyond the NFCBP, FTA funds fuel cell bus research at several universities and transit agencies. Details were documented in a recent FTA report [15].

2.1. Performance data

The data presented in this section were compiled by the National Renewable Energy Laboratory (NREL) and represent the most recent published results through July 2013 [4]. These data come from five different FCEB demonstrations at four agencies: AC Transit, CTTRANSIT, SunLine, and Capital Metro. All but one of the FCEBs presented in this section have hybrid systems that are fuel cell dominant. The Proterra bus is a battery dominant system. Table 2 provides some specifications of the FCEBs. The FCEBs are pictured in Fig. 4.

Conventional baseline bus data are provided for all three agencies for comparison with FCEB data. For AC Transit and CTTRANSIT, the primary comparisons are with diesel buses. The baseline buses at SunLine are CNG because the agency doesn't operate diesel buses.

2.1.1. Total miles and hours

Table 3 summarizes miles, hours, average speed, and average monthly miles per bus for the FCEBs. The AFCB at SunLine has the highest average speed at 15.3 mph, followed by the Nutmeg buses at 12.8 mph. SunLine AT bus operates primarily on one specific route, while the AFCB has operated on several routes within the service area. The ZEBA buses in service at AC Transit have the lowest average speed at just under 9 mph. The transit agencies continue to operate their fuel cell buses fewer miles than they operate their

Table 2
Selected specifications of the FCEBs at four transit agencies.

	ACT ZEBA	CTT Nutmeg	SL AT	SL AFCB	TX Proterra
Transit agency	AC Transit	CTTRANSIT	SunLine	SunLine	Capital Metro
Number of buses	12	4	1	1	1
Bus OEM	Van Hool	Van Hool	New Flyer	ElDorado	Proterra
Bus length (ft)	40	40	40	40	35
Fuel cell OEM	ClearEdge	ClearEdge	Ballard	Ballard	Hydrogenics
Fuel cell power (kW)	120	120	150	150	16(x2)
Hybrid system integrator	Van Hool	Van Hool	Bluways	BAE Systems	Proterra
Design strategy	FC dominant	FC dominant	FC dominant	FC dominant	Battery dominant
Energy storage OEM	EnerDel	EnerDel	Valence	A123	Altairnano
Energy storage type	Li-ion	Li-ion	Li-ion	Li-ion	Li-titanate
Energy storage power	21 kWh	21 kWh	47 kWh	11 kWh	54 kWh
H2 storage pressure (psi)	5000	5000	5000	5000	5000
Hydrogen cylinders	8	8	6	8	4
Hydrogen capacity (kg)	40	40	43	50	29

Fig. 4. FCEBs included in the data summary: AC Transit ZEBA (top left), CTTRANSIT Nutmeg (top right), SunLine AFCB (bottom left), SunLine AT (bottom right).

baseline buses; however there is a general upward trend for the fuel cell buses. Fig. 5 shows the average monthly bus use for the fuel cell buses and their respective baseline buses. Some buses have operated as much as 20 h in a day, 7 days per week.

2.1.2. Availability

Availability is the percentage of days that buses are planned for operation compared to the percentage of days the buses are actually available. Table 4 summarizes the availability of the fuel cell buses at each transit agency. Availability varies from site to site with a low of 31% and a high of 81%. The average availability for the group is 69%. Fig. 6 tracks the monthly availability for the FCEBs by project. The percent availability is shown as a separate line for each of the projects with the combined overall average for all FCEBs in dark blue.

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

The ACT ZEBA (medium blue line in the graph) buses were out of service during the beginning of the data period while the hydrogen station was down. Once the buses went into service, the availability showed an increase over its past availability data. The buses at CTTRANSIT (light blue line) are the same design as the ZEBA buses. The availability during the period began low but increased over time. One of the four buses was moved to Flint, Michigan, and has

Table 3
Miles and hours for the fuel cell buses.

ID	Period	Months	No. of buses	Miles	Hours	Speed (mph)	Monthly miles
ACT ZEBA	3/13–7/13	5	12	156,789	18,251	8.6	2613
CTT Nutmeg	8/12–1/13	6	4	24,479	1914	12.8	1020
SL AT	8/12–7/13	12	1	9340	906	10.3	778
SL AFCB	8/12–7/13	12	1	36,339	2380	15.3	3028
TX Proterra	10/12–3/13	6	1	1374	N/A	NA	229

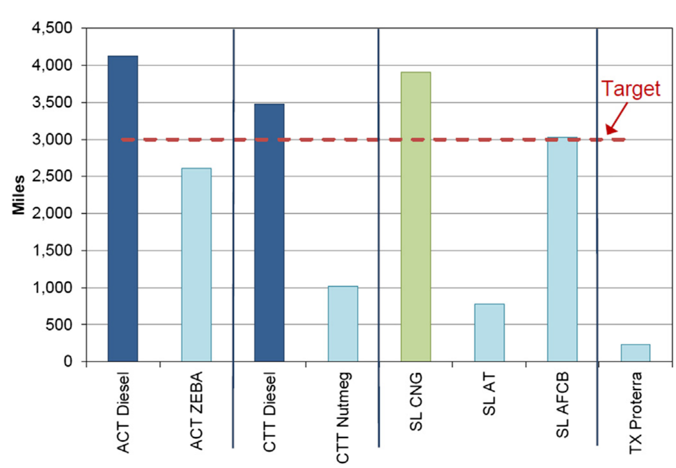


Fig. 5. Average monthly miles per fuel cell and baseline buses.

Table 4
Availability of the fuel cell buses.

ID	Period	Months	No. of buses	Planned days	Days avail.	% Avail.
ACT ZEBA	3/13–7/13	5	12	1486	1209	81
CTT Nutmeg	8/12–1/13	6	4	437	222	51
SL AT	8/12–7/13	12	1	280	88	31
SL AFCB	8/12–7/13	12	1	331	247	75
TX Proterra	10/12–3/13	6	1	82	46	56

been in service there for the entire data period. When the planned demonstration ended in early 2013, ClearEdge Power ended service for the three remaining buses at CTTRANSIT. ClearEdge has made a business decision to focus on the stationary power market and will transfer the ownership of the buses to other parties.

The Proterra bus in Texas had several issues during its planned demonstration that caused extended downtime. The primary issues have been with the hybrid propulsion system and the fuel cell. The bus availability for December calculates to 100%; however it was only scheduled for eight days during the month.

Fig. 7 presents the overall monthly availability and shows the reasons that the buses were not available by category. The blue line on the graph is the combined monthly availability for the buses in all five demonstration projects. The stacked bars show the total number of days the buses were unavailable each month by primary system category. The majority of issues affecting the availability for the buses were general maintenance (52%), followed by traction batteries (21%), fuel cell system (20%), and hybrid system (7%).

2.1.3. Fuel economy

Fig. 8 shows the average fuel economy in miles per diesel gallon equivalent (DGE) for each type of FCEB compared to the conventional baseline bus technology at the same site. The fuel economy for hybrid fuel cell systems tends to vary from site to site depending on the duty-cycle. The FCEBs continued to show improved fuel economy compared to the baseline buses in similar service. New FC bus designs have twice the fuel economy as diesel buses. FTA's performance target for FCEB fuel economy is at least two times higher than that of diesel buses. The FCEBs showed improved fuel economy ranging from 1.8 to 2.4 times higher than the fuel economy of diesel and CNG baseline buses.

2.1.4. Roadcalls

A roadcall or revenue vehicle system failure is a failure of an in-service bus that causes the bus to be replaced on route or causes a

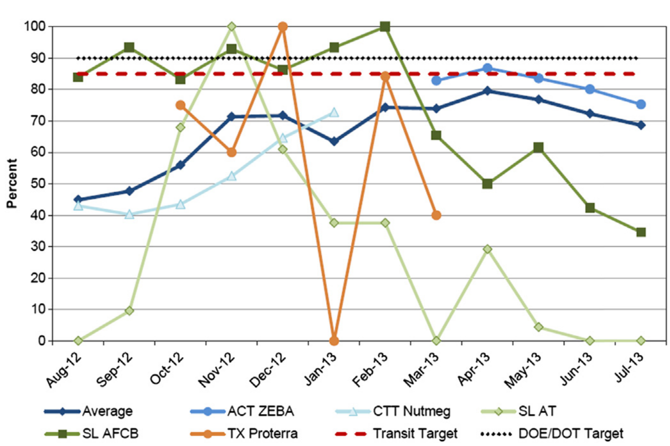


Fig. 6. Monthly availability for the FCEBs.

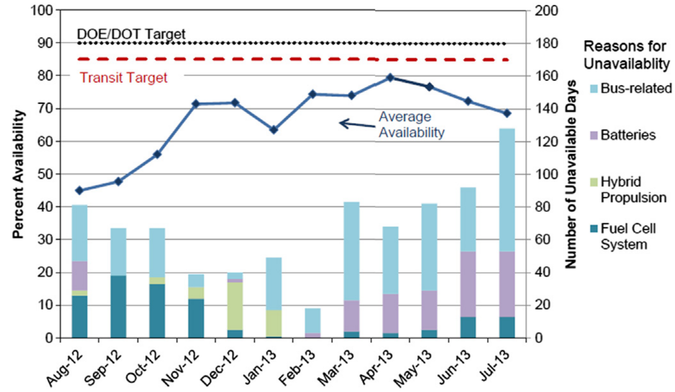


Fig. 7. Average monthly availability and number of unavailability days by category.

significant delay in schedule. If the bus is repaired during a layover and the schedule is maintained, then no roadcall is recorded. Fig. 9 shows miles between roadcalls (MBRC) for all roadcalls, for propulsion-related-only roadcalls, and for fuel-cell-system-only roadcalls for the FCEBs during the data period. The gray dotted line marks the target for all MBRC (4000) and the brown and red hashed lines are the 2016 and ultimate targets for FC system (15,000 and 20,000 miles, respectively). Most recent data indicate that FC MBRC has increased to 17,558 miles, exceeding the 2016 target. While the bus MBRC rates are still lower than the targets, the reasons are not typically due to the fuel cells.

2.1.5. Hydrogen fueling

NREL has tracked total hydrogen use for FCEBs at all of the sites. Since the first bus went into service in January 2006 through July 2013, these FCEBs have been fueled with more than 150,000 kg of hydrogen with no fueling safety incidents. The amount of hydrogen dispensed continues to grow as new buses are placed into service. Fig. 10 shows the total hydrogen dispensed for the three primary sites. During the data period from August 2012 through July 2013, the FCEBs at the three sites were fueled 1835 times with a total of 35,754 kg of hydrogen. The average fill amount for these fuel cell dominant FCEBs was about 19.5 kg per fill.

2.2. Achievements and challenges

While bus performance and fuel cell system durability have continued to improve, there are still major challenges to overcome to move FCEB technology to a commercial product. This section

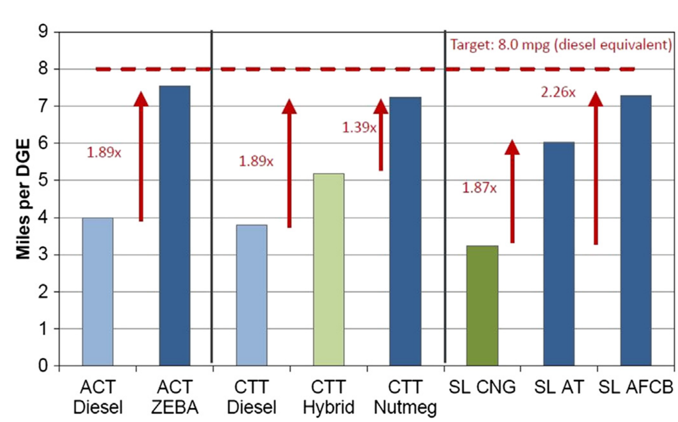


Fig. 8. Average fuel economy comparisons between FCEBs and baseline buses.

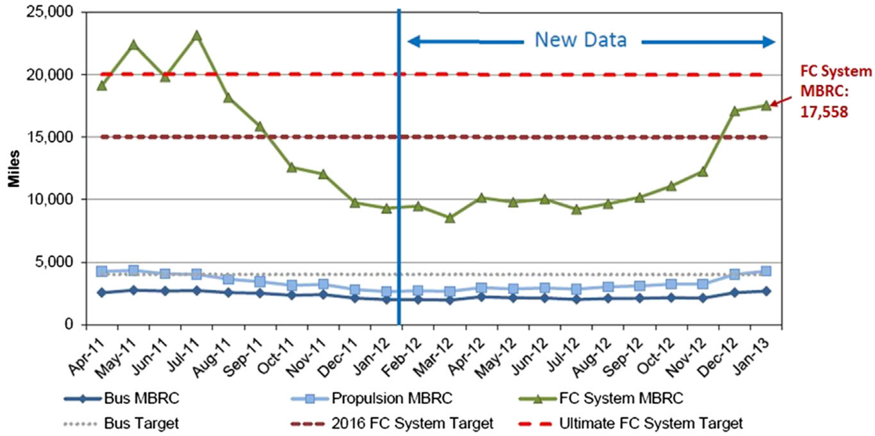


Fig. 9. MBRC rates for fuel cell buses compared to the targets.

outlines the on-going challenges as well as lessons learned from recent issues.

2.2.1. Integration/optimization of components

Over the past years, manufacturers continued to work on issues with systems integration and optimization, which is still one of the major challenges for FCEBs. When new FCEB designs first go into service, there is a characteristic break-in period where the manufacturers review the early performance results and make changes to optimize and correct any issues that occur. This break-in period can take many months as new issues arise that did not show up in laboratory testing. In many cases, the issue is due to communication problems between the different sub-systems that can be resolved through software updates.

2.2.2. Hydrogen fueling

Access to hydrogen fuel continues to be one of the biggest hurdles to adoption of any fuel cell vehicle. Several demonstration projects have been delayed because of issues with access to fuel. There is a need to develop large stations at transit agencies that could handle larger fleets of buses. One of those stations began operation in August 2011 at AC Transit's Emeryville Division [1]. The Emeryville station is a combined facility for light-duty fuel cell electric vehicles and FCEBs. Hydrogen is provided from two sources: liquid hydrogen delivery and a solar-powered electrolyzer. The electrolyzer is capable of producing 65 kg of hydrogen per day.

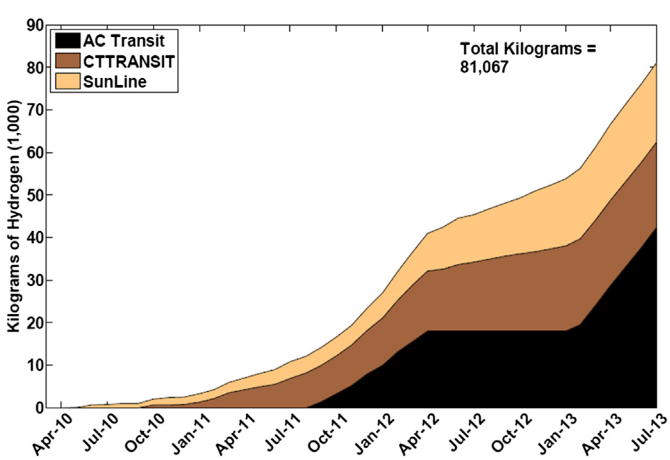


Fig. 10. Hydrogen dispensed for the FCEBs at the four demonstrations.

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

2.2.3. FCEB development teams

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

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

2.3. Summary

Highlights of progress with 2nd generation FCEBs in the United States include

- Mileage accumulation at ~2000 miles/month
- FCEB fuel economy consistently higher than diesel and CNG baseline buses
- FCEB designs approach twice the fuel economy of diesel and CNG baseline, meeting target of 8 mpdge

- Average availability at 69% with most recent availability at up to 100%
- Fuel cell system MBRC is increasing – 56% improvement over 1st generation FCEBs
- Reliability data show road calls not typically due to FC system
- Top FC power plant surpasses 12,000 h

3. Fuel cell bus activities in Europe

The European Union (EU) is committed to significantly reducing its greenhouse gas (GHG) emissions and in order to meet their target of an 80% reduction from 1990 levels, road transport emissions may need to be cut by as much as 95% [16]. As a result, and in parallel with increasingly stringent vehicle emissions regulations, a range of alternative drivetrain technologies are being rolled out and supported through both European and national funding schemes.

The current level of technical readiness for FCEBs is seen as significantly better than equivalent battery electric buses (e.g., opportunity or overnight e-buses), with over 30 standard 12-m or 18-m hydrogen fuel cell buses deployed across Europe, but no equivalent electric buses in operation, as shown in Fig. 11.

Many of the existing FCEB deployments have been supported by the European Fuel Cell and Hydrogen Joint Undertaking (FCH JU), a public-private partnership between the EU and Industry, with the aim of supporting the commercialization of hydrogen and fuel cell-based technologies in Europe.

The first major coordinated FCEB deployments in Europe occurred through the CUTE and HyFleet:CUTE projects, which ran from 2003 to 2009 and deployed a total of 27 non-hybridized FCEBs in 9 European cities. This was followed by the CHIC project which began in 2011 with the aim of deploying 26 new hybridized FCEBs across five European cities from 2012 onwards, while also sharing lessons learned and data with existing FCEB deployments in three other European cities. This has been followed by the HyTransit and High.V.Lo.City, which will deploy 6 of the latest generation of hybridized FCEBs in Aberdeen and 14 FCEBs in three European regions respectively. Table 5 lists the cities/regions with active FCEB fleets in Europe.

Additionally, a number of European and global cities and regions (including Amsterdam, Barcelona, Berlin, British Columbia, Cologne, Hamburg, London, South Tyrol and Western Australia) with large bus fleets have formed the Hydrogen Bus Alliance (HBA), with the aim of sharing information on the performance of and lessons learned from deployed FCEBs, as well as collaborating on future potential FCEB procurements. These cities and regions represent a cumulative fleet of over 12,000 buses and an average purchase of over 1200 city buses each year. They are characterized by high level political support for hydrogen bus deployment programs and all intend to move towards procuring hydrogen buses on a continuous basis as hydrogen buses move towards commercial viability.

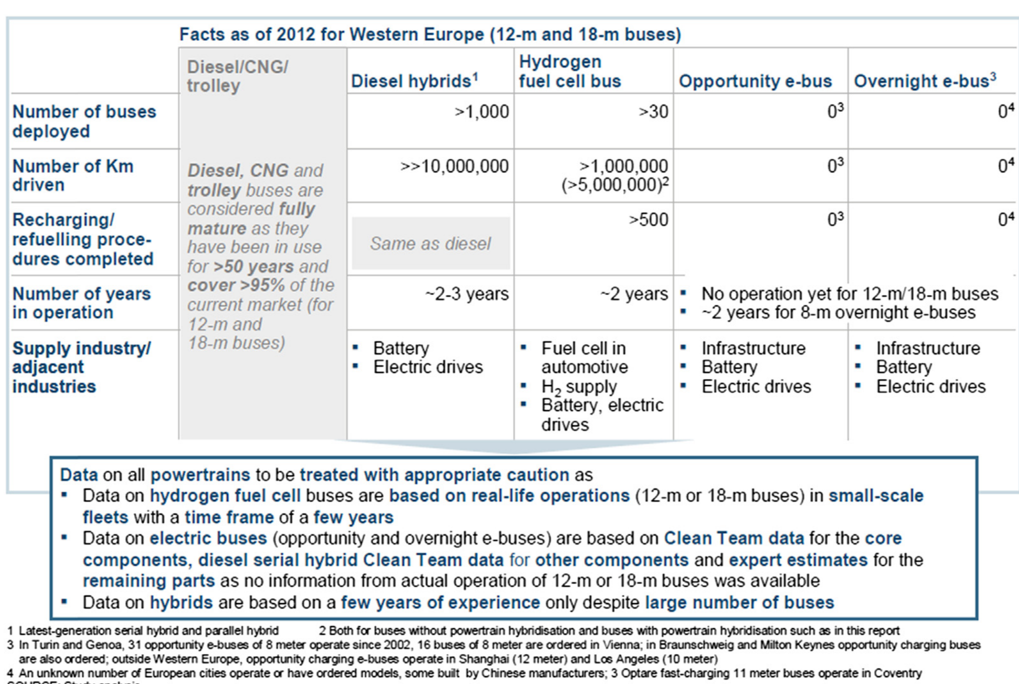
The latest round of FCEBs deployed are based on series hybrid technology, with a choice of either batteries or super capacitors (depending on the journey profile) storing power from regenerative braking and providing a buffer to allow minimal sizing of the fuel cell system, thereby minimizing costs.

In parallel with these bus deployments, each of the above cities has also deployed hydrogen refueling infrastructure to service the bus fleets. These have ranged from solutions relying on liquid hydrogen deliveries to refill local storage tanks, to on-site electrolysis for green hydrogen production.

3.1. Performance data

Although the HyFleet:CUTE project reported on reliability and performance data for non-hybridized FCEBs over the period 2003–2009 (>92% bus availability, >2 million km driven, <10 road calls per 1000 h operation [17]), there is currently limited publically available data from the follow-on CHIC project and its new generation of hybridized FCEBs.

Early indications from CHIC are that there has been a step change improvement in performance from the earlier non-hybridized generation of FCEBs and that current environmental



Facts as of 2012 for Western Europe (12-m and 18-m buses)

	Diesel/CNG/ trolley	Diesel hybrids[1]	Hydrogen fuel cell bus	Opportunity e-bus	Overnight e-bus[3]
Number of buses deployed	*Diesel, CNG and trolley buses are considered fully mature as they have been in use for >50 years and cover >95% of the current market (for 12-m and 18-m buses)*	>1,000	>30	0[3]	0[4]
Number of Km driven		>>10,000,000	>1,000,000 (>5,000,000)[2]	0[3]	0[4]
Recharging/ refuelling procedures completed		Same as diesel	>500	0[3]	0[4]
Number of years in operation		~2-3 years	~2 years	▪ No operation yet for 12-m/18-m buses ▪ ~2 years for 8-m overnight e-buses	
Supply industry/ adjacent industries		▪ Battery ▪ Electric drives	▪ Fuel cell in automotive ▪ H_2 supply ▪ Battery, electric drives	▪ Infrastructure ▪ Battery ▪ Electric drives	▪ Infrastructure ▪ Battery ▪ Electric drives

Data on all powertrains to be treated with appropriate caution as
- Data on hydrogen fuel cell buses are based on real-life operations (12-m or 18-m buses) in small-scale fleets with a time frame of a few years
- Data on electric buses (opportunity and overnight e-buses) are based on Clean Team data for the core components, diesel serial hybrid Clean Team data for other components and expert estimates for the remaining parts as no information from actual operation of 12-m or 18-m buses was available
- Data on hybrids are based on a few years of experience only despite large number of buses

1 Latest-generation serial hybrid and parallel hybrid 2 Both for buses without powertrain hybridisation and buses with powertrain hybridisation such as in this report
3 In Turin and Genoa, 31 opportunity e-buses of 8 meter operate since 2002, 16 buses of 8 meter are ordered in Vienna; in Braunschweig and Milton Keynes opportunity charging buses are also ordered; outside Western Europe, opportunity charging e-buses operate in Shanghai (12 meter) and Los Angeles (10 meter)
4 An unknown number of European cities operate or have ordered models, some built by Chinese manufacturers; 3 Optare fast-charging 11 meter buses operate in Coventry
SOURCE: Study analysis

Fig. 11. Status of different low emission bus drivetrain technologies in Europe. (Source: 'Urban buses: alternative powertrains for Europe')

Table 5
Active FCEBs in Europe.

CHIC		High V.LO-City		HyTransit		Independent	
Location	Buses	Location	Buses	Location	Buses	Location	Buses
Aargau	5	Aberdeen	4	Aberdeen	6	Amsterdam	2
Bolzano	5	Antwerp	5			Amhem	1
Cologne	2	Liguria	5			Barth	1
Hamburg	4					Dusseldorf	2
London	8					Hamburg	1
Milano	3					Neratovice	1
Oslo	3						

and fuel cell reliability performance has been either in-line with or slightly better than the performance of United States and Canadian FCEB fleets. However teething problems with many of the bus fleets' non-fuel cell components has led to availabilities being below expected targets, at least in the early part of deployments. A number of easily avoidable issues have been singled out as unnecessarily causing a reduction in availability:

- Supply chain issues: Extended downtime due to unavailability of, or long lead times on spare parts.
- Software teething problems: Initial low availability of vehicles in service was often due to 'false' error signals, over sensitive error messages, or other problems caused by differences between testing in an artificial scenario and in true passenger service.
- Poorly prepared support staff and local employees: Transit agencies had patchy safety knowledge with regards to hydrogen, tank inspection, pressure systems, thereby causing extended downtime as a result of minor faults.

Despite the current lack of official data from the CHIC project, some initial data from the hybridized FCEBs deployed in London has been released by Transport for London, as described below.

3.1.1. Fuel consumption

Fuel consumption for the fleet of hybridized FCEBs in London has been on average around 9 kg/100 km, which is significantly below the 11–13 kg/100 km target set by the FCH JU and less than half of the 22 kg/100 km observed from the non-hybridized FCEBs in the CUTE and HyFleet:CUTE projects, as shown in Fig. 12.

The fuel consumption observed is also an improvement over the calorific equivalent consumption of a diesel bus (equivalent consumption of 11–15 kg/100 km).

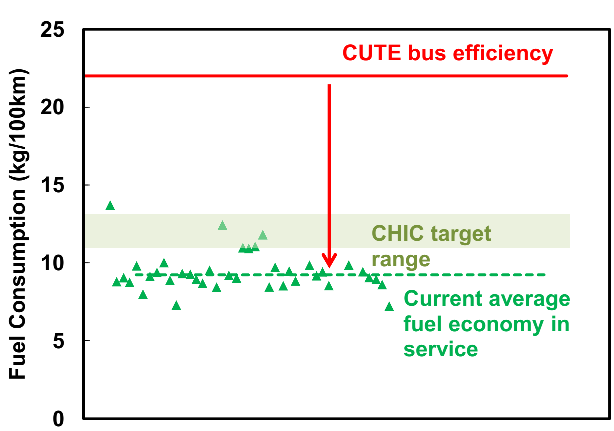


Fig. 12. Average fuel consumption of FCEBs in London.
(Source: Transport of London)

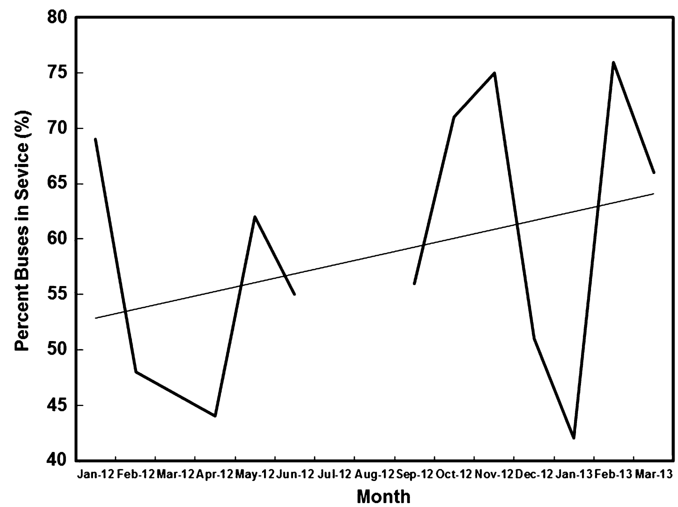


Fig. 13. Availability of London FCEBs January 2012–March 2013. Note: no data between June–September 2012, as the buses were withdrawn from service during the London Olympics period.
(Source: Transport of London).

3.1.2. Availability

Availability for the fleet of FCEBs deployed in London has been significantly below that for equivalent diesel buses, as shown in Fig. 13. This is also below the 92% availability observed for the non-hybridized FCEBS in the CUTE and HyFleet:CUTE projects.

However, as illustrated in Fig. 13, there is a clear upward trend in availabilities due to the fact that many of the issues observed towards the start of the deployment were related to early teething problems and supply chain issues, as previously described. The trend is towards an improved overall availability level above 70% for all the buses deployed.

On an individual bus basis however, availabilities of over 90% have been achieved as shown in Fig. 14. This illustrates that the technology is capable of very high levels of availability similar to that observed with diesel buses, although this is not being achieved on a consistent basis due to an immature supply chain and some component specific problems.

Fig. 15 illustrates that much of the downtime observed with the London FCEB deployment has been unrelated to the fuel cell systems, but rather has been attributable to balance of plant issues, as

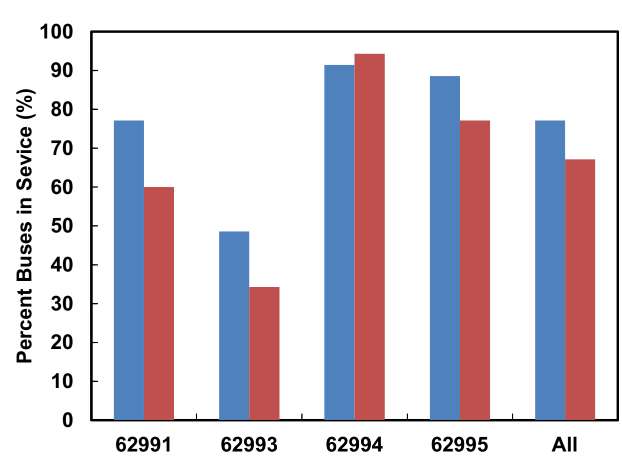


Fig. 14. Individual bus availability data for the London FCEB deployment, February March 2013.
(Source: Transport of London)

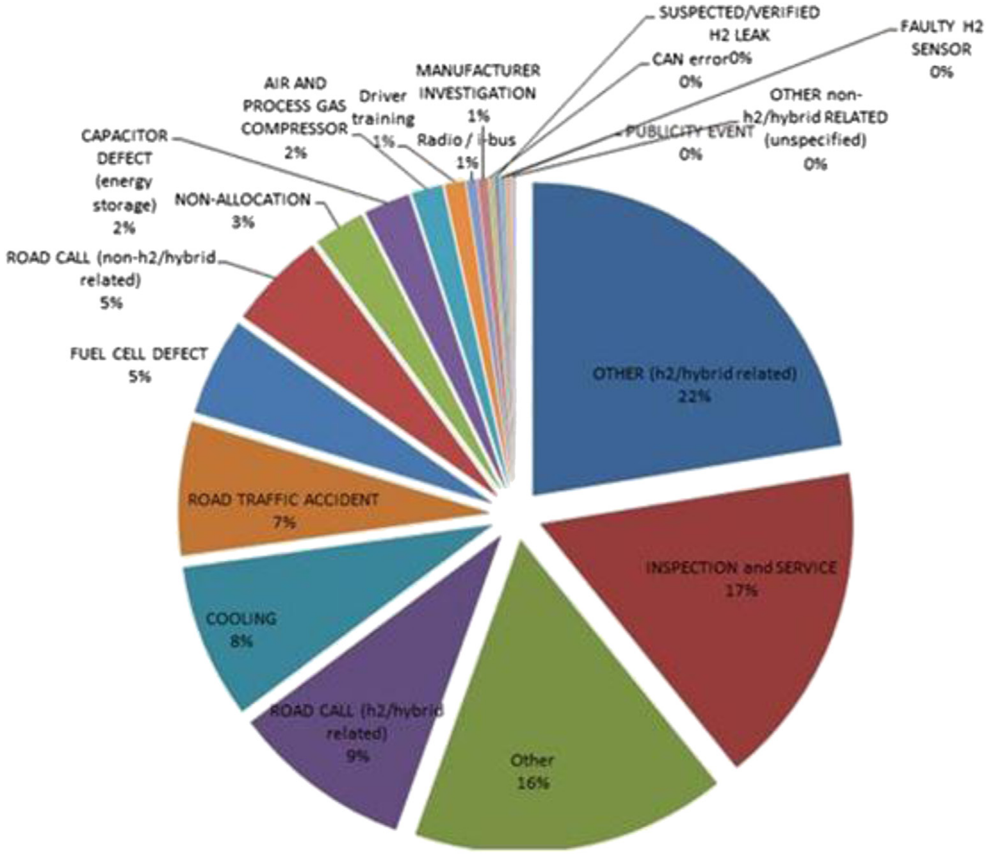


Fig. 15. Reasons for downtime in London FCEB deployment.
(Source: Transport of London)

well as unexplained warning lights (22% of downtime under 'OTHER (h2/hybrid related)'). It is expected that these types of issue will gradually be resolved as the current generation of FCEBs settles into service across the CHIC project and as the next generation of FCEBs are deployed in future projects, allowing the buses to achieve much closer to their potential availability exceeding 90%.

The indication across the rest of the CHIC project is that with many of the early teething problems and supply chain issues being addressed, FCEB availability will show a significant improvement in the next few months of operation. However it is not expected that the current generation of hybridized FCEBs will reach the long-term availability exceeding 90% which is expected for the next generation of buses.

3.1.3. Refueling time

Refueling time of the FCEBs deployed in London has ranged on average between 7 and 10 min for a full refueling of 30 kg. Note that due to the better-than-expected fuel efficiency of the FCEBs in the London fleet deployment, the onboard storage capacity was reduced from 46 kg to 30 kg by removing 2 of the 6 original storage tanks, in order to increase their passenger carrying capacity and this has had a positive effect on refueling times.

3.1.4. Future data availability from CHIC and other European projects

In addition to the above data, it is expected that considerably more performance and reliability data will become available over the coming year, for both European FCEB deployments from a range of projects including CHIC, and their supporting infrastructure.

4. Fuel cell bus activities in Canada

In Canada, the British Columbia (BC) Transit was charged with implementing a demonstration project by acquiring 20 fuel cell buses to provide zero emission transit service at the Resort Municipality of Whistler (the RMOW) in time for the 2010 Winter Olympics. This fleet operates as the backbone of the transit service in the RMOW. It continues to be the largest fuel cell fleet to operate in a single location at one time. Unlike other fuel cell bus programs (where small fleets have been introduced into larger fleets), the service in the RMOW relies almost exclusively on the hydrogen fuel

Table 6
Key performance data from January 2011 through May 2012.

Parameter	Unit	Value
Jan 2001 to May 2002		
Fleet accumulated mileage	km	2,189,974
Bus average accumulated mileage	km	108,499
CO_2 emission avoided	tons	3202
Hydrogen delivered to station	kg	549,143
Hydrogen dispensed to buses	kg	316,486
April 2011 to May 2012		
Average fuel economy	kg/100 km	15.3
Maintenance cost	$/km	1.0
Average range	km	366
Average bus availability	%	71
Mean distance between road call	km	2740
Hydrogen fuel cost	$/km	2.28
	$/kg	15.37
Average monthly fill rate	kg min^{-1}	2.2

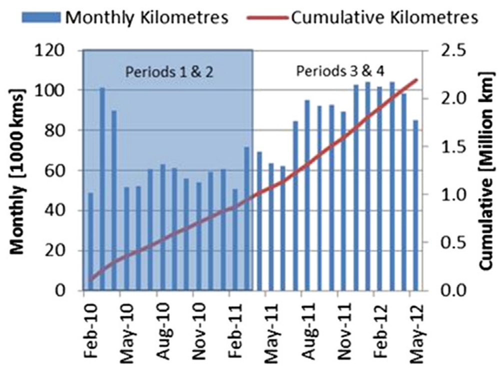


Fig. 16. Accumulated distance of complete fleet from February 2010 to May 2012.

cell powered buses for transit service. To date, the fuel cell fleet has logged approximately 3.8 million kilometers [18].

Not only does the operation in the RMOW have the largest fuel cell bus fleet, it also requires the largest hydrogen fueling station in the world to provide the fuel for the fleet. The hydrogen is shipped and stored in liquid form and dispensed into the demonstration fleet in a gaseous state.

The transit service in the RMOW is the most aggressive environment and duty cycle of all of BC Transit's transit systems. Coupling this environment with the largest fuel cell bus fleet and the largest hydrogen fueling station has provided a bench test that mimics the most aggressive transit environments in Canada.

4.1. Performance data

Table 6 summarizes the key performance data collected from January 2011 through May 2012. Additional data can be found in Ref. [19]. The data is shown and highlighted by the four project periods of operation. Periods 1 and 2 run from January 2010 to March 2011. During these periods, all buses were delivered to the RMOW in time for the Olympics. The buses were supported through an extensive team from Ballard, New Flyer and ISE Corp. These periods included significant commissioning and upgrades work. The fuel cell bus fleet was supplemented with a significant contingency fleet during this period to ensure that service was maintained. During Periods 1 and 2, operations and maintenance activities were generally developmental with inconsistent tracking and data recording. Data from these periods are therefore considered information only and are not used in any performance analysis.

Periods 3 and 4 run from April 2011 to May 2012. The buses were phased in through 15 day trials where each bus had to achieve 15 days of fault-free service. All buses completed the 15 day trial. Period 3 was a transitional period and is included in the analysis so that a full year can be reviewed (and to avoid seasonal skewing). Period 3 assessments result in a variety of measures that are not significantly different than Period 4. Period 4 is considered the key period for evaluation, as it reflects the closest to normal operations and is best suited to project the operational performance of the fleet for the remainder of the program.

4.1.1. Total kilometers and hours

Fig. 16 shows the monthly and total cumulative kilometers for the whole fleet. The figure shows the increase in usage experienced in Periods 3 and 4. Early commissioning and reliability issues kept the fleet from being fully utilized in Periods 1 and 2. Based on 2.1 million accumulated kilometers, the fuel cell fleet has avoided 3202 tons of CO_2 emissions.

4.1.2. Availability

Availability was calculated using the "Whistler Allocation Sheets," which provide a daily history of the buses – deployed, under maintenance or failed in service. The data are based on morning roll out availability and shown in Fig. 17. The average availability for Periods 3 and 4 was 71%, but shows evidence of seasonal fluctuations. The higher availability rate for Periods 1 and 2 was the result of a large vendor presence onsite. In Periods 3 and 4, the service became more dependent on the fuel cell fleet with the removal of eight Nova diesel buses from the RMOW fleet due to service cuts.

4.1.3. Roadcalls

The mean distance between roadcalls (MDBRC), shown in Fig. 18, was measured using Whistler Transit's maintenance records. These records yielded a fleet average MDBRC of 2740 km for periods 3 and 4 but, as with availability, there is evidence of seasonal influences on fleet reliability.

4.1.4. Fuel economy and cost

Fig. 19 shows the average monthly fuel economy of the fleet. Fuel economy decreases as the ambient temperature decreases through the winter months because the buses consume more fuel to provide heat to the passengers (via a 20 kW heater) and there is a sharp increase in passenger loads through the winter ski season.

Fuel cost per kilometer, shown in Fig. 20, was calculated based on the monthly minimum fuel costs plus the Monthly Facility Fee (MFF) paid to Air Liquide. The cost per kilometer has been

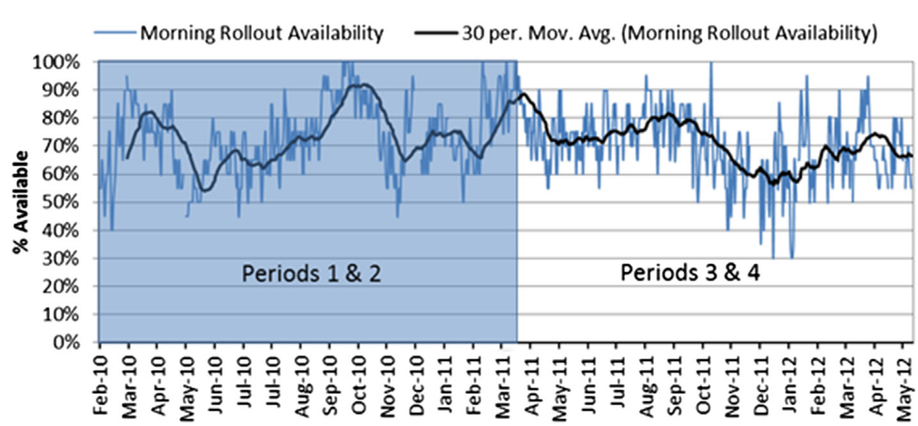


Fig. 17. Fleet availability from February 2010 to May 2012.

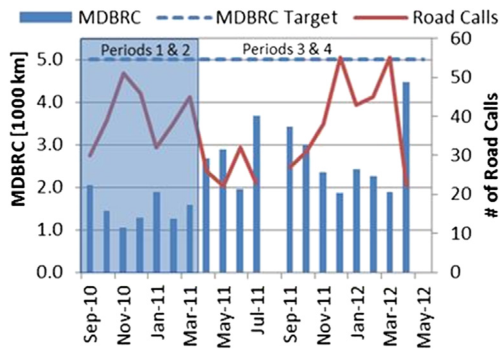


Fig. 18. Mean distance between road calls.

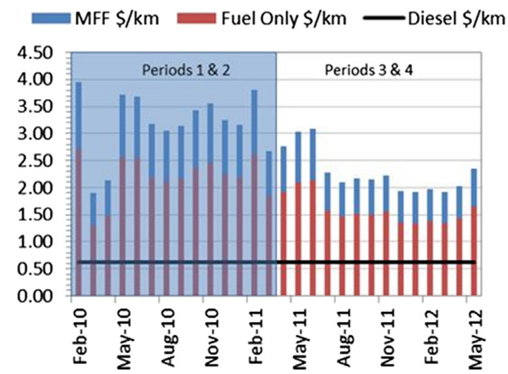


Fig. 20. Total fuel cost per km including monthly facility fee and monthly minimum consumption.

decreasing as usage of the fleet increases, due to the 'take-or-pay' terms of the contract with Air Liquide. The average cost for Periods 3 and 4 was $2.28/km (trending to $2.00 with full utilization of the 'take or pay'), compared to $0.60/km for the Whistler 2008 Nova diesel fleet operation in 2009.

4.1.5. Hydrogen fueling

Fig. 21 shows the quantity of fuel delivered to the site by Air Liquide. It also shows the division between fuel dispensed and fuel lost in the process. The large proportion of losses (40–45%) is not well understood and is pending an investigation by Air Liquide and BC Transit. Usage is defined by what is dispensed at the nozzle (blue lines); therefore, the losses do not impact the program.

Fig. 22 shows the average monthly fueling rate from the Air Liquide station. The data show a near-constant fueling rate throughout the project and are independent of the reliability of the fleet. The target fueling rate, established early in the project, is 5 kg min^{-1} (10 min fill for 50 kg). The significantly slower fueling rate has resulted in the requirement for an additional service person position at Whistler Transit.

4.2. Achievements and challenges

The buses have achieved the contractual performance requirements, except in the following areas: availability, reliability, noise and operating range. Based on the latest operating data, without significant design changes to the demonstration fleet there will be little or no change to availability or reliability.

The operational costs for the fuel cell buses are much higher than the costs for the Nova diesel bus fleet. The fuel cell buses lag incumbent diesel technology in the following areas: fuel costs (approximately twice that of a diesel bus), bus maintenance costs (approximately twice that of a diesel bus) and fueling service time requirements.

The fuel cell buses are capable of meeting the duty cycle of Whistler Transit with the continued effort and support of the suppliers. While there have been no apparent nor significant issues related to the fuel cell module and glider components, the propulsion and system integration designed by ISE Corp will remain an ongoing issue.

Fueling station performance and fuel delivery logistics have been sufficient; however, fueling times are over twice as long as originally proposed.

There is a need to address a number of performance factors to drive costs down and availability up, if performance is to approach that of incumbent technologies such as diesel buses. This includes the following:

- Improve reliability to reduce the need for contingency buses —due to availability, reliability and fuel range issues in winter months, the operation will likely need to be supplemented with contingency buses
- Reduce maintenance costs through improved reliability and lower component costs – fleet defects still remain (i.e. Eaton compressor) and some of these components are extremely expensive due to their exotic nature
- Reduce fuel costs by reducing fuel consumption to a level that provides the required 450 km range – system optimization targeted to reliability and bus availability has significantly affected fuel consumption
- Reduce the cost of hydrogen fuel – on a diesel equivalent basis, the price of hydrogen is over three times more expensive than diesel fuel (based on contract with Air Liquide)

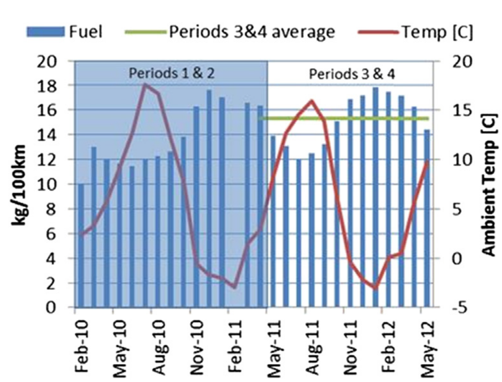


Fig. 19. Average monthly fuel economy.

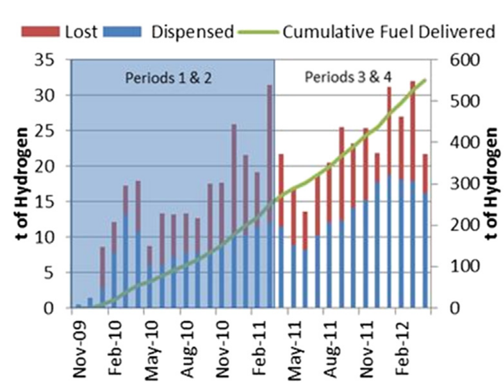


Fig. 21. Total fuel delivered including cumulative and the split between dispensed fuel and lost fuel.

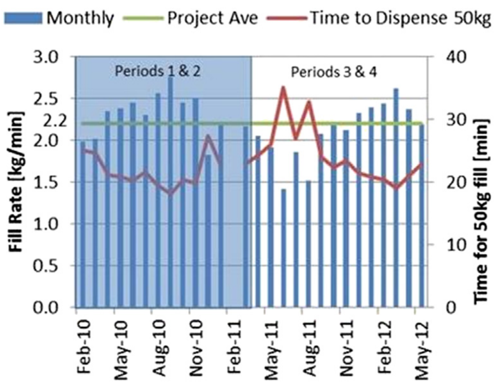


Fig. 22. Average fueling rate. The project average and time to dispense 50 kg are also shown.

- Design changes to deal with challenging environments – the extreme environment of the RMOW has shown some limitation in the technology

5. Fuel cell 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.
- The ClearEdge 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^{-1}.
- 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.

Some technical challenges and progress of ClearEdge Power's PEM power plants are discussed in this section. It should be noted that U.S. Hybrid has recently taken over the FTA contract from ClearEdge Power. The fuel cell stack utilizes unique water management strategy, which has been shown to enable higher power density and durability, as compared to solid plate fuel cells. Fig. 23 compares porous plate water management technology with that of solid plate fuel cells. Using a porous plate, the reactant gases are humidified internally. Any condensate is also adsorbed by the porous plate, keeping the flow fields clear of any liquid.

Fig. 24 shows the fleet operating cycle that is typically seen in any given hour of operation. A typical cycling frequency is ~100 load cycles per hour, with approximately 30% time spent at an idle condition, or high voltage condition. Load cycling has been shown

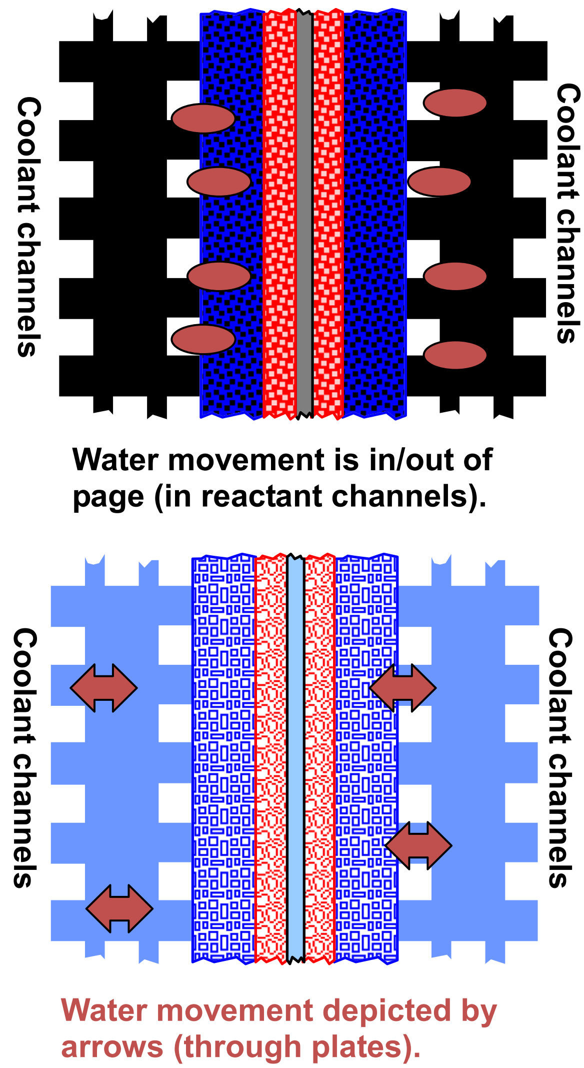


Fig. 23. Schematic comparing solid plate water management strategy (top image) and ClearEdge Power's porous plate water management strategy.

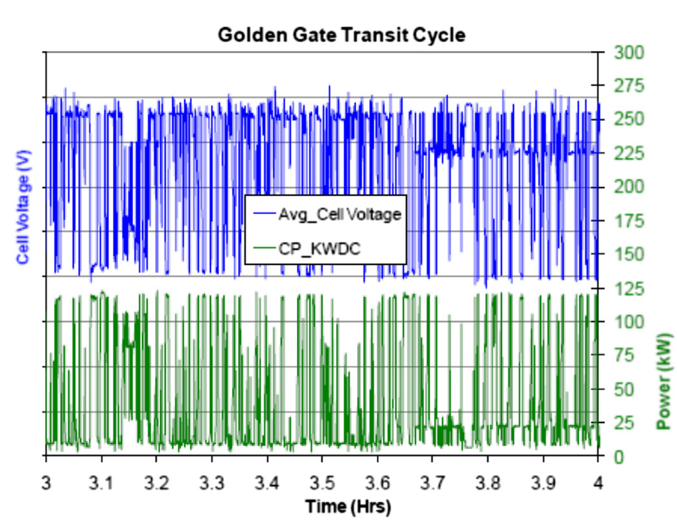


Fig. 24. Typical load-voltage profile for ClearEdge Power bus fleet.

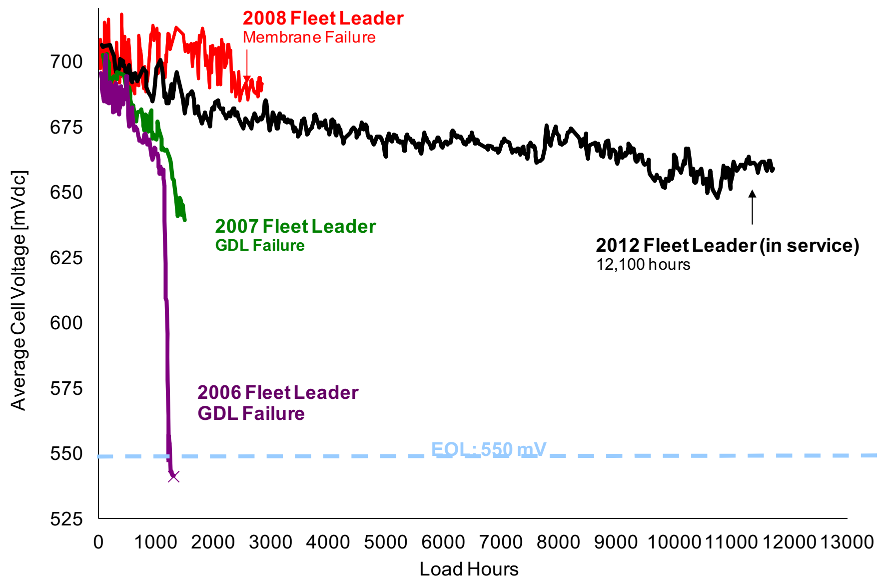


Fig. 25. ClearEdge Power fleet data.

to exacerbate platinum dissolution and carbon corrosion, inducing performance loss. Since the reactant flows follow the load, the membrane experiences hydration-dehydration cycling, which in turn cause failure, due to fatigue. In addition to load cycling, the bus is subjected to frequent start/stop cycles. Both mechanisms have led to early failure of bus power plants.

Three different versions of the Pure Motion 120 kW cell stacks have been deployed. The performance versus time for each version is shown in Fig. 25. The first version, labeled "2006 fleet leader", failed after roughly 1000–1500 h of operation. For those early units, the bus utilization was relatively low, and the service time was approximately one year. After 1000–1500 h of load time, the cell performance dropped rapidly, until the bus could not meet the minimum power requirement and had to be removed from service. Accelerated stress testing (AST) of the cell stack materials revealed that the microporous layer was vulnerable to oxidation. A new microporous layer showed a two-fold improvement in durability in the AST. Changes were made to the system to decrease start/stop losses, as well. After incorporating the new microporous layer and systems changes, the performance decay decreased, but unfortunately, the 2nd version, labeled "2008 fleet leader", failed after 2800 h, due to membrane failure near the air inlet.

During load cycling, the relative humidity of the gases changes at the reactant inlets. Fig. 26 shows model prediction of relative humidity during cycling. Results from mechanical stress modeling, shown in Fig. 27, show mechanical stress in the membrane reaches up to 7 MPa during load cycling. During 2800 h, the fuel cell undergoes over 300,000 of these stress cycles, ultimately failing due to mechanical fatigue.

A more durable membrane was evaluated in a combined membrane mechanical-chemical AST, as shown in Fig. 28. The more durable membrane showed at least a 10-fold improvement in durability in the membrane AST. This membrane was deployed in version 3, the "2012 fleet leader". The 2012 fleet leader has reached over 12,000 h, with a decay rate of 2 μV h^{-1} and no signs of membrane degradation. The bus has been in service for over 5 years.

As mentioned previously, the Whistler Bus demonstration program, the largest fuel cell bus fleet globally, was in service from October 2009 to March 2014. During this time it accumulated more than 3,800,000 km and more than 190,000 h of operation with 16,000 hydrogen refueling events. This fleet successfully operated

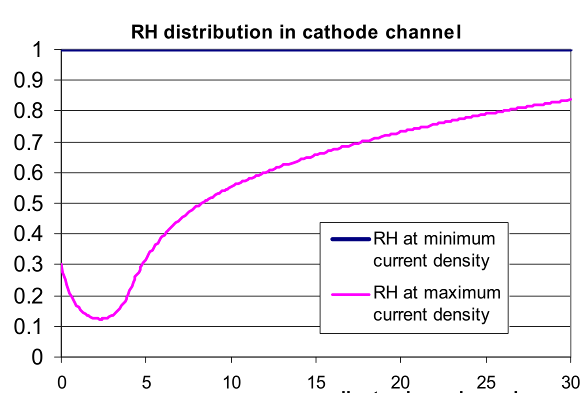


Fig. 26. Model results showing relative humidity of gases in cathode channel as function of distance from air inlet. The RH at minimum current density is unity.

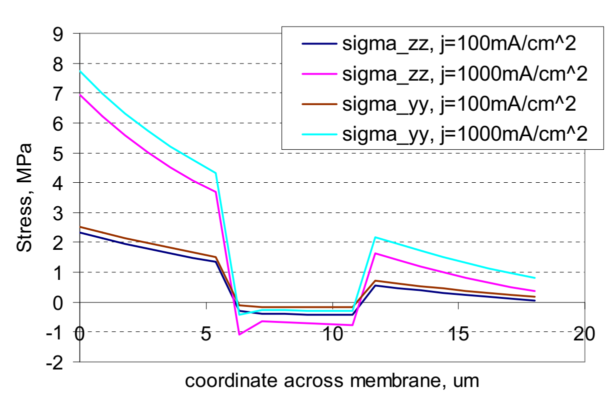


Fig. 27. In-plane elastic stress profiles in the membrane near air inlet ($y = 0.5$ cm) at the middle of the channel ($x = L_{ch}/2$) for two current densities ($j = 100$ mA cm^{-2} and $j = 1000$ mA cm^{-2}).

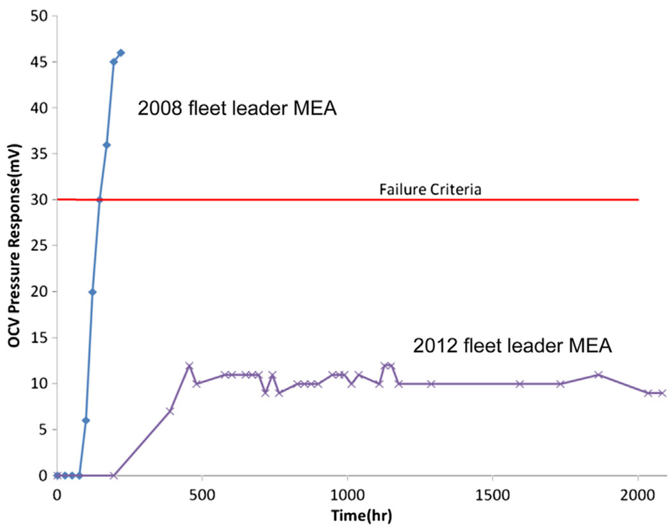


Fig. 28. Comparison of 2012 and 2008 fleet leader MEA in membrane mechanical-chemical AST.

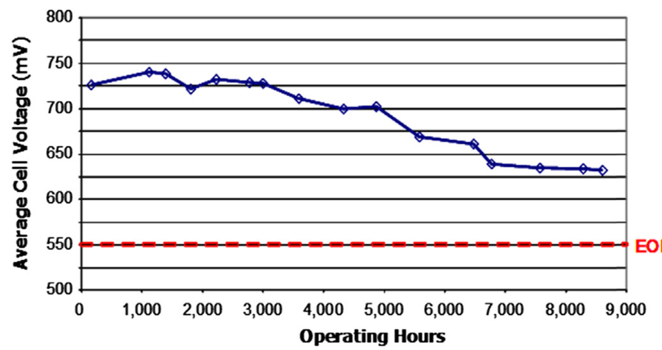


Fig. 30. Fuel cell stack performance at 250 A after ~9000 h of operation in Whistler.

on six different routes that include a challenging terrain that included steep up-hill and down-hill driving, encountered ambient temperatures from −12 °C to 27 °C that included snowfall from November to May, and salted roads. The buses generally encountered two start-up and shut-down conditions in a 14 h driving shift.

The dynamic driving conditions with idling at bus stops and traffic lights and start-up/shut-down conditions generally cause stress on the membrane electrode assembly (MEA) components promoting degradation of the polymer electrolyte membrane and the catalyst layers. Fig. 29 presenting the operational profile that was encountered by the Whistler buses, shows the dynamic current profile and corresponding humidity response.

Overall, the fuel stack performance of the buses met the end of demonstration target of 15% voltage loss based on the beginning of stack performance. In fact, the stack performance after ~9000 h was still well above the targeted performance loss as shown in Fig. 30. MEAs selected from stacks that operated in the field for ~4000 and 8000 h were analyzed for membrane and catalyst layer degradation and compared to MEAs that operated in the laboratory. The results, shown in Fig. 31, were compared to laboratory stacks that used the same MEA as the Whistler stacks and tested under the same temperature operating conditions and at 100% RH using a duty cycle that simulated field operation however, without shut-down/start-up event. The evaluation of membrane thinning, one of the measures of membrane degradation, did not show significant differences between the MEAs operated in field stacks or in the laboratory (Fig. 31). Thus global membrane thinning has not contributed to the performance degradation. However, some MEAs from both the bus and laboratory stacks showed evidence of some local pinhole formation. Fig. 32 shows a typical IR image of the MEA revealing thin spots and potential pinholes within the membrane. After carefully removing the catalyst layer from the membrane, pinholes and divots were exposed within the membrane which will affect fuel cell performance. This evidence is also supported by the observed leak rate within the stack.

An analysis of the electrochemical catalyst surface area (ECSA) of the cathode catalyst layer, Pt in the membrane, and catalyst layer thickness provides some insight into the catalyst layer degradation mechanisms. The ECSA change, an indication of Pt dissolution and subsequent agglomeration (shown in Fig. 33 for the cathode), shows the same trend for stacks operated in the field and those in the laboratory. One might argue that the field returns have somewhat lower ECSA loss which may be associated with the dynamic

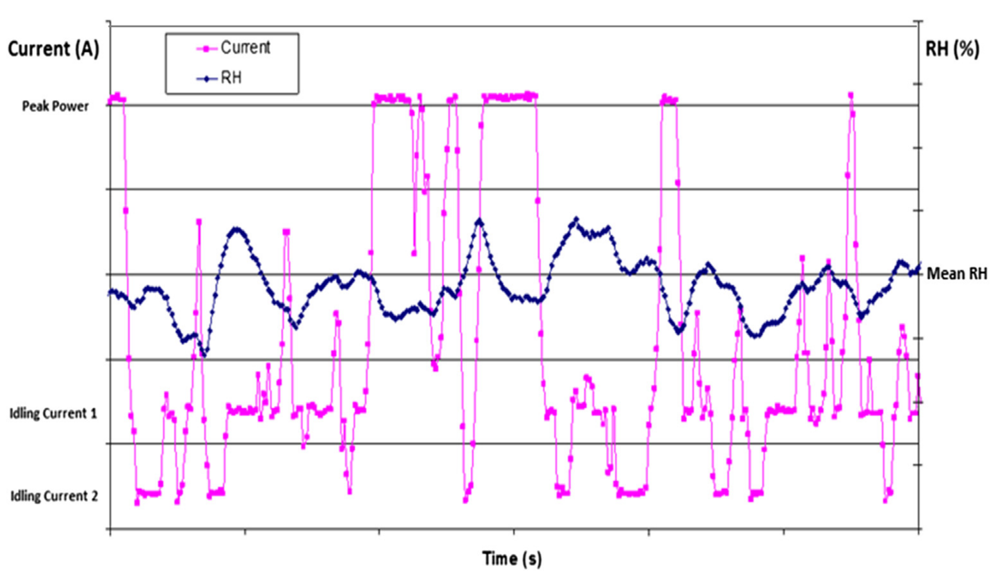


Fig. 29. Current profile and corresponding humidity profile of the Whistler buses.

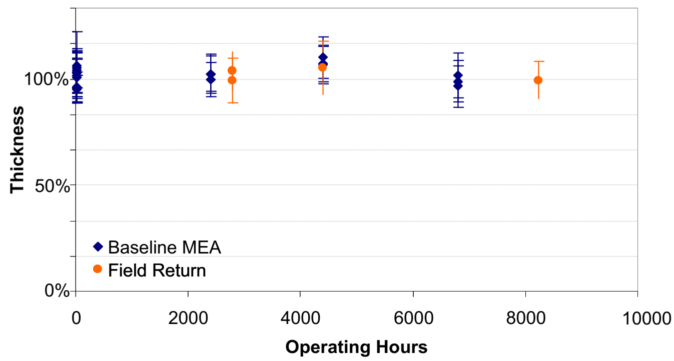


Fig. 31. Membrane thickness variation with operating hours of MEAs from the Whistler buses and stacks with the same MEA (baseline) operated in the laboratory.

humidity profile the field stacks experienced (shown in Fig. 29), while the ones in the lab operated at a constant RH of 100%. Pt dissolution has been shown to increase with increasing RH operation.

Platinum dissolution also causes Pt to migrate from the cathode into the membrane where it forms a Pt band [20]. Fig. 34, a comparison of the Pt in the membrane content of the field operated stacks and those tested in the lab, again shows very little difference however in agreement with the slightly lower ECSA loss, the Pt in the membrane is also slightly lower.

A thinning of the catalyst layer with operation would indicate corrosion of the carbon support of the Pt catalyst due to high cathode voltage excursions experienced during shut-down/start-up operation. As shown in Fig. 35 no significant differences in cathode thickness were observed in field operated vs. lab tested results.

In summary, the voltage loss of the bus stacks is likely at least in part caused by the development of local pin holes in the membrane. While the overall ECSA loss with operation seems substantial, this loss cannot account for the observed performance degradation of the Whistler buses. Small scale laboratory results have shown that for baseline MEAs an ECSA loss of 50% does not significantly affect fuel cell performance.

In parallel to technology developed at the fuel cell manufacturers, fuel cell technology for buses has been actively pursued in the academia. Beyond the NFCBP, FTA funds fuel cell bus research at several universities. The research at the universities in North America and Europe has produced improvement in fuel cell technology for electric bus ranging from modeling tools to assist in the design of the supervisory energy management [21] to the development of a hydrogen range extender in hybrid electric bus [22].

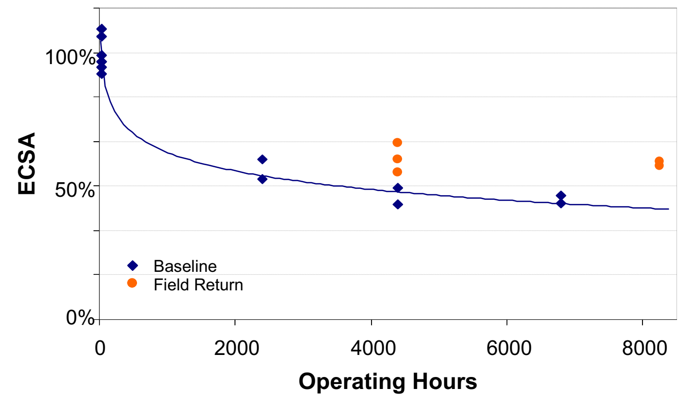


Fig. 33. Cathode ECSA changes with operating hours for MEAs from the Whistler buses and stacks with the same MEA (baseline) operated in the laboratory.

6. Hydrogen infrastructure

6.1. North America

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. 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 in the United States are:

- Proterra fuel cell bus: 66 kg storage capacity with 120 kg day^{-1} maximum dispensing amount; 7000 psi off-board storage pressure for 5000 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.

The Emeryville station is a combined facility for light-duty fuel cell electric vehicles (FCEVs) and FCEBs. Funding from the state of California made the light-duty FCEV fueling access possible – dispensers are available to fuel at 350 and 700 bar pressure.

Fig. 36 provides a simple block diagram of the station and primary components. Hydrogen is provided from two sources: liquid

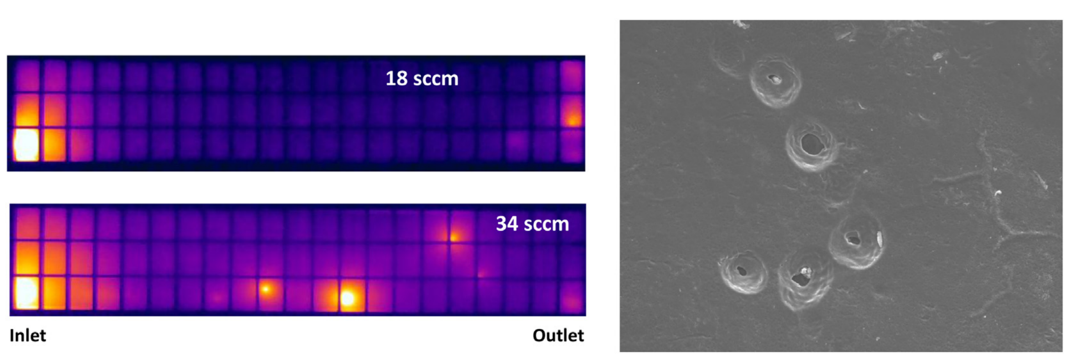


Fig. 32. Typical IR image and pinhole in the membrane of an MEA that was operated in the Whistler fuel cell stack.

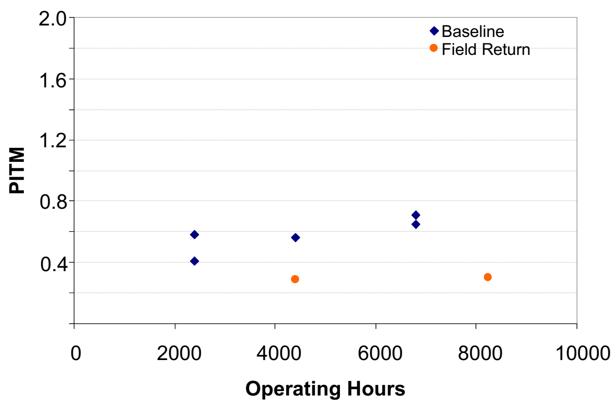


Fig. 34. Platinum migrated into the membrane after different operating hours of MEAs from the Whistler buses and laboratory stacks with the same MEA (baseline).

hydrogen delivery and a solar-powered electrolyzer. Hydrogen from both sources feeds into high-pressure gaseous storage tubes for fueling buses and autos. The electrolyzer is capable of producing 65 kg of hydrogen per day. When combined with the liquid hydrogen delivered, the station has the capacity to dispense up to 600 kg of hydrogen.

The station uses two compressors: one is a high-pressure mechanical compressor and the other is an ionic compressor. The mechanical compressor (MF-90) handles the FCEV side of the station and is capable of filling at both 350 and 700 bar. Linde's ionic compressor (IC-50) handles the bus fueling side of the station. This compressor uses a proprietary ionic liquid in place of a mechanical piston. Ionic liquids are made up of organic salts that remain in a liquid state within a specific temperature range. Composed entirely of particles with negative and positive charges, the liquid is nearly incompressible and behaves like a solid material during compression. Using liquid instead of conventional metal pistons means fewer moving parts and no need for lubricants that could cause contamination. This also results in higher operating efficiency. The station also has an emergency dispenser for the buses in case there are issues with the primary fueling dispenser. The buses can be fueled quickly – 30 kg in about 6 min.

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^{-1}), liquid vaporization and

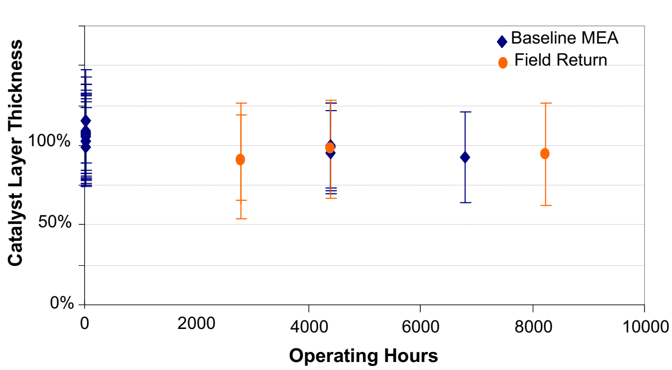


Fig. 35. Catalyst layer thickness changes with operating hours of MEAs from the Whistler buses and laboratory stacks with the same MEA (baseline).

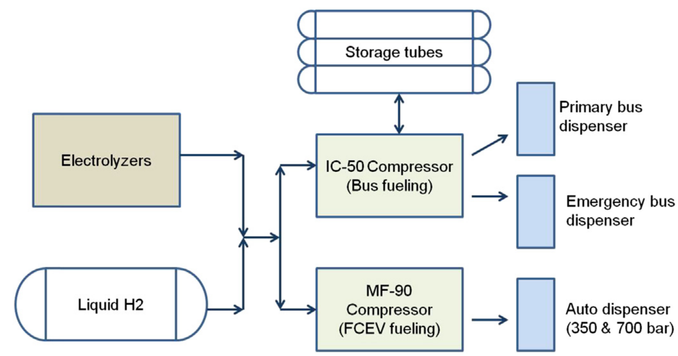


Fig. 36. Block diagram of the Emeryville station.

gas compression to 1000 bar, by gas booster for up to 10 kg day^{-1} or by membrane compressor for 100–1000 kg day^{-1}. 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^{-1}, 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 5300 kg; 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.

Air Products has been involved in H_2 energy projects since 1993, with an accumulated experience base of more than 130H$_2$ 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 5000 kg in 6 h, corresponding to an average fill rate of 13.9 kg min^{-1}. Industrial customers, by comparison, are more varied: refinery, 283,000 kg day^{-1}, 24/7 demand; large liquid H_2 customer, 5000 kg day^{-1}, 24/7 demand; forklift site, 75–200 kg day^{-1}, 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 7200 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.

6.2. Europe

Details of the new refueling sites deployed as part of CHIC are listed in Table 7. To date, the sites in London, Aargau and Oslo, are fully operational. However, as with the bus performance and reliability data, no data has yet been released from the CHIC project in relation to the performance and reliability of the refueling infrastructure deployed, except for the London deployment where an excellent availability level of over 99% has been achieved.

Data is available from the CUTE and HyFleet:CUTE projects running from 2003 to 2009 (>555 tons of hydrogen dispensed, >13,000 refuelings, 89.8% overall station availability, etc.), but this does not represent the state-of-the-art of hydrogen refueling technologies and initial data from the CHIC stations suggest reliability over 98% is regularly being achieved.

Table 7
List of new hydrogen refueling infrastructure deployed in Phase 1 CHIC cities.

Phase 1 partners	Pre-existing fueling infrastructure	Capacity	Second fueling infrastructure	Capacity
London	Delivered liquid – Air Products	320 kg day^{-1}	High pressure tube trailer	100 kg day^{-1}
Bolzano	Delivered hydrogen	Delivered hydrogen	Electrolyzer to be procured	500 kg day^{-1}
Aargau/St. Gallen	Not required		Electrolyzer to be procured	200 kg day^{-1}
Milan	Reformer	30 kg day^{-1}	Electrolyzer to be procured	200 kg day^{-1}
Oslo	Delivered hydrogen	22 kg day^{-1}	Delivered hydrogen or Electrolyzer to be procured	200 kg day^{-1}

7. Projections and targets

7.1. United States

Table 8 lists the 2016 and ultimate targets for fuel cell transit buses. The targets [23] were established by the Department of Energy and the Department of Transportation's Federal Transit Administration in collaboration with private and public entities. The 2013 status of FCEBs performance are also shown for comparison. Several of the technical performance targets have been achieved or nearly achieved. These include fuel economy, range, operation time, maintenance cost, bus availability and roadcall frequency.

Based on industry input, the capital cost of an FCEB, currently at $2,000,000, can meet the 2016 target of $1,000,000 through a limited production of FCEBs of the same design, while the $600,000 target requires high volume manufacturing at fully commercial level [24]. Increasing the durability and reliability of the fuel cell system continues to be a key challenge for manufacturers. The FTA life cycle requirement for a full size bus is 12 years or 500,000 miles. A fuel cell power plant (FCPP) needs to last about half of that time; this is similar to a diesel engine that is typically rebuilt at about mid-life of the bus. DOE/FTA set an ultimate performance target of 4–6 years (or 25,000 h) durability for the fuel cell propulsion system, with an interim target of 18,000 h by 2016. Manufacturers have continued to make significant progress toward meeting the target over the last year. As of July 2012, an FCPP manufactured by ClearEdge Power has reached 12,000 h.

7.2. Europe

A number of studies have been undertaken to project the future performance and cost for FCEBs in Europe. The two most relevant and recent studies [25,26] are sponsored by FCH JU and 'Nexthylights', an FCH JU-funded industry collaboration project. The results of these studies are illustrated here. Both the FCH JU and the Hydrogen Bus Alliance have set targets relevant to Europe for a range of performance metrics and these are referenced in the results of the above studies.

Table 8
2013 DOE/DOT/FTA performance, cost, and durability targets for fuel cell transit buses.

	Units	2013 Status	2016 Target	Ultimate target
Bus lifetime	years/miles	5/100,000	12/500,000	12/500,000
Power plant lifetime	hours	1000–12000	18,000	25,000
Bus availability	%	53–84	85	90
Fuel fills	per day	1	1 (<10 min)	1 (<10 min)
Bus cost	$	2,000,000	1,000,000	600,000
Power plant cost	$	700,000	450,000	200,000
Hydrogen storage cost	$	100,000	75,000	50,000
MBRC, Bus	miles	2000–3500	3500	4000
MBRC, fuel cell system	miles	7000–20,000	15,000	20,000
Operation time	h d^{-1}, d week^{-1}	19/7	20/7	20/7
Maintenance cost	$/mile	0.39–1.30	0.75	0.4
Range	Miles	220–325	300	300
Fuel economy	mpgde	6–7.5	8	8

7.2.1. Bus costs

The capital cost of the latest generation of hybridized FCEBs deployed in Europe has ranged from approximately €1–1.5 mn, as shown in Fig. 37. The cost-down trajectory from earlier trials is consistent with achieving the HBA target of a price range of €400–750 k by 2015.

However, Fig. 38 illustrates industry projections for cost-volume reductions to 2020, in which the 2015 HBA lower target is only realistically expected to be achieved by 2020. It is expected that cost reductions from 2010 to 2015 will occur as a result of technological improvements and learning lessons, whereas from 2015 to 2020 cost reductions will rely on the volume of fuel cell systems produced and cross-industry cost-volume reductions from the widespread rollout of FCEVs in the car industry. It is expected that with significant deployment volumes by 2030, the cost of FCEBs will remain €100–200 k higher than conventional diesel buses, and. €50–100 k higher than diesel hybrid buses.

7.2.2. Availability

Availability for hybridized FCEBs is targeted to range from 85 to 95% by 2015, as shown in Fig. 39. While this target has already been met for non-hybridized FCEBs (92% availability during the HyFleet:CUTE project), hybridized FCEB deployments have not yet achieved targeted availabilities, for a range of reasons mainly related to the novelty of hybridized designs, with causes of failure including:

- Failures centered on the hybrid-enabling components, such as power electronics, batteries, control systems and integration issues, rather than the core fuel cell components. These types of issues are expected to improve with each subsequent

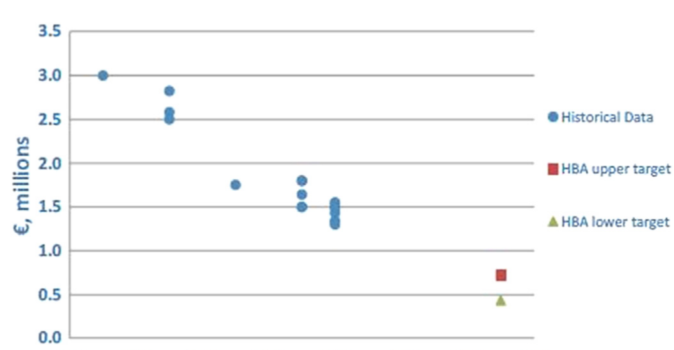


Fig. 37. Historical FCEB capital costs, with HBA targets.

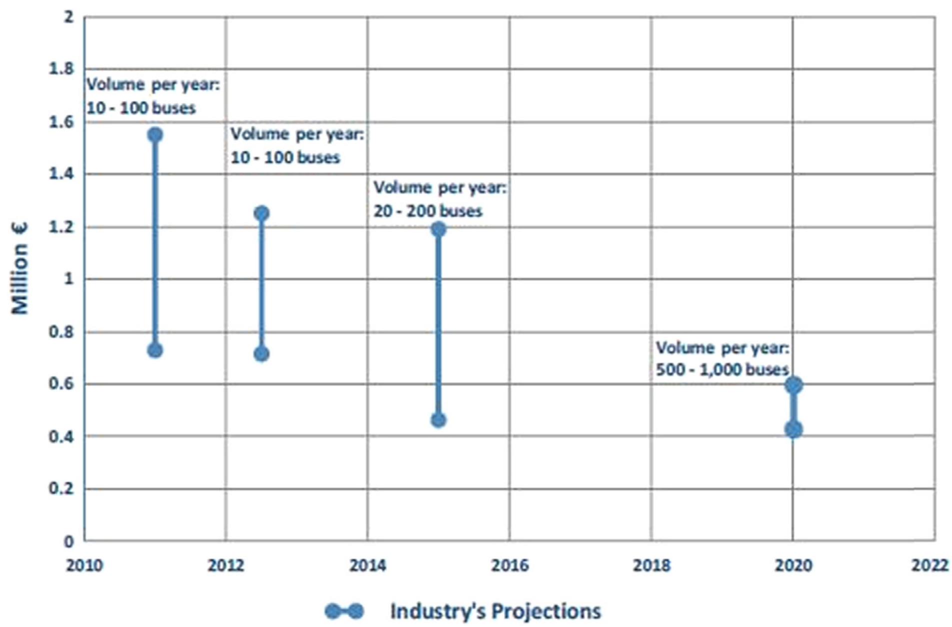


Fig. 38. FCEB capital cost industry projections.
(Source: Nexthylights)

generation of FCEBs and as learning lessons from the widespread deployment of diesel hybrid buses take effect.

- Lower than expected availability in a number of projects due to early teething problems and immature supply chains for the maintenance of the vehicles. This is expected to improve rapidly as lessons are learned from existing deployments.

7.2.3. Range and fuel economy

With the recent introduction of the latest generation of hybrid FCEBs with superior fuel efficiency to non-hybridized FCEBs, 2015 range targets of 500 km are now either being met or within reach, as shown in Fig. 40.

For those buses with insufficient range ability servicing certain more rural routes, the integration of additional hydrogen storage tanks would enable them to achieve their range targets, at the expense of reducing passenger capacity.

In parallel with the increase in range ability of FCEBs, their fuel economy has shown a step change between non-hybridized and the latest hybridized deployments in Europe, improving from 22 kg/100 km to 10 kg/100 km, as shown in Fig. 41.

The best of the latest fuel economy figures already exceed the JTI targets, while the more stringent HBA target of 8 kg/100 km is expected to be achieved with the next generation of hybridized fuel cell systems.

It must be noted that different drive cycles between projects result in inconsistent results, so a standardized drive cycle testing procedure would benefit the industry in terms of understanding fuel economy performance in greater detail.

7.2.4. Weight

Weight restrictions are an important factor in the future commercial deployment of FCEBs, with the current range of FCEBs weighing up to 2.5 tons more than a conventional diesel bus. This is likely to cause an issue for busy urban routes where maximizing passenger capacity is a key operational requirement.

However, the weight of FCEBs is expected to converge on the weight of conventional buses as improved efficiencies result in reduced hydrogen storage equipment weight and improved design

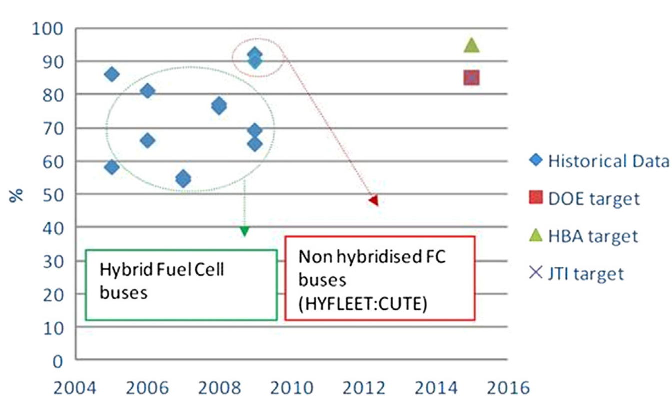


Fig. 39. Current and future expected FCEB availability.
(Source: Nexthylights)

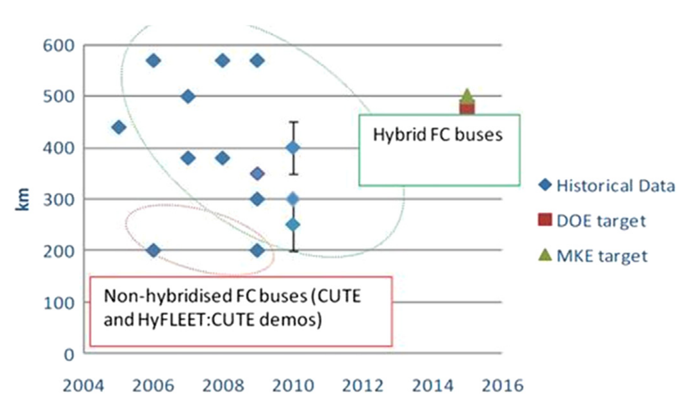


Fig. 40. Current and future expected FCEB range.
(Source: Nexthylights)

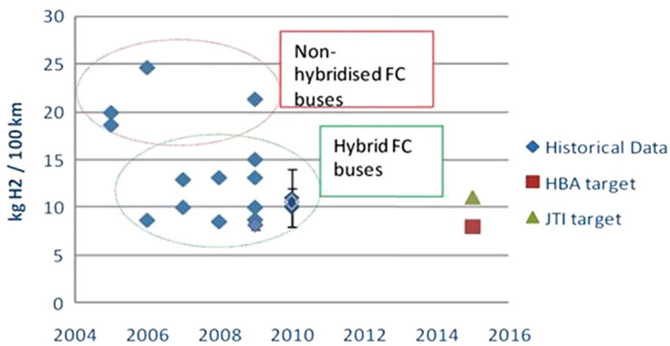


Fig. 41. Current and future expected FCEB fuel economy.
(Source: Nexthylights)

of the hybridized system result in lower balance-of-plant and other supporting equipment weight.

8. Summary

FCEBs have been proven to operate with zero local emissions, reduced noise and reduced emissions on a well-to-wheel basis compared to traditional diesel buses. In addition, FCEBs are significantly more fuel efficient. The performance data for FCEBs deployed in demonstration projects in North America and Europe is improving substantially over time. Some technical targets for commercialization have been met or are within reach. These include fuel economy, range, availability, operation time, MBRC and maintenance cost. The main barriers for FCEBs, compared to conventional diesel buses, are a lack of infrastructure for refueling, the high bus capital cost and meeting a fuel cost of \$5–7 per kg H_2 [26] at which price the fuel cost per mile will be competitive with conventional buses. These challenges are being addressed in demonstration projects globally.

Acknowledgments

This work was supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. Argonne National Laboratory, a U.S. Department of Energy Office of Science laboratory, is operated by UChicago Argonne, LLC, under Contract No. DE-AC02-06CH11357. The authors acknowledge the contribution of the Advanced Fuel Cells Implementing Agreement, IEA, from which this paper results, specifically the activities of Annex 26: Fuel Cells for Transportation. Please see www.ieafuelcells.com for more information.

References

[1] L. Eudy, K. Chandler, Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: Second Results Report, July 2012. NREL Technical report, NREL/TP-5600–55367.
[2] R. Zaetta, B. Madden, Hydrogen Fuel Cell Bus Technology State of the Art Review, Feb 2011. NextHyLights Report, Version 3.1.
[3] International Fuel Cell Bus Collaborative, http://gofuelcellbus.com/index.php/the-collaborative/all-active-demonstrations.
[4] L. Eudy, C. Gikakis, Fuel Cell Buses in U.S. Transit Fleets: Current Status 2013, December 2013. NREL Technical report, NREL/TP-5400–60490.
[5] L. Jerram, Fuel cell buses in perspective: international program and the global transit bus market, in: National Fuel Cell Bus Workshop, October 2011.
[6] See http://chic-project.eu/.
[7] See http://highvlocity.eu/.
[8] See http://busonline.ca/fuelcell/fleet.cfm.
[9] T. Ikeda, FCV/Infrastructure Demonstration Program in Japan, in: IEA Advanced Fuel Cells Annex 26 Workshop, May 14, 2013.
[10] See Hyundai Press Release, http://worldwide.hyundai.com/WW/Corporate/News/News/DF_GT_GLOBALNEWS_063.html?testValue=DF_WW_RD_GLOBALNEWS&title=DF_GT_GLOBALNEWS_063&selx2=.
[11] R. Lin, X. Pan, X. Li, Chinese hydrogen and fuel cell activities in 2010–2011, in: International Partnership for Hydrogen and Fuel Cells in the Economy Joint SC/ILC Meeting, Vancouver, Canada, May 2011.
[12] Ballard Press Release. http://www.ballard.com/about-ballard/newsroom/news-releases/news09261301.aspx.
[13] Ballard Press Release. http://www.ballard.com/about-ballard/newsroom/news-releases/news12271101.aspx.
[14] Ballard Press Release. http://www.ballard.com/about-ballard/newsroom/news-releases/news01271201.aspx.
[15] K. Chandler, L. Eudy, FTA Fuel Cell Bus Program: Research Accomplishments through 2011, March 2012. FTA Report No. 0014.
[16] McKinsey Global GHG Abatement Cost Curve; International Energy Agency World Energy Outlook, US Environmental Protection Agency; European Environment Agency (EEA), 2009.
[17] HyFleet:CUTE, A Report on the Achievements and Learnings from The HyFleet:CUTE Project 2006-2009. http://hyfleetcute.com/data/HyFLEETCUTE_Brochure_Web.pdf.
[18] Ballard, http://www.ballard.com/fuel-cell-applications/bus.aspx.
[19] L. Eudy, M. Post, BC Transit Fuel Cell Bus Project: Evaluation Results Report, February 2014. NREL Technical Report, NREL/TP-5400-60603.
[20] T. Cheng, E. Rogers, A. Young, S. Ye, V. Colbow, S. Wessel, J. Power Sources 196 (2011) 7985–7988.
[21] K. Simmons, Y. Guezennex, S. Onori, J. Power Sources 246 (2014) 736–746.
[22] F. Sergi, L. Andaloro, G. Napoli, N. Randazzo, V. Antonucci, J. Power Sources 246 (2014).
[23] U.S. DOE Fuel Cell Bus Targets. http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf.
[24] A Road Map for Fuel Cell Electric Buses in California, California Fuel Cell Partnership, March 2013. http://cafcp.org/sites/files/A_Roadmap_for_Fuel_Cell_Electric_Buses_in_California_FINAL.pdf.
[25] Building a Commercially Viable National Fuel Cell Electric Bus Program, Fuel Cell and Hydrogen Energy Association, March 2011. http://cafcp.org/sites/files/Building%20a%20Commercially%20Viable%20National%20Fuel%20Cell%20Transit%20Bus%20Program.FINAL_.v10.03-25-11.pdf.
[26] Urban Buses: Alternative Powertrain for Europe. http://www.fch-ju.eu/sites/default/files/20121029%20Urban%20buses,%20alternative%20powertrains%20for%20Europe%20-%20Final%20report_0.pdf.