# A Road Map for Fuel Cell Electric Buses in California

***A zero-emission solution for public transit.***

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# *EXECUTIVE SUMMARY*

California has made great strides towards improving its air quality over many decades, but transportation remains the state's dominant source of air pollution. If California is to meet its air quality improvement and emissions reduction goals, it must begin developing the commercial markets for zero-emission vehicles (ZEVs) now, including fuel cell electric buses (FCEBs). The magnitude of these changes will require the complete transformation of transportation to zero or near-zero technologies by 2050.

The California Fuel Cell Partnership and its members believe the introduction of fuel cell electric buses in California is key to achieving these goals. However, the environmental benefits of zero-emission vehicles and the policy goals which promote them can only be achieved if the capital and operating costs of FCEBs can be accommodated through local, state and federal budgets. An investment in the deployment of FCEBs, at production volumes rather than multiple small demonstrations, realizes the next critical step towards FCEB commercialization by enabling the cost reductions required for widespread adoption.

*A Road Map for Fuel Cell Electric Buses in California* establishes a plan for the introduction of FCEBs in California by:

- Illustrating the connection to state policy objectives
- Providing a review of existing demonstrations with an emphasis on California sites
- Analyzing the state of the technology for the vehicles and fueling infrastructure, using the federal government's Technology Readiness Level (TRL) and published DOE/DOT performance, cost and durability targets.

This road map provides a specific strategy and investment cost for the implementation of ***two Centers of Excellence*** in Northern and Southern California. Two centers will allow for economies of scale sufficient to achieve 2016 DOE/DOT targets and begin to overcome the primary barriers to market: the capital cost of the vehicles and the cost of fuel.

Lastly, *A Road Map* offers recommended state and federal actions required to support this strategy and move forward.

*The California Fuel Cell Partnership is a collaboration of organizations, including auto manufacturers, energy providers, government agencies and fuel cell technology companies, that work together to promote the commercialization of hydrogen fuel cell electric vehicles. By working together, we help ensure that vehicles, stations, regulations and people are in step with each other as the technology comes to market.*

## *INTRODUCTION*

While California has made great strides towards improving its air quality over many decades, residents living in several regions still experience the worst air quality in the nation.[1] Transportation remains the state's dominant source of air pollution. About 96% of the vehicles in California use petroleum-based fuels, and produce 50% of the criteria pollutants and 38% of greenhouse gas emissions.

Transportation-related air pollution will need to be reduced by 90-95% below 2010 levels by 2050 if these regions are to meet national health-based air quality standards as required by federal law,[2] and greenhouse gas emissions from transportation will need to fall by 85%. Both are necessary to meet California's 2050 climate goals.[3] The magnitude of the changes needed in the coming decades will require the complete transformation of transportation to zero or near-zero technologies by 2050. If California is to meet its emissions reductions goals it needs to begin developing the commercial markets for zero-emission vehicles (ZEVs), including buses, now.

Light-duty passenger vehicles and heavy-duty vehicles -especially buses- powered by hydrogen fuel cells will be an important element in California's plan to achieve its targets for air quality and pollution reductions. The critical role of zero-emission buses is acknowledged in Governor Brown's *2013 ZEV Action Plan*.[4]

California has gained considerable experience with the development and demonstration of zero-emission vehicle (ZEV) technologies through its zero-emission bus (ZBus) program. Fuel cell buses have consistently demonstrated superb operating performance in their ability to maintain sustained power and acceleration in a wide spectrum of operating conditions, smooth and quiet operation, and unmatched fuel efficiency.

The ZBus program takes advantage of the fact that transit agencies tend to be first adopters of advanced heavy-duty vehicle technologies. Such programs enable the private sector to adopt these technologies. Supporting ZEBs will not only help local transit agencies contribute to reduced on-road emissions, it will also help develop the technology for use in other medium and heavy-duty platforms.

These environmental benefits and policy goals can only be achieved, however, if buses are available at capital and operating costs that meet the budgets of transit as well as state and federal agencies. Achieving these targets is possible with the deployment of fuel cell electric buses (FCEBs) at production volumes rather than through small demonstration fleets, an approach supported by the funding model for zero and near-zero emission buses in the federal transportation bill "Moving Ahead for Progress in the 21st Century Act" (MAP-21).[5]

*A Road Map for Fuel Cell Electric Buses in California* was created by members of the California Fuel Cell Partnership to address the question: **"How can FCEBs become one of the advanced vehicle technologies that transit agencies will choose to fulfill California's goal of decreasing transportation air pollution?"** This strategy document characterizes the steps necessary to move from the pre-commercial phase of FCEB deployment and manufacturing (2012-2015) to the early commercial phase (2016- 2017) to a commercial model in 2018 and beyond, including the requisite fueling infrastructure. It draws the best available information from members and other stakeholders involved with the deployment of fuel cell buses and fueling stations.

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[1] American Lung Association, State of the Air 2012. http://www.stateoftheair.org/.

[2] CARB, SCAQMD & SJVAPCD, June 27, 2012. Vision for Clean Air: A Framework for Air Quality and Climate Planning, Public Review Draft. http://www.arb.ca.gov/planning/vision/vision.htm. **Note**: Interim targets for NOx under State Implementation Plans (SIPs) seek 80 percent reductions below 2010 levels by 2023, and nearly 90 percent reductions by 2032

[3] *Ibid.*, Also see: Governor Schwarzenegger Executive Order S-3-05, June 1, 2005., Also see: Governor Brown Executive Order B-16-2012, March 23, 2012.

[4] Available at: http://opr.ca.gov/docs/Governor's_Office_ZEV_Action_Plan_(02-13).pdf.

[5] Available at: http://www.fmcsa.dot.gov/about/what-we-do/MAP-21/Map21.aspx.

## California context, policy goals

In 1990, as one of its strategies, the California Air Resources Board (ARB) adopted an ambitious program to dramatically reduce the environmental impact of light-duty vehicles through the gradual introduction of zero-emission vehicles (ZEVs). The state's commitment to zero-emission vehicles reflects the understanding that advanced vehicle technology is necessary to achieve public health goals, including reductions in criteria pollutants and greenhouse gas emissions. It also reflects the fact that several regions continue to exceed state and federal air quality standards.

Following the implementation of the ZEV program, the ARB created the Zero-Emission Bus (ZBus) regulation in January 2000 which mandated ZBus demonstration fleets, leading to a 15% purchase requirement for transit agencies with fleets larger than 200 urban buses.[6,7] Industry responded to the ARB regulation with competitive development activities and a series of improved bus designs, including fuel cell electric buses (FCEBs). The development of the hybrid fuel cell electric bus led to ZBuses with a 250- to 300-mile range and fuel economy nearly twice that of conventional technology. Worldwide, more than 10 bus manufacturers have incorporated hybrid fuel cell electric drive trains into their buses, which have accumulated millions of miles in daily revenue service. The largest demonstration test programs in North America are located in the San Francisco Bay Area, which is served by a fleet of 12 FCEBs; and Whistler Village in Canada, where 20 FCEBs make up the majority of the bus fleet. In recent years, the 15% purchase requirement of the ZBus regulation was placed on hold to allow for technology enhancements, cost reduction and more definitive demonstration data from the most recent series of FCEBs.

To encourage further progress with California's environmental, technology, and energy goals, Governor Brown signed Executive Order B-16-2012 on March 23, 2012 directing state agencies to support and facilitate the rapid commercialization of ZEVs. The order directs the ARB, California Energy Commission (CEC), California Public Utilities Commission (CPUC) and other relevant agencies to collaborate with the Plug-in Electric Vehicle Collaborative (PEVC) and the California Fuel Cell Partnership (CaFCP) in working toward these major milestones:

- **2015** - Communities are ready for plug-in and hydrogen vehicles and infrastructure
- **2020** - California will have established adequate infrastructure to support 1 million ZEVs
  - Widespread use of ZEVs for public transportation and freight transport
- **2025** - More than 1.5 million ZEVs will be on the roads and the market is expanding

The commercial launch for passenger FCEVs in Northern and Southern California has been addressed in the recent California Fuel Cell Partnership document, *"A California Road Map,"* which focuses on the locations and funding for a network of hydrogen fueling stations to support the state's goals. This document lays out a parallel path for FCEBs.

[6] "Urban bus" defined in the California Code of Regulations, Title 13, Section 2023 (a) (13).
[7] Current Zero Emission Bus Regulation is California Code of Regulations, Title 13, Section 2023.3 or http://www.arb.ca.gov/msprog/bus/zeb/zbusregorderfinal.pdf.

## Fuel cell electric bus technology

A *proton exchange membrane* fuel cell electrochemically combines hydrogen and oxygen from the air to produce electricity, heat and water. To obtain the desired amount of electrical power, individual fuel cells are combined to form a fuel cell stack. In the case of a fuel cell electric bus, a fuel cell engine (including fuel cell stack and supporting sub-systems) is integrated with a hydrogen fuel storage system and electric drive components to achieve the required performance for the bus duty cycle. Figure A below illustrates this design.

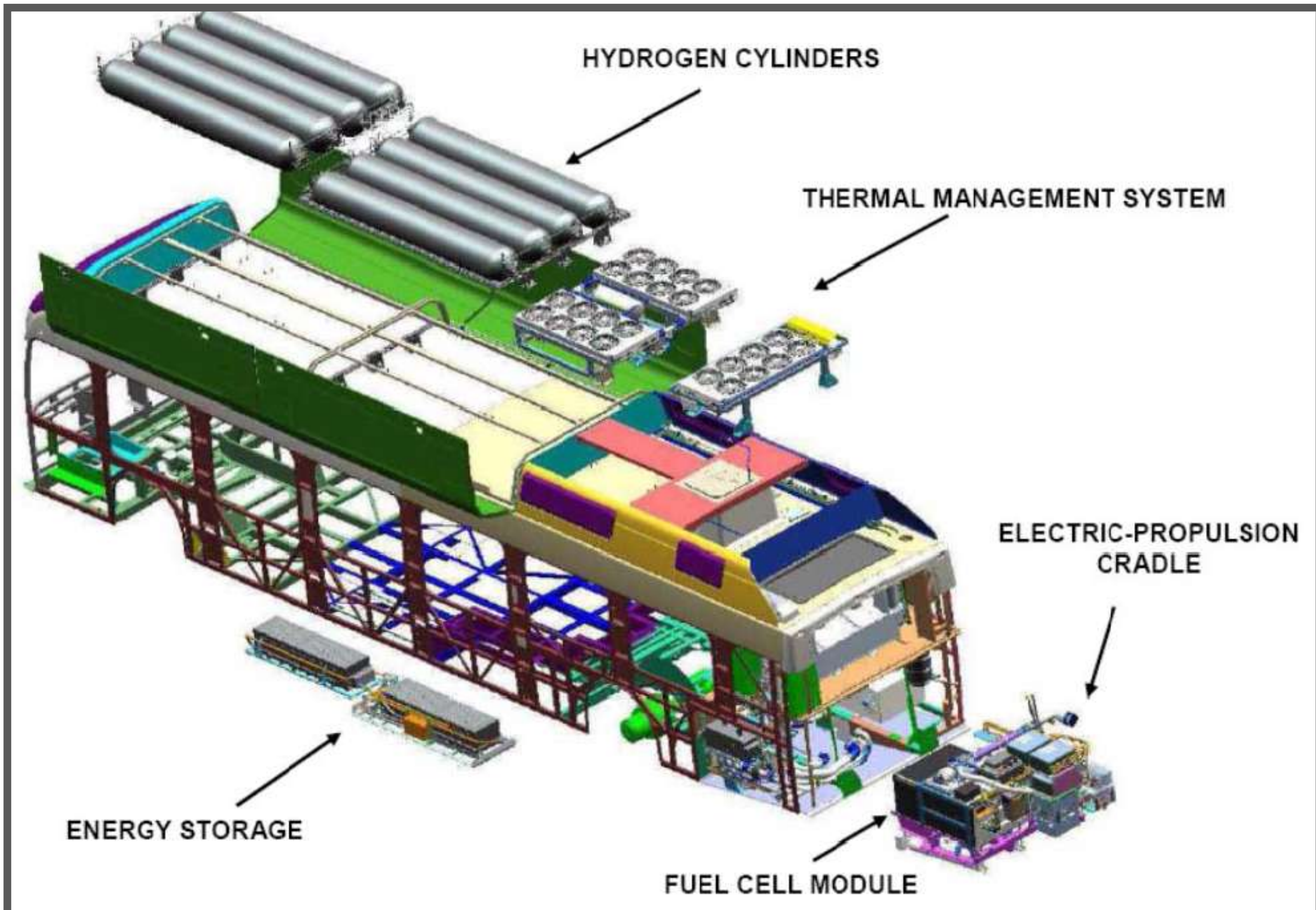


**Figure A. FCEB components – Source: Ballard Power Systems**

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.[8]

[8] Urban buses: alternative powertrains for Europe (study): http://www.fch-ju.eu/news/fch-ju-launches-its-study-urban-buses-alternatives-power-trains-europe.

## History

After the concept of hydrogen fuel cell buses was first proven in the 1990s in Chicago (USA), Vancouver (Canada) and Munich (Germany), the Clean Urban Transportation for Europe (CUTE) program was established as the first coordinated multi-city fuel cell bus transportation demonstration in 2003. Thirty fuel cell buses were placed in 10 European cities for an initial period of two years. All the buses used the same Mercedes-Benz Citaro platform with a Ballard fuel cell system as the sole non-hybrid power propulsion system. Additionally, the cities of Perth, Australia and Beijing, China each operated three buses of the same design and technology. U.S.-funded efforts included three Gillig buses with the same drive system demonstrated in revenue service in California by the Santa Clara Valley Transportation Authority (VTA) in Silicon Valley. Combined, these buses traveled more than two million miles in revenue service.

During the same 1999-2005 period, a UTC Power powered 30-foot prototype hybrid electric-drive fuel cell bus was introduced at SunLine Transit in Thousand Palms, CA using batteries to store captured excess energy. This configuration used regenerative braking to capture the kinetic energy of vehicle movement to recharge the battery, which then could be used for acceleration as well as reducing transient loads on the fuel cell system. Following this demonstration, AC Transit in Oakland introduced three Van Hool hybrid electric fuel cell buses using a larger UTC fuel cell system. SunLine Transit also received and operated a bus of the same design, as did Connecticut Transit. To date, one of these UTC fuel cell system modules has surpassed 12,000 hours of operation in revenue service, and continues to perform at rated power, with two other systems approaching this same durability milestone.[9]

Subsequent designs have been developed by industry and there are now more than 80 full-size FCEB's currently in operation in various locations in North America, Europe, Asia, and South America.[10]

## *PATH TO COMMERCIALIZATION*

To provide perspective on the commercial development path of FCEBs, Table 1 lists the nine Technology Readiness Levels (TRL) of FCEBs, as developed by the National Renewable Energy Laboratory (NREL). NREL created these levels using the U.S. Department of Energy's Technology Readiness Assessment Guide as a model.[11] A similar concept[12] is used by the manufacturing industry to work towards target prices and technical goals for different FCEB components.

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[9] As of August 1, 2012.
[10] For an overview of global FCEB programs, go to: http://www.gofuelcellbus.com/index.php/the-collaborative/all-active-demonstrations/.
[11] DOE Technology Readiness Assessment Guide, G 143.3-4a, https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view.
[12] Manufacturing Readiness Levels (MRL).

**Table 1 - NREL Technology Readiness Levels for FCEB Commercialization**[13]

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

Using this chart, FCEB technology in California is currently at level seven or “full-scale validation in relevant environments,” and requires two more levels to become a fully commercial product. To reach level eight, action is required and this document details what steps are needed.

## FCEB Programs in Operation

At publication, 15 fuel cell electric buses operate in revenue service in California among several transit agencies, including:

- AC Transit and other San Francisco Bay Area transit agencies[14]
- SunLine Transit

[13] “Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012”. L. Eudy, K. Chandler, C. Gikakis (2012). Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fceb_status_2012.pdf.

[14] Golden Gate Transit, San Mateo Transit, San Francisco MTA, Santa Clara Valley Transportation Authority.

Focusing on the typical platform of a full-size urban bus, it is instructive to consider the performance of the VanHool buses at AC Transit, and the American Fuel Cell bus at SunLine Transit, since both represent the current capabilities of FCEB platforms in California. These demonstrations show that ZBuses are approaching the performance expectations of the transit agencies:

- Bus availability of 85% for the SunLine American FCEB for more than four of the eight months in service[15]
- Availability of the AC Transit FCEBs that progressively improved to 97% in March and April 2012[16]
- Increasing "miles between road calls" (MBRC), with most of the road calls due to issues other than the fuel cell system
- Fuel economy of up to 7.84 mpdge (miles per diesel gallon equivalent)[17]
- Fuel cell system durability beyond 12,000 hours[18]

Despite improving performance among FCEBs, capital and operating costs remain a barrier to commercialization.

## Hydrogen Fueling Stations

Supply of hydrogen is a major component of fuel cell electric bus fleet implementation. The National Fuel Cell Bus Program (NFCBP), which includes the AC Transit and SunLine Transit FCEB programs, provides early indications that the infrastructure might be an appropriate focus of early planning, and current experience bears that out.

SunLine Transit's hydrogen station in Thousand Palms is the longest running hydrogen transit bus fueling station in operation in the U.S (Figure B), beginning operations in April 2000. This station serves as a dual-use (shared dispenser) station for both buses and passenger vehicles using 35 MPa hydrogen fuel (H35).[19] The station has on-site production of hydrogen through the use of an auto-thermal reformer, with a production capacity of 212 kilograms (kg)/day.[20] The three FCEBs currently in daily revenue service fill in about 25 minutes per bus. Excluding the capital cost for hydrogen station implementation, the combined cost of operations and maintenance (O&M) and hydrogen is approximately $12.50/kg dispensed.

[15] Eudy, L., Chandler, K., Gikakis, C., Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012, NREL report November 2012.
[16] Source: UTC Power Dashboard Report Data provided to NREL.
[17] Eudy, L., Chandler, K., Gikakis, C., Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012, NREL report November 2012.
[18] Hours accumulated without stack replacement on a fuel cell system that came from the previous generation AC Transit FCEBs, the new second generation system is integrated in 9 of 12 FCEBs and have a longer expected durability. Source: UTC Power.
[19] Per NIST Handbook 130- 2013 Edition: H35 is the definition for hydrogen fuel with a pressure of 35MPa, 350 bar or 5000psi. Handbook available at: http://www.nist.gov/pml/wmd/pubs/hb130-13.cfm.
[20] Chandler, K., Eudy, L., June 2008. SunLine Transit Agency Hydrogen-Powered Transit Buses: Third Evaluation Report and Appendices, http://www.nrel.gov/hydrogen/pdfs/43741-2.pdf.

**Figure B. SunLine Transit fueling station**

AC Transit’s hydrogen station in Emeryville is currently the largest and most-modern transit bus fueling station in the U.S (Figure C). The station, which started operation in August 2011, serves as a dual-use station where passenger vehicles can access a public dispenser outside the bus yard. The separate bus and car dispensers share much of the station’s hydrogen equipment, capitalizing on the need for each of the transit and private-use vehicle markets. The station has a scalable capacity, with a baseline capacity of 360 kg of hydrogen fuel per day for buses at 35 MPa and 240 kg per day for cars at both 35 and 70 MPa, an amount sufficient to fuel 12 fuel cell buses and between 40 and 60 cars.[21] Excluding the implementation and capital costs for the hydrogen station equipment, the combined cost of O&M and hydrogen to fuel buses at this station is approximately $10.50/kg dispensed.

The performance of this station to fill multiple buses consecutively at a speed of six to eight minutes per fill -a rate equivalent to diesel bus fueling- is achieved through the use of fast-fuel technology. Should AC Transit decide to increase the number of FCEBs, the station system is designed to easily expand its capacity to accommodate up to 24 buses by adding additional compression and gaseous storage equipment. A second station in Oakland will open in late 2013 with a design capacity to fuel 12 buses rapidly and in succession. It also can be expanded to fuel 24 buses. Typical scheduling and service requirements make it necessary to fuel the buses between 11 p.m. and 5 a.m. to enable the buses to stay in continuous service from 5 a.m. to 11 p.m.

**Figure C. AC Transit fueling station** (Photo courtesy of L. Eudy, NREL)

For comparison, BC Transit’s hydrogen station in Whistler, Canada is the largest transit bus fueling station in North America. It began operation in November 2009, serving only buses. The station can

[21] Currently restricted to 20 cars per day.

scale up to fuel more than 30 buses with 35 MPa hydrogen fuel with its baseline capacity of 1,400 kg of hydrogen fuel per day. Currently the station fills 20 transit FCEBs for daily revenue service, with a combined cost of O&M and hydrogen at approximately $11.70/kg dispensed.[22]

The station's performance in filling multiple buses consecutively at a speed of 2.5 to 5 kg/min -10 to 15 minutes per fill, a rate equivalent to diesel bus fueling- is achieved through the use of liquid hydrogen pump technology.

## COMMERCIAL AND TECHNICAL TARGETS

The Department of Energy and the Department of Transportation's Federal Transit Administration (FTA) collaborated with private and public entities to establish commercial targets for fuel cell electric buses, using the 2012 status of FCEBs in operation as the benchmark, as shown in Table 2.[23]

At a summary level, the technical performance targets (e.g. range or fuel economy) have been achieved or are within line of sight without major technology advances. Daily bus roll-out availability has improved with the current generation of fuel cell buses, despite the use of more complex electronic and battery systems. For example, the American Fuel Cell Bus (AFCB) at SunLine reported 83% availability from March until December 2012,[24] and the Whistler fleet has averaged 70 -75% availability over 1.5 million miles in revenue service. [25] Durability has increased significantly with the UTC Power fuel cell module, having achieved 12,094 hours in operation with an older design that continues in revenue service in three FCEBs.[26] The major fuel cell system manufacturers have made technology improvements to the fuel cell system stacks that are expected to achieve the commercial targets set out by the U.S. DOE within the next few years.

[22] Per input of BC Transit and Air Liquide, based on operation of 20 FCEBs for 365 days/year, $20 million to supply fuel, O&M and equipment until March 2014, see: http://www.bctransit.com/fuelcell/download/20071210_fuelcell_buses.pdf.
[23] U.S. DOE Fuel Cell Bus Targets. http://hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf.
[24] Eudy, L., Chandler, K., "American Fuel Cell Bus Project: First Analysis Report"– Preliminary report, to be published.
[25] Source: Ballard Power Systems.
[26] 9,945 hrs (next highest time), 7,666 hrs (3rd highest time), continuing operating in revenue service. Source: UTC Power.

**Table 2 – 2012 DOE/DOT FTA performance, cost, and durability targets for fuel cell transit buses.**

| | Units | 2012 Status | 2016 Target | Ultimate Target |
|---|---|---|---|---|
| | | | | |
| **Bus Lifetime** | years/miles | 5/100,000[1] | 12/500,000 | 12/500,000 |
| **Power Plant Lifetime[2,3]** | hours | 12,000 | 18,000 | 25,000 |
| **Bus Availability** | % | 60 | 85 | 90 |
| **Fuel Fills[4]** | per day | 1 | 1 (< 10 min) | 1 (< 10 min) |
| **Bus Cost[5]** | $ | 2,000,000 | 1,000,000 | 600,000 |
| **Power Plant Cost[2,5]** | $ | 700,000 | 450,000 | 200,000 |
| **Hydrogen Storage Cost** | $ | 100,000 | 75,000 | 50,000 |
| **Road Call Frequency (Bus/Fuel Cell System)** | miles between road calls | 2,500/10,000 | 3,500/15,000 | 4,000/20,000 |
| **Operation Time** | hours per day/days per week | 19/7 | 20/7 | 20/7 |
| **Scheduled and Unscheduled Maintenance Cost[6]** | $/mile | 1.20 | 0.75 | 0.40 |
| **Range** | miles | 270 | 300 | 300 |
| **Fuel Economy** | miles per gallon diesel equivalent | 7 | 8 | 8 |

[1] Status represents data from NREL fuel cell bus evaluations. New buses are currently projected to have 8 year/300,000 mile lifetime.
[2] The power plant is defined as the fuel cell system and the battery system. The fuel cell system includes supporting subsystems such as the air, fuel, coolant, and control subsystems. Power electronics, electric drive and hydrogen storage tanks are excluded.
[3] According to an appropriate duty cycle.
[4] Multiple sequential fuel fills should be possible without an increase in fill time.
[5] Cost projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only, and does not represent an anticipated level of sales.
[6] Excludes mid-life overhaul of power plant.

The capital cost of a full-size FCEB is currently more than $2 million,[27] significantly higher than the targets in Table 2, primarily due to customized designs and low bus-manufacturing volumes. Based on industry input, the $1 million target can be achieved through a limited production of FCEBs of the same design, while the $600,000 target requires commercial volumes. These factors led to recent industry and government discussions regarding the deployment of a few centralized fleets, allowing production runs large enough to amortize investments in production tooling and optimize the manufacturing process.

Relative to the fueling infrastructure, the station designs at AC Transit (Linde) and BC Transit in Whistler (Air Liquide) meet the performance requirements for a larger fleet. The challenge lies in meeting a fuel cost of $4-7,[28] at which the fuel cost per mile will be competitive with conventional buses. For the early

[27] Based on a fuel cell dominant configuration meeting all performance requirements.
[28] "Building a Commercially Viable National Fuel Cell Electric Bus Program," Fuel Cell and Hydrogen Energy Association, March 2011. Available at: http://cafcp.org/sites/files/Building%20a%20Commercially%20Viable%20National%20Fuel%20Cell%20Transit%20Bus%20Program.FINAL_.v10.03-25-11.pdf.

hydrogen stations at transit agencies with smaller FCEB fleets (1 to 12 FCEBs), the throughput for fuel and related fuel savings are insufficient to cover the higher upfront capital cost and O&M cost of the station, and government funding will help offset this. In a commercial market (TRL 9), these costs will be offset by high throughput of hydrogen supplied for larger fleets.

## *PROPOSED STRATEGY*

Establishing two Centers of Excellence in California is the next step in the introduction of FCEBs to the California transit bus market. In March 2011, the Fuel Cell & Hydrogen Energy Association submitted a white paper to DOT Secretary Ray LaHood proposing "five regional Centers of Excellence on the east and west coasts, the mid-west, and the south or southeast, building upon existing experience and core competencies." Although this program was not adopted explicitly in MAP-21, the principles of the program are sound and these Centers of Excellence should be considered for Northern and Southern California. In creating these programs and realizing the goal of 40 buses per fleet, industry input indicates that production runs of 40 FCEBs will be large enough to reduce the capital cost per bus at or below $1.0 million and fleet size will be sufficient to enable a fuel cost per mile competitive with a conventional bus.

### Centers of Excellence in California

Similar to the automotive strategy of concentrating deployment on a limited number of sites for early stage commercialization, the best path forward for implementing fuel cell electric buses in California is to focus on the development of *two Centers of Excellence in California*, one in the north and the other in the south. The key tenets of these programs are:

- A single fuel cell hybrid bus configuration at each site, manufactured under a serial production run of 40 units over one to two years
- Vehicles that comply with transit agency requirements and are operated in normal revenue service on scheduled runs (e.g. no compromise or deviation in service)
- A 12-year operating period
- A single hydrogen fueling station with throughput sufficient to provide throughput sufficient to achieve a fuel cost per mile comparable to conventional buses
- Vehicles introduced in the 2015-2016 timeframe
- Regional training and education for transit staff and community stakeholders

## Fueling Infrastructure

Each Center of Excellence will have a single fueling station capable of meeting the requirements in Table 3.

**Table 3 - Fueling station technical assumptions**

| Fueling station category | Details |
|---|---|
| Station lifetime | 15-20 years |
| Fuel quality | SAE J2719 |
| Fuel pressure | 35 MPa or 350 bar |
| Fill time per bus (pending on bus design) | 5-8 minutes |
| Average fill amount per bus | 30 kg/day |
| Station capacity (based on 30 kg/day/bus, 40 FCEBs) | 1,200 kg/day |
| Number of dispensers capable of fueling simultaneously | 2 dispensers |
| Bus fleet fueling window[29] | 4-5 hours/day |
| Station location | Northern and Southern California |

When considering the implementation of a hydrogen station, every transit property will be unique with regards to their specific requirements, as it is not a one-size-fits-all situation related to budget and schedule for each specific property. Considering the costs involved, fleets may initially choose to be more flexible with their scheduling requirements to accommodate a broader fueling window.

Currently, the four most feasible hydrogen fuel delivery methods for transit agencies based on the capacity and design assumptions are:

- ***Delivered liquid hydrogen*** with compression and storage on site. Hydrogen production and liquefaction occurs at a central production plant, delivery by truck.
- ***Hydrogen pipeline*** with compression on site. Hydrogen production at a central location connected to an industrial hydrogen pipeline.
- ***On site reformation.*** Hydrogen fuel is generated on site from natural gas with compression and storage on site.
- ***On site electrolysis.*** Hydrogen fuel is generated on site from water using electricity with compression and storage on site.

With the previous assumptions in mind, hydrogen fuel and station equipment suppliers provided input that the fueling station cost for the aforementioned hydrogen fuel delivery methods per location are anticipated to be approximately $5 million or less, which includes $1 million for site improvements and local jurisdiction use requirements to install a H35 (aka 35MPa or 350 bar hydrogen fuel) fueling station. Station operating and maintenance (O&M) costs incurred by transit agencies are $200,000 per year. The cost of fuel delivered to the station is $4-7 per kilogram, depending on hydrogen station location, mode of hydrogen supply and access to production facilities. This fuel cost is equivalent to $2.26 to $4.75 per gallon of diesel fuel, taking into account 1.6 to 2 times better fuel economy of a FCEB over a diesel bus.[30]

[29] Transit agencies refuel their buses at the end of the day within a specific time window to be ready for pull out the next morning.

[30] "Building a Commercially Viable National Fuel Cell Electric Bus Program," Fuel Cell and Hydrogen Energy Association, March 2011. Available at: http://cafcp.org/sites/files/Building%20a%20Commercially%20Viable%20National%20Fuel%20Cell%20Transit%20Bus%20Program.FINAL_.v10.03-25-11.pdf.

## Budget

Assuming a 12-year operating period, a cost of $1 million per bus, maintenance facility upgrade of up to $2 million (retrofits of three to four service bays to accommodate a 40-bus fleet), mid-life powerplant overhauls for all buses of $80,000/bus[31] and infrastructure capital costs of approximately $5 million per site,[32] the cost for each Center of Excellence would be $50.2 million including rolling stock and infrastructure. Table 4 details the costs.[33] For comparison, the cost of purchasing a fleet of forty conventional buses is $19.2 million (vehicle cost only).[34] Funding for each Center of Excellence may come from federal, state and local sources.

Normal bus operational costs including fuel at $4-7 kg[35] and the operating and maintenance costs for the fueling station (estimated at approximately $200,000/year) may be borne by the transit operator.

**Table 4 - Cost overview of one Center of Excellence**

| Capital equipment | Per Center of Excellence | Capital cost per location |
|---|---|---|
| FCEBs | 40 | $40M |
| H2 station | 1 | $5M |
| Maintenance facility | 1 | $2M |
| Mid-life overhaul of bus power plant | 40 | $3.2M |
| **Total** | **n/a** | **$50.2M** |

## Funding

The new federal transportation bill "Moving Ahead for Progress in the 21st Century Act" (MAP-21) includes a provision that not less than 65% of any funds which are appropriated to the Federal Transit Administration (FTA) for research, development, demonstration and deployment projects be made available for zero and near-zero-emission bus deployment; and not less than 10% of those funds for facilities and related equipment. As the bill authorizes $70 million to be appropriated in both fiscal years 2013 and 2014, if the bill is fully funded, that would mean a minimum of $45.5 million a year for bus deployment, and $7 million for facilities and related equipment, contingent on appropriations. This funding will be programmed through the FTA. A fuel cell electric bus deployment program in California utilizing this federal funding source is consistent with the program's stated objectives.

At the state level, monies invested in the Greenhouse Gas Reduction Fund through carbon auction proceeds could be used in conjunction with FTA funding to address the costs of the rolling stock (buses) and the fueling infrastructure. How these proceeds will be administered has yet to be determined,

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[31] Includes both fuel cell and battery replacement and/or refurbishment.
[32] Including site improvement costs and local jurisdiction use requirements.
[33] The total cost per location is an approximate cost, as building requirements per location can differ due to local requirements.
[34] Average cost per standard transit bus purchased in 2010-2011 $479,585, "2012 Public Transportation Fact Book" Appendix A: Historical Tables. Available at: http://www.apta.com/resources/statistics/Documents/FactBook/2012-Fact-Book-Appendix-A.pdf.
[35] Depending on the mode of supply.

however, a state entity such as the California Air Resources Board, the California Energy Commission or California State Treasurer's Office could be used to manage and allocate these funds.

Assuming near parity in fuel costs based on the larger-scale fueling station and vehicle throughput, there would likely be a small incremental cost related to vehicle maintenance that the transit property would be expected to incur as part of their operating budget, which is simply based on the introduction of a new propulsion system to the bus fleet. It is also anticipated that this incremental cost will diminish over time as the technicians become familiar with the more durable and easier-to-maintain electric traction motors and all-electric auxiliary systems.

## *NEXT STEPS AND RECOMMENDATIONS*

CaFCP members will work with local, state and federal stakeholders to develop a funding model that supports the road map and implementation of the Centers of Excellence.

### Recommendations for State of California Action

Governor Brown convened a "ZEV Summit" in 2012 to address the key issues in implementing his Executive Order for widespread deployment of zero-emission vehicles (ZEVs). Bus and truck stakeholders participated in this process, and this road map is intended to provide guidance for state support of heavy-duty bus fleets and infrastructure consistent with the objectives of the Executive Order.

The Governor's *2013 ZEV Action Plan* identified several bus-related goals, including monitoring the current FCEB demonstration fleet and the development of this road map. Although not identified in the 2013 ZEV Action Plan, California should assist the advancement of ZBuses to Technology Readiness Level 8, the last step before commercialization. The following actions are recommended to reach this goal and the DOE/DOT FTA targets listed in Table 2.

1. Include the concept of two California Fuel Cell Electric Bus *Centers of Excellence* in the 2013 ZEV Action Plan.
2. Continue support of National Renewable Energy Laboratory data collection to record and communicate progress towards the DOE/DOT FTA 2016 targets, critical to the public credibility and transparency of the FCEB program.
3. Validate and verify (using a third party) the incremental cost over traditionally configured buses and the prospects for FCEB commercialization.
4. Study the effect of zero-emission buses on ridership. Include the extent to which car owners abandon driving in favor of public transit and the extent to which the quality of ride impacts the decision.
5. Study the health benefits of replacing conventional buses with zero-emission buses in inner-city neighborhoods and the benefits that would accrue to Title VI Environmental Justice communities.
6. Integrate this large-scale production run/deployment concept into the Air Resources Board zero-emission bus regulatory planning.
7. Utilize state funding for alternative fuels and carbon reduction programs to leverage maximum funding opportunities with the federal government.
8. Work with the federal government to identify and put in place the funding and timing conditions required to implement the Centers of Excellence strategy in Northern and Southern California with the following recommended timeline.
    a. Develop and release procurement documentation (Q2 2014)

b. Complete procurement contracting (Q4 2014)
c. Station commissioning (Q2 2016)
d. Vehicle commissioning (Q2 2016)

To implement these recommendations, industry, for their part, must be willing to provide credible and defensible data so that funding agencies have confidence that the commercial and technical targets can be achieved, and that the funding allocation is sufficient.

### Recommendations for Federal Government Action

The actions recommended below build on the achievements of the Federal Transit Administration's National Fuel Cell Bus Program and its efforts to achieve the emission and efficiency goals identified in the Electric Drive Strategic Plan. These recommendations are in-line with the strategy outlined in the Fuel Cell & Hydrogen Energy Associations' white paper that develops a nationwide path toward commercialization of FCEBs. Strong state and federal collaboration will play a significant role in achieving these goals.

1. Work directly with California agencies to identify and put in place the funding conditions required to implement this strategy; consider making funding available under MAP-21 legislation for FCEB Centers of Excellence in ozone, CO and/or particulate matter (PM 2.5[36]) nonattainment or maintenance areas in California.[37]
2. Identify funding that covers the cost difference between the 2016 target FCEB cost and typical cost of transit buses for the involved transit agencies that operate the Centers of Excellence.
3. Explore how the federal government can make funding available for hydrogen infrastructure implementation at Centers of Excellence.
4. Continue support of National Renewable Energy Laboratory data collection, critical to the public credibility and transparency of the FCEB program. (Q1, 2013 – Q4, 2016)

## *CONCLUSION*

California requires the introduction of zero emission technology vehicles, including fuel cell electric buses, in order to meet its air quality improvement and emissions reduction goals. These buses have proven their value with millions of miles in revenue service around the world over the last two decades across a diverse set of operating environments. There have been significant technology advances in the performance, reliability and durability of the buses to the point where they have achieved, or are approaching, commercial targets and meeting end-user expectations.

The establishment of two Centers of Excellence is the next step in the introduction of the technology and consistent with California's leadership in the adoption of zero-emission vehicles. These centers will provide a means for reducing the costs and overcoming the remaining commercial barriers that prevent widespread adoption of fuel cell electric buses in the state, country and worldwide.

[36] MAP-21: http://www.fhwa.dot.gov/map21/cmaq.cfm.
[37] U.S. EPA non-attainment zones: http://www.epa.gov/oaqps001/greenbk/ancl.html.