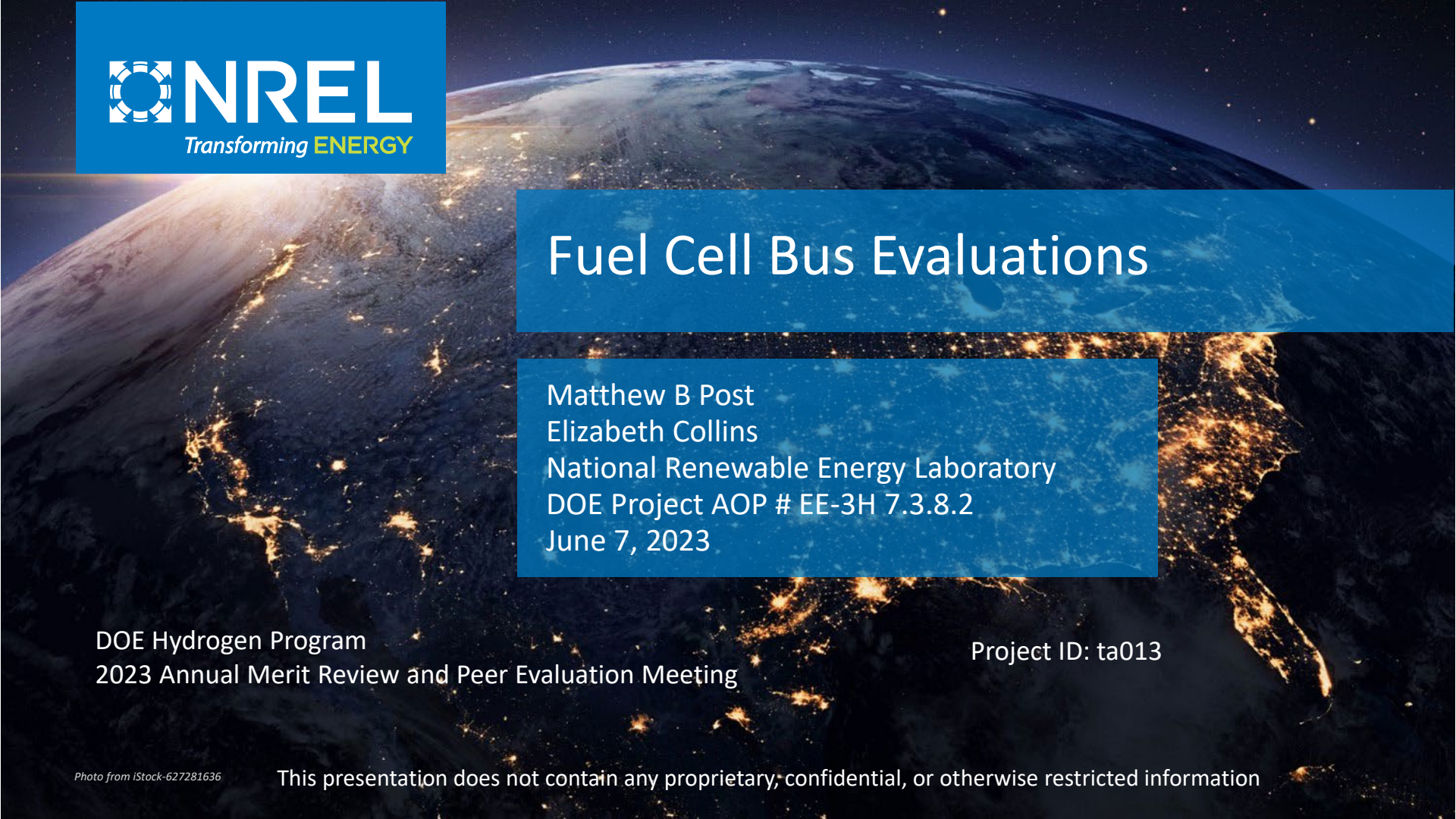


Fuel Cell Bus Evaluations

Matthew B Post
Elizabeth Collins
National Renewable Energy Laboratory
DOE Project AOP # EE-3H 7.3.8.2
June 7, 2023

DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

Project ID: ta013

Photo from iStock-627281636

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project Goal

- Validate fuel cell electric bus (FCEB) performance and cost
  - Determine status toward meeting DOE/DOT technical targets
  - Compare to conventional technologies in similar service
- Document progress on implementing FCEBs in transit operations
  - Share early adopter lessons learned
  - Address barriers to market acceptance
  - Publish results for widespread industry and stakeholder use
- Assess future research needs to increase durability and reliability

Overview

Timeline and Budget

- Project start date: 09/01/2003
- FY22 DOE funding: $150K
- FY23 planned DOE funding: $150K
- Total DOE funds received to date*: $4.875M
  * Since the project started

Barriers

- Technology Validation
  - 3.6.5.A - Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data
  - 3.6.5.D - Lack of Hydrogen Refueling Infrastructure Performance and Availability Data

Partners

- Matthew Post (PI, NREL)
- Partner organizations
  - Transit fleets: Operational data, fleet experience
  - Manufacturers: Vehicle specs, data, and review
  - Fuel providers: Fueling data and review

Potential Impact

With industry input, DOE and DOT established technical targets that FCEBs need to meet to reach commercial viability.

Data collected are used to assess the progress toward meeting those targets and to provide feedback to DOE on what research is needed.

Selected Targets from DOE/DOT Program Record

Metric[a]	Units	2016 Target	Ultimate Target
Bus lifetime	years/miles	12/500,000	12/500,000
Powerplant lifetime	hours	18,000	25,000
Bus availability	%	85	90
Roadcall frequency (bus/fuel cell system)	miles between roadcall	3,500/15,000	4,000/20,000
Operation time	hours per day/ days per week	20/7	20/7
Maintenance cost	$/mile	0.75	0.40
Fuel economy	miles per diesel gallon equivalent	8	8
Bus Cost	$	1,000,000	600,000

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

Approach

Data Collection/ Analysis

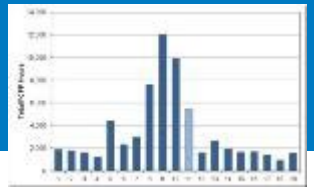
- Standard protocol, uses existing data from transit agencies
- Third-party analysis with comparisons to conventional technology

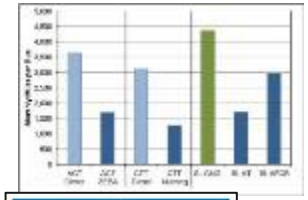
Individual Reports

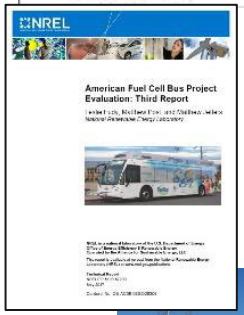
- Document performance by transit site
- Builds database of results
- Reports posted on NREL website for industry access

Annual Status Report

- Analysis comparing results for all sites
- Assess progress toward meeting technical and cost targets
- Provide input to DOE for future R&D needs







Approach – Data Summary for 2022

FCEB Fleets Included in Data Summary

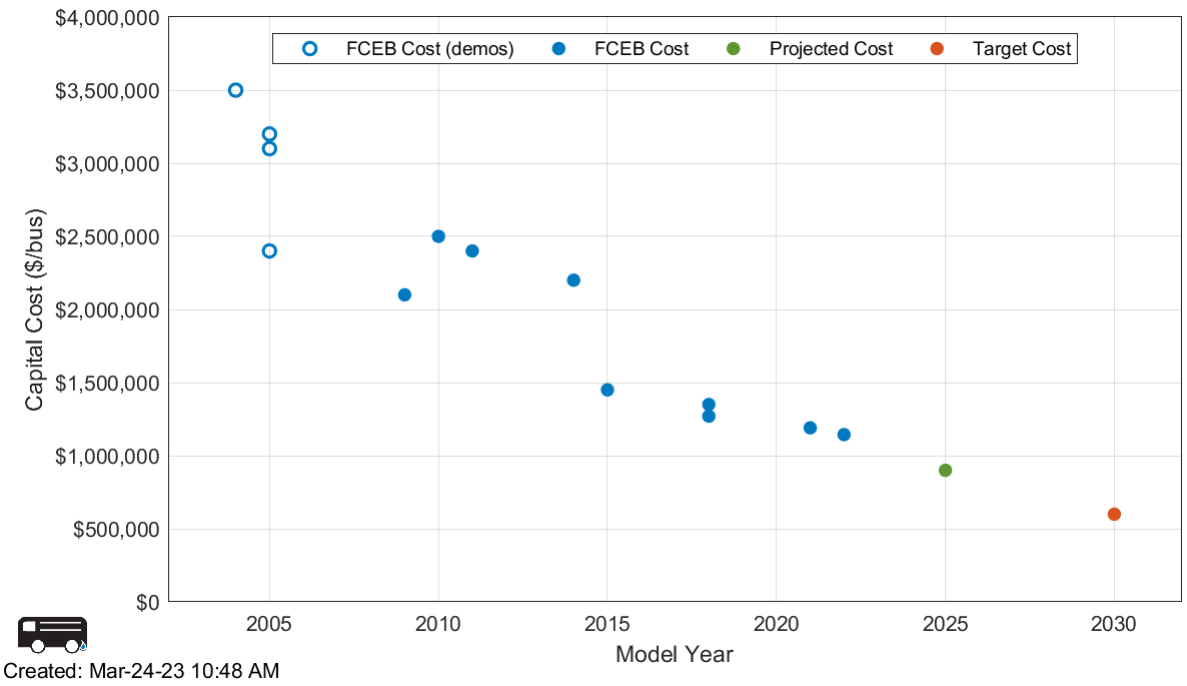
Transit Agency	Location	Bus OEM	# Buses	Data Included
AC Transit	Oakland, CA	New Flyer	10	Continuing
SunLine Transit Agency	Thousand Palms, CA	New Flyer	5	Through Dec. 2021
Orange County Transportation Authority (OCTA)	Santa Ana, CA	New Flyer	10	Through Jun. 2021
Foothill Transit (FHT)	West Covina, CA	New Flyer	33	Potential New Fleet
Champaign–Urbana Mass Transit District (MTD)	Champaign, IL	New Flyer	12	Potential New Fleet
Southeastern Pennsylvania Transportation Authority (SEPTA)	Philadelphia, PA	New Flyer	10	Potential New Fleet

AC Transit, New Flyer

OCTA, New Flyer

SunLine, New Flyer

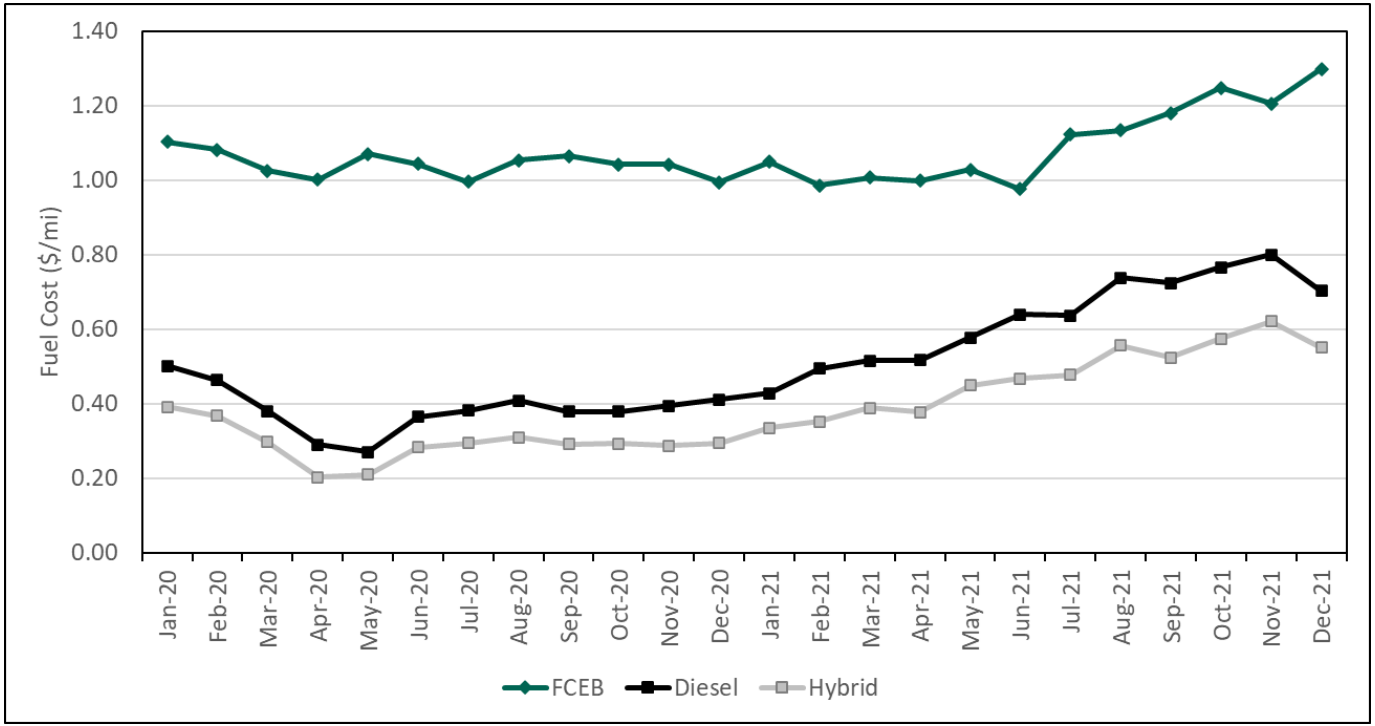
Accomplishments and Progress
FCEB Cost



- FCEB cost continues to trend downward
- Ultimate target has not yet been met
- Estimated timeframe to meet target has been increased
- Supply issues have kept prices high

FCEB cost is still about twice the ultimate target

Accomplishments and Progress
Fuel Cost



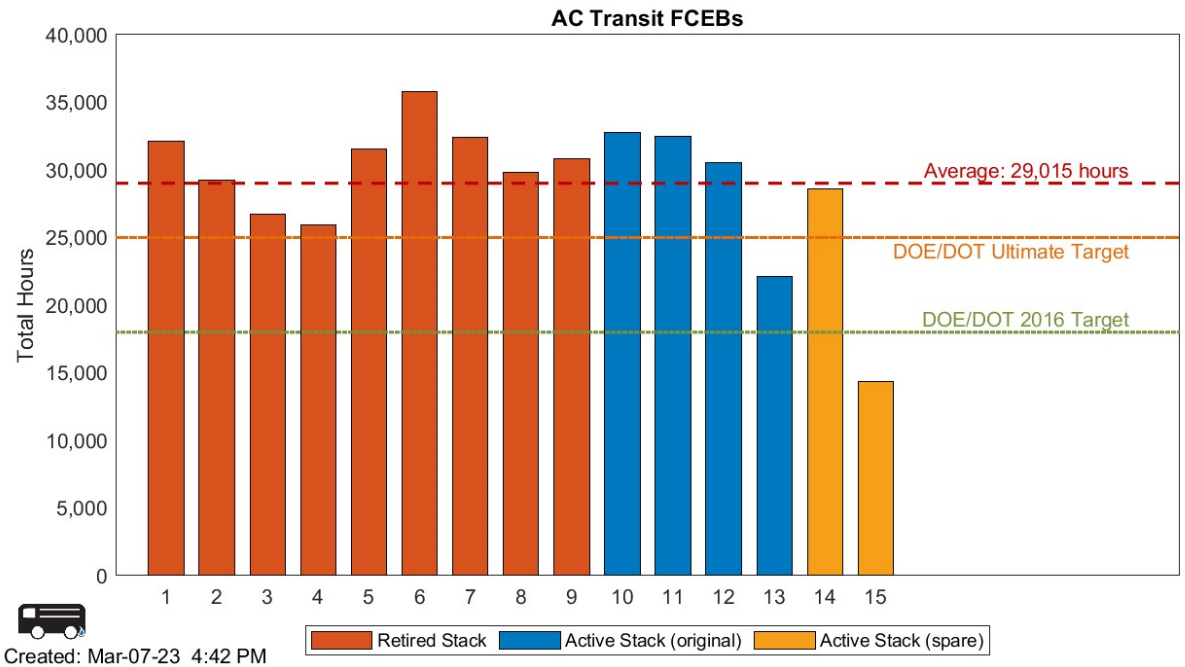
Average fuel cost
- H_2 2020 = $8.43 /kg
- H_2 2021 = $8.64 /kg
- Diesel 2020 = $1.60 /gal
- Diesel 2021 = $2.55 /gal

Average cost per mile
- H_2 2020 = $1.04
- H_2 2021 = $1.10
- Diesel 2020 = $0.39
- Diesel 2021 = $0.63
- Hybrid 2020 = $0.29
- Hybrid 2021 = $0.47

Hydrogen fuel cost per mile is still double that of diesel

Accomplishments and Progress
Fuel Cell Powerplant Hours

AC Transit VanHool FCEB Fleet



Total hours accumulated on each FCPP as of 8/31/2022

- Top fuel cell powerplant (FCPP) >35,000 hours
- All 13 FCPPs have surpassed 25,000 hours

Durability
DOE's benchmark is 20% FC voltage degradation, but FCPP voltage/current data were not available. Therefore, using fuel economy as alternative, AC Transit's FCEBs reached 20% degradation at 17,000 hours, nearing interim target

Accomplishments and Progress
Fueling Stations

Hydrogen Fueling Station Capabilities and Costs[1]

Transit Agency	# Dispensers	Pre-cooling	Electrolysis	Liquid Storage	Max Fills/Day	Year Built	Station Cost	Maintenance Cost
AC Transit Oakland[2]	2	–	65 kg/day	9,000 gallons	13	2014	$6.3 million	$15,500/month
AC Transit Emeryville[2]	–	–	–	9,000 gallons	13	2011	$5.1 million	–
AC Transit Emeryville[2]	2	–	–	15,000 gallons	65	2020 upgrade	$4.424 million	$11,800/month
OCTA[3]	2	10°C	–	18,000 gallons	50	2019	$4.7 million	–
SunLine[4]	2	–	900 kg/day	–	32	2019	$8.3 million	$0 for 3 years
SARTA[5]	1	–	–	9,000 gallons	20	2017	$2.9 million	$10,000/month
Foothill Transit[6]	–	–	–	5,000 kg	–	2022–2023	$6.6 million	–

- Hydrogen fueling station and dispenser installation cost is still quite variable.
- Contributing factors include:
  - Location
  - Maintenance Contract
  - Delivered vs. Onsite Production
  - Capacity
  - Others
- Stations specifications vary based on the needs of the transit agency.
- Standardizing will bring down costs and reduce installation delays

1. Jeffers, Matthew, Kelly, Kenneth, Lipman, Timothy, Fernandes Tomon Avelino, Andre, Johnson, Caley, Li, Mengming, Post, Matthew, and Zhang, Yimin. 2022. "Comprehensive Review of California's Innovative Clean Transit Regulation: Phase I Summary Report". United States. https://www.osti.gov/servlets/purl/1892294.
2. AC Transit. 2021. Zero Emission Transit Bus Technology Analysis: Report Period: July 2020–December 2020. Oakland, CA: AC Transit. https://www.actransit.org/sites/default/files/2021-06/0604-20%20Report-ZEB%20Perf_FNL_062321.pdf.
3. Leslie Eudy and Matthew Post. 2021b. "Orange County Transportation Authority Fuel Cell Electric Bus Progress Report - Data Period Focus: Feb. 2020 through Jul. 2020." NREL/PR-5400-78250. https://www.nrel.gov/docs/fy21osti/78250.pdf.
4. Leslie Eudy and Matthew Post. 2021. "SunLine Transit Agency Fuel Cell Electric Bus Progress Report - Data Period Focus: Jan. 2020 through Jul. 2020." NREL/PR-5400-78078. https://www.nrel.gov/docs/fy21osti/78078.pdf.
5. Leslie Eudy, Matthew Post, Jonathan Norris, and Steve Sokolsky. 2019. Zero-Emission Bus Evaluation Results: Stark Area Regional Transit Authority Fuel Cell Electric Buses. Washington, D.C.: Federal Transit Administration. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/134491/zero-emission-bus-evaluation-results-sarta-fta-report-no-0140_0.pdf.
6. Foothill Transit. 2021. Executive Board Meeting, West Covina, CA, Friday, October 1, 2021. West Covina, CA: Foothill Transit. http://foothilltransit.org/wp-content/uploads/2021/09/10-01-2021-Agenda-Packet-Executive-Board-Meeting1.pdf.

Accomplishments and Progress
Mobile Dispensers

SEPTA Experience

- SEPTA is planning a pilot project with 10 FCEBs
- SEPTA will be utilizing a mobile hydrogen fueler for the project
- The mobile hydrogen fueler is their main planned method to fuel the 10 initial buses for the 12-year bus lifetime
- Pilot is focused on the buses ability to handle the routes and not the associated infrastructure
- A permanent station will follow a successful pilot

Foothill Transit Experience

- FHT is utilizing an Air Liquide mobile hydrogen fueler
- Temporary solution while permanent station is under construction
- Delays to construction caused by supply issues

Picture Taken by Roland Cordero, Foothill Transit 75798

Transit agencies are using mobile fueling as an option during construction or for bus prove-out phases

Accomplishments and Progress
BEB and FCEB Comparison

Battery Electric Bus Experience

- Battery electric buses (BEBs) are an important part of the energy transition
- Some US transit agencies are revisiting plans that include full or mostly BEB fleets
- Foothill Transit has reported that the range of their initial BEB fleet has fallen short of their need and caused early retirement of those BEBs
- SEPTA has changed a Low-No grant from BEB to FCEB after initial BEB experiences
- BEB fires at SEPTA and CT Transit are causing more hesitancy in adoption

Fuel Cell Electric Bus Experience

- Fuel cell electric buses (FCEBs) are another zero-carbon emission option for buses
- Some US transit agencies have shifted to either add FCEBs or increase the number of FCEBs in their plans
- Hesitancy has been expressed based on station footprint and the length of time stations are taking to be installed
- Cost of hydrogen is also seen as a barrier to adoption
- Early demonstrations have shown that FCEB fueling time and range are the main benefit

Accomplishments and Progress:
Response to Previous Year Reviewers' Comments

- This project was not reviewed in the previous year AMR.

Collaboration and Coordination

- Transit agencies (1) provide data on buses, fleet experience, and training and (2) review reports
  - California: AC Transit, SunLine, OCTA
- Manufacturers provide some data on buses and review reports. Current FCEBs OEMs:
  - Bus OEM: New Flyer
  - Fuel cell OEM: Ballard
  - Hybrid system OEM: New Flyer
- Other organizations share information and analysis results
  - California Air Resources Board
  - Center for Transportation and the Environment
  - CALSTART

Remaining Challenges and Barriers

- For technology acceleration and data collection project:
  - Data collection requirements expire with grant timeline
  - Finding additional transit agencies willing to add to the data set
  - Incorporating findings into future cross-cutting analyses
- For industry to commercialize FCEBs:
  - Deploy larger fleets:
    - Lower per-bus price: OEMs estimate ~$1M/bus for higher volumes
    - Incorporate training into current course work
    - Accelerate learning curve for staff
    - Add trained technicians to staff at local OEM support centers
  - Install hydrogen stations
    - High capital cost to install, but easier to scale up compared to battery fleet
    - Standardization: each installation is different, making it challenging to plan budget

Proposed Future Work

- Remainder of FY 2023
  - Finalize analysis on new designs at AC Transit, 10 New Flyer FCEBs
  - Complete the following data analyses/reports:
    - Individual Reports for each Transit Agency
    - Annual Status Report combining the above findings
  - Work with OEMs to determine what detailed data can be collected
    - Begin collecting data from participating transit agencies
    - Enter data into standard analyses
    - Incorporate lessons learned into reporting
- FY 2024
  - Implement data collection process for new OEMs with FCEB fleets
  - Complete annual crosscutting analysis across sites

Any proposed future work is subject to change based on funding levels

Summary

- Project uses existing data primarily from transit agencies to assess the progress of FCEB technology toward commercialization
- Finalized initial data on newest FCEB design at three agencies
- Collected data on three baseline technologies for comparison: CNG, diesel, and diesel hybrid
- Documented progress toward meeting DOE/DOT targets:
  - Fuel economy/range: 8 mpg/300 miles
    - New bus model meets fuel economy target at 8.95 mpdge
    - Range based on 95% useful fuel capacity (37.5 kg tank) is 280 miles
  - Road Call Frequency
    - FCEBs have met this measure of durability
- Published reports to aid other transit agencies considering FCEBs
- Currently, FCEBs in public transit are at a transitional point with many projects in an early phase. NREL will continue to follow progress and report on lessons learned.

Thank You

www.nrel.gov

NREL/PO-5700-85826

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Technical Backup and Additional Information

Technology Transfer Activities

- Project provides non-biased evaluation of technology developed by industry
- Project documents performance results and lessons learned to aid market in understanding needs for full commercialization
  - Manufacturers
  - Transit agencies
  - Policymaking organizations
  - Funding organizations
- No technology (hardware/software) is developed through this project

Publications and Presentations

- Collins, Elizabeth, and Matthew Post. Orange County Transportation Authority Fuel Cell Electric Bus Progress Report - Data Period Focus: Feb. 2020 through Jul. 2021, 2022.
- Collins, Elizabeth, and Matthew Post. SunLine Transit Agency Fuel Cell Electric Bus Progress Report - Data Period Focus: Jan. 2020 through Dec. 2021, 2022.
- Post, Matthew B. "Hydrogen Fuel Cell Electric Bus (FCEB) Evaluations in US Public Transit Service." Conference Presentation at 2023 WCX SAE World Congress Experience, Detroit, MI, April 18, 2023.