NREL
Transforming ENERGY

Hydrogen Fuel Cell Electric Bus (FCEB) Evaluations in US Public Transit Service

Matthew Post
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NREL at-a-Glance

2,926

Workforce, including

219 postdoctoral researchers

60 graduate students

81 undergraduate students

World-class

facilities, renowned technology experts

More than **900**

Partnerships

with industry, academia, and government

Campus

operates as a living laboratory

Hydrogen and Fuel Cell Research

Enabling hydrogen to be a common means of transporting, storing, and transforming energy at the scale necessary for a clean and vibrant economy.

Research Challenges

- Improving the economics of hydrogen production to enable it to shift energy across time, sectors, and location—including providing electric grid support and energy storage
- Developing advanced materials for polymer electrolyte fuel cells and electrolyzers, focusing on the emerging markets of intermittent H_2 production and heavy-duty transportation
- Enabling safe fueling for heavy-duty hydrogen trucks, reducing the cost and improving reliability of fueling fuel cell electric vehicles
- Researching hybrid bio-electrochemical processes and advanced cell concepts.

NREL Role in Zero Emission Buses Evaluation

3rd party evaluation of advanced technology in real-world service

- Established evaluation protocol provides consistent data collection and reliable analysis
- Unbiased results in common format
- Comparison to baseline conventional technology and technical targets

Transit Agencies

Share information with the transit industry that will aid in advanced technology purchase decisions & fleet operations

Government

Provide feedback to federal, state and local government to understand technology status and prioritize funding for necessary R&D

OEMs

Collaborate with tech providers to understand status and share performance results for ZEB and baseline buses

Approach

Data Collection/ Analysis

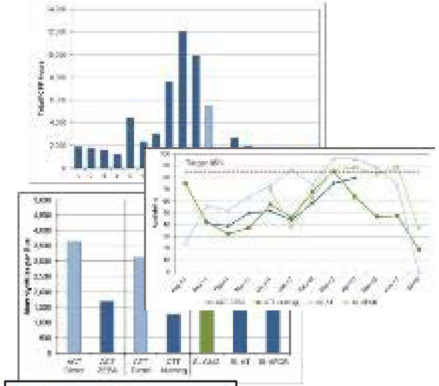
- Standard protocol, uses existing data from transit agencies
- Third-party analysis with comparisons to conventional technology

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



Data Collection Process

NREL works closely with the transit agencies and other partners to gather data including:

- Fueling records – cost and efficiency calculations
- Maintenance records – cost per mile by system
- Daily bus use & availability – reliability
- Roadcalls – reliability
- Fleet experience – lessons learned

Data Summary

FCEB Fleets Included in Data Summary

Transit Agency	Location	Bus OEM	# Buses	Data Included
AC Transit	Oakland, CA	Van Hool	13	Fuel cell hours only
		New Flyer	10	All
SunLine Transit Agency	Thousand Palms, CA	New Flyer	5	All
Orange County Transportation Authority (OCTA)	Santa Ana, CA	New Flyer	10	All

AC Transit, New Flyer

OCTA, New Flyer

SunLine, New Flyer

AC Transit, Van Hool

Evaluation Buses

Vehicle System	OCTA FCEB	SunLine FCEB	OCTA CNG	SunLine CNG
Number of buses	10	5	10	5
Bus manufacturer/model	New Flyer, Xcelsior	New Flyer, Xcelsior	New Flyer, Xcelsior	New Flyer, Xcelsior
Model year	2018	2018	2016	2019
Bus purchase cost* ($)	$1.3 M	$1.2 M	$580,000	$681,000
Length/width/height	41 ft/102 in./129.6 in.	40 ft/102 in./129.6 in.	40 ft/102 in./130.8 in.	40 ft/102 in./130.8 in.
Curb weight (lb.)	33,500	30,900	30,000	30,500
GVWR (lb.)	44,533	44,000	42,290	44,000
Hybrid system	Siemens ELFA2, Permanent Electronic Motor, 210 kW	Siemens	N/A	N/A
Fuel cell or engine	Ballard FCvelocity-HD85, 85 kW	Ballard FCvelocity-HD85, 85 kW	Cummins Westport ISL G 280 hp @ 2,200 rpm	Cummins L9N 280 hp @ 2,200 rpm
Energy storage	A123 Systems, lithium-ion, 100 kWh	A123 Systems, lithium-ion, 100 kWh	N/A	N/A
Accessories	Electric	Electric	Electric and Mechanical	Mechanical
Fuel capacity	Gaseous hydrogen, 5 Type 4 composite cylinders, Agility Fuel Solutions, 37.5 kg at 5,000 psi	Gaseous hydrogen, 5 Type 4 composite cylinders, Agility Fuel Solutions, 37.5 kg at 5,000 psi	CNG, 6 cylinders, Lincoln Composites 156 gge at 3,600 psi	CNG, 6 carbon fiber cylinders, Agility Fuel Solutions, 158 gge at 3,600 psi

Targets

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

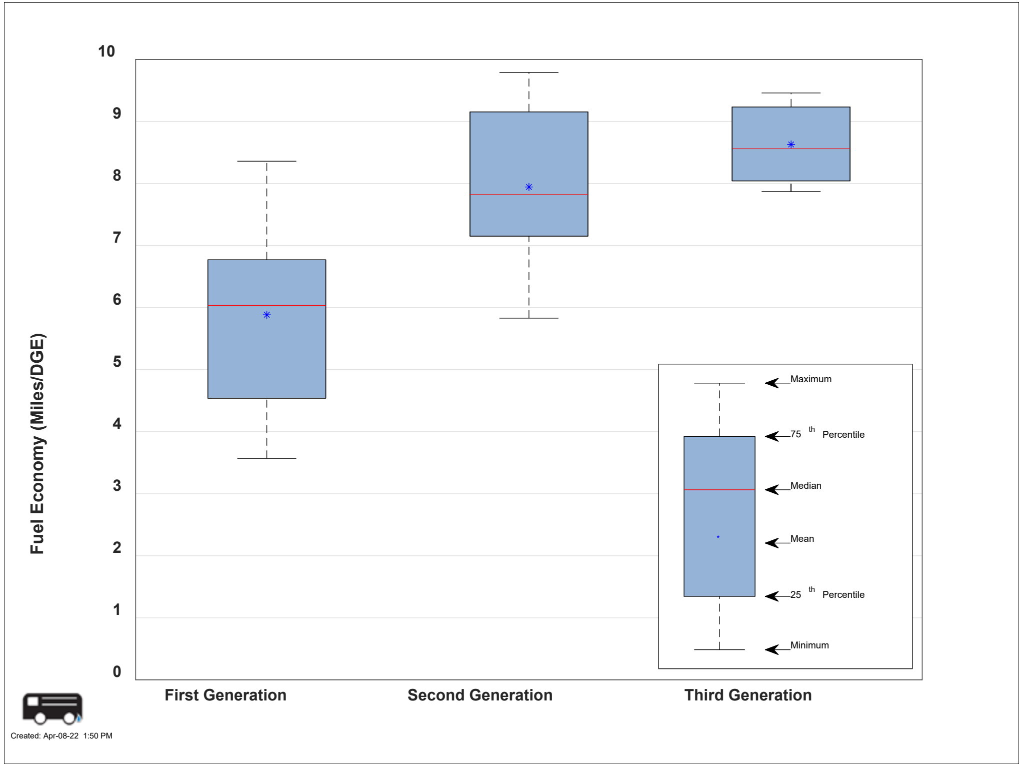
Data collected are used to assess the progress toward meeting those targets and to provide feedback to DOE on what research is needed.

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

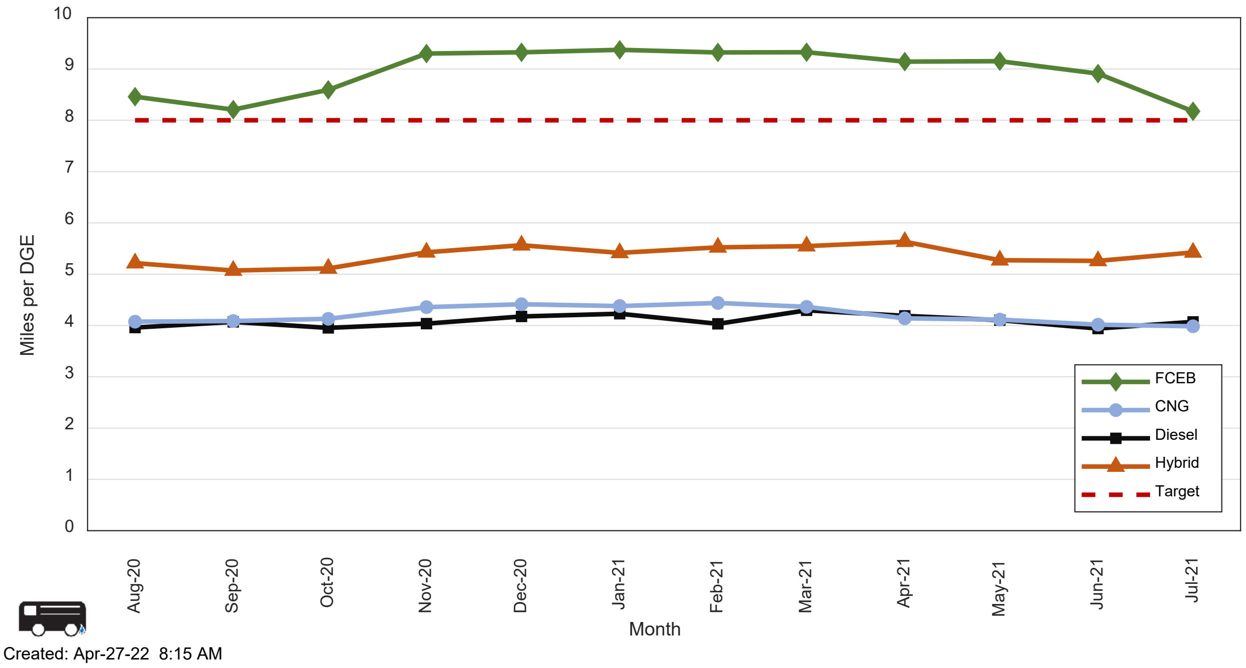
Initial Fuel Economy by FCEB Generation



Current generation FCEB average fuel economy has exceeded the ultimate target of 8 Miles/DGE

- The New Flyer FCEBs in this evaluation are their second generation, but considered an overall third generation after lessons learned from previous manufacturers
- Initial Fuel Economy is defined as the fleet average of the first full year in service

Fuel Economy Continues to Surpass Target



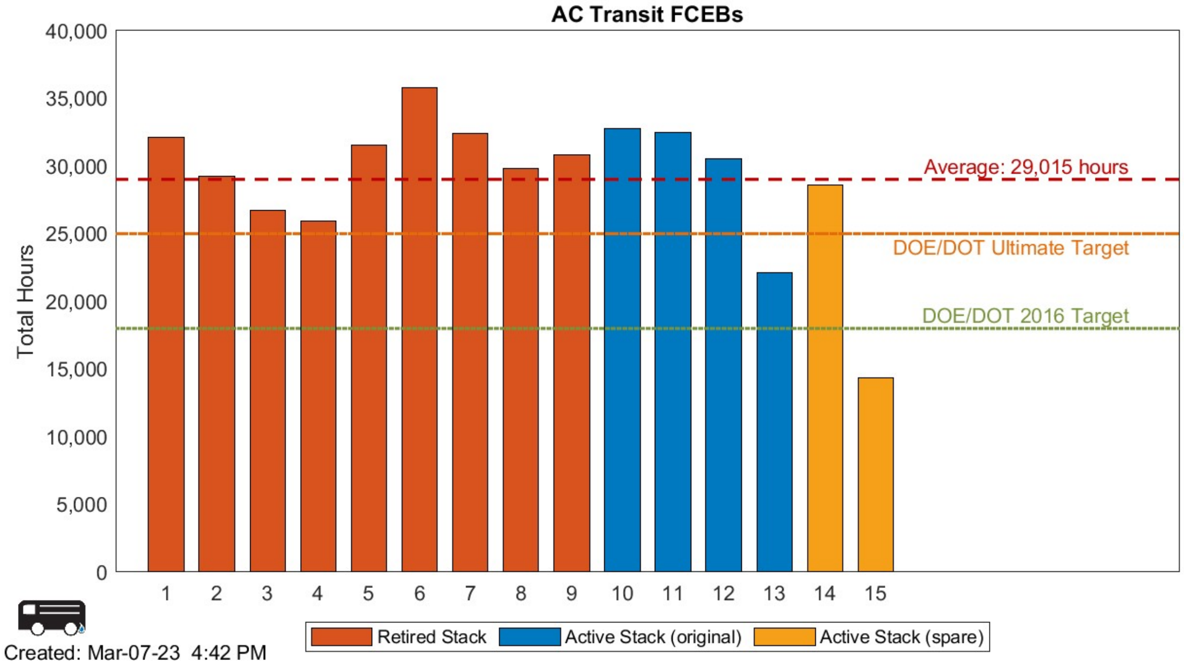
Bus type	mpdge
FCEB	8.95
CNG	4.20
Diesel	4.09
Hybrid	5.37

FCEB fuel economy continued to be >2 times that of CNG and diesel buses and >1.6 times that of hybrid buses

FCEB fuel economy stayed above target all seasons

Top Fuel Cell Powerplant Exceeds 35,000 Hours

AC Transit VanHool FCEB Fleet



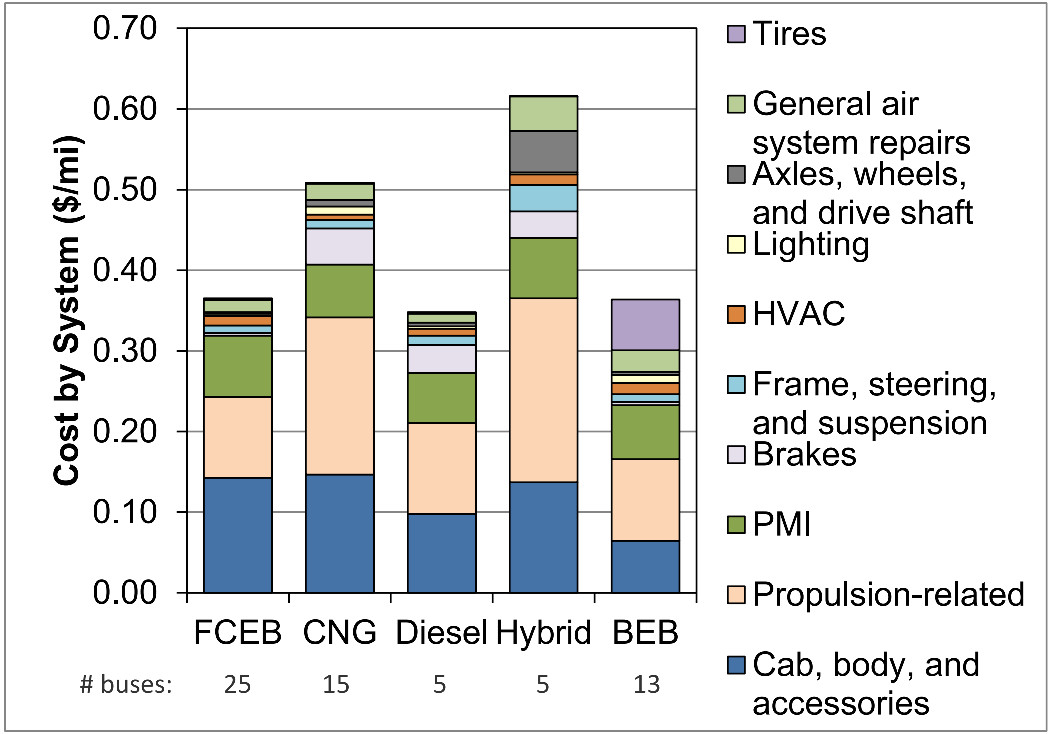
Total hours accumulated on each FCPP as of 8/31/2022

- Top fuel cell powerplant (FCPP) >35,000 hours
- 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

Maintenance Cost by System

New Flyer FCEB Fleets

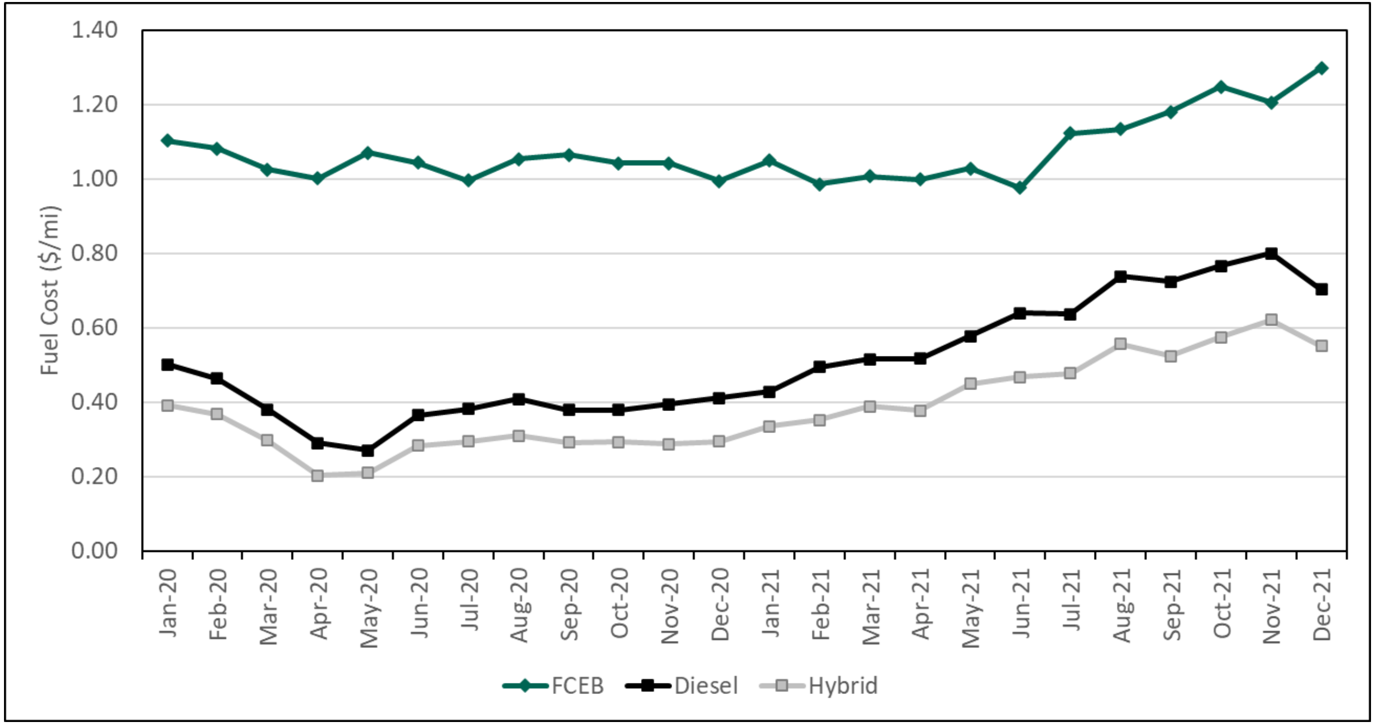


- Cost for FCEB similar to that of diesel and BEB
- Propulsion costs include:
  - Labor for troubleshooting
  - Consumables
- PMI is labor for inspections

- Cumulative cost from in-service date
- Labor @ $50/h

BEB = battery electric bus
BOP = balance of plant
PMI = preventive maintenance inspection
HVAC = heating, ventilation, and air conditioning

Monthly Average Fuel Cost Per Mile



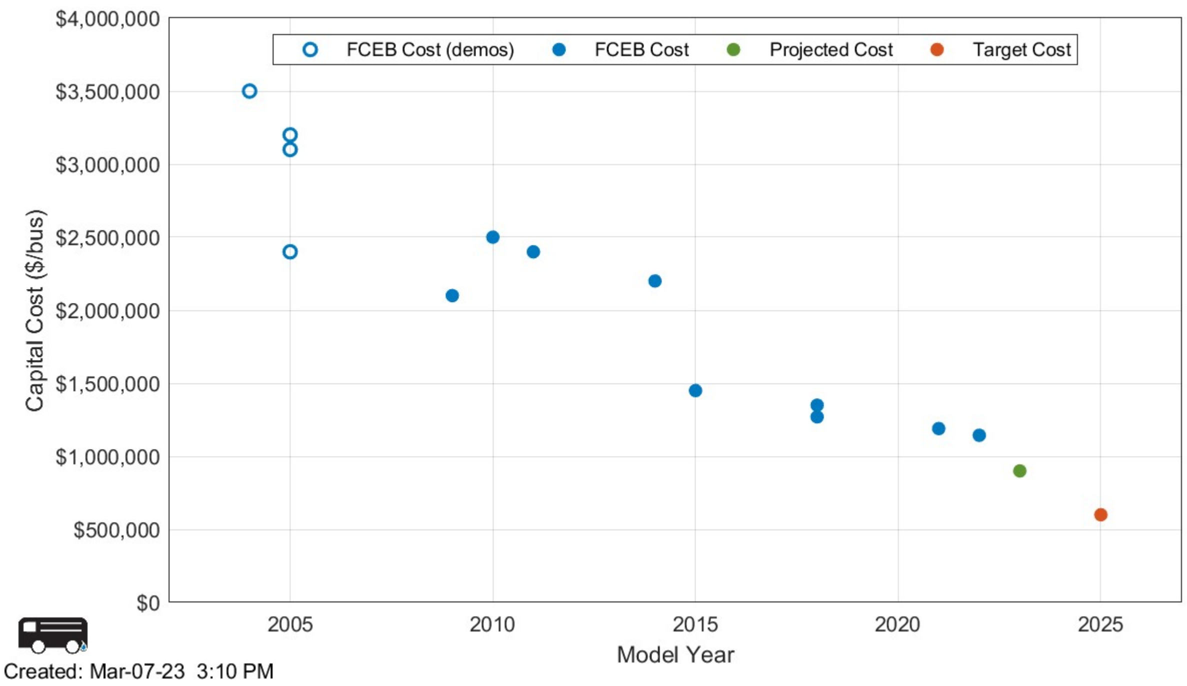
Average fuel cost

- 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

FCEB Cost Trends



- FCEB cost continues to trend downward
- Ultimate target has not yet been met
- Larger volume orders have not yet been made in order to make significant cost reductions

FCEB cost is still about twice the ultimate target

Hydrogen Stations

Hydrogen Stations

Transit Agency	# Dis-pensers	Pre-cooling	Electrolysis	Liquid Storage	Max Fills/Day	Year Built	Station Cost	Maintenance Cost
AC Transit Oakland [102]	2	–	65 kg/day	9,000 gallons	13	2014	$6.3 million	$15,500/month
AC Transit Emeryville [102]	–	–	–	9,000 gallons	13	2011	$5.1 million	–
AC Transit Emeryville [102]	2	–	–	15,000 gallons	65	2020 upgrade	$4.424 million	$11,800/month
OCTA [81]	2	10°C	–	18,000 gallons	50	2019	$4.7 million	–
SunLine [109]	2	–	900 kg/day	–	32	2019	$8.3 million	$0 for 3 years
SARTA [79]	1	–	–	9,000 gallons	20	2017	$2.9 million	$10,000/month
Foothill Transit [110]	–	–	–	5,000 kg	–	2022–2023	$6.6 million	–

Comprehensive Review of California’s Innovative Clean Transit Regulation: Phase I Summary Report
https://www.nrel.gov/docs/fy23osti/83232.pdf

Remaining Challenges and Barriers

For industry to fully commercialize FCEBs:

- Deploy larger fleets
  - Lower per-bus price: OEMs estimate ~$1M/bus for higher volumes
  - Accelerate learning curve for staff
  - Combine orders for multiple agencies
- Incorporate training for FCEBs into standard maintenance training
- Install hydrogen stations
  - High capital cost to install, but easier to scale up compared to battery fleet
  - Turn-key stations where fuel provider owns, operates, and maintains station can help with stabilizing cost for long-term budget planning
  - Long-term fuel contracts can lock in lower cost
  - Station utilization—higher volumes can mean lower per-unit cost

Thank You

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Matthew.Post@nrel.gov NREL/PR-5700-85623

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