

**FUEL CELL ELECTRIC BUSES:
MARKET DEVELOPMENT REVIEW AND SUPPLY CHAIN SURVEY
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Prepared by

Greentree Consulting LLC

P.O. Box 472

Lebanon, OH 45036

www.greentreeconsulting.net

Ohio Fuel Cell Coalition

151 Innovation Drive, Suite 320 D

Elyria, OH 44035

www.fuelcellcorridor.com

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Authors

Patrick Fullenkamp, Greentree Consulting LLC

Dee Holody, Greentree Consulting LLC

Pat Valente, Ohio Fuel Cell Coalition

Linda Buckosh, Ohio Fuel Cell Coalition

Editors

Andrew Thomas, Cleveland State University

Mark Henning, Cleveland State University



Table of Contents

- Executive Summary 2**
- 1 Introduction. 6**
- 2 Literature Review 6**
 - 2.1 Transit Bus Component Technology Forum..... 6
 - 2.2 FTA Zero-Emission Bus Evaluation Results for SARTA 9
 - 2.3 California Fuel Cell Partnership 2019 Bus Road Map..... 12
 - 2.4 How Can California Transit Agencies Access Hydrogen Fuel? 13
 - 2.5 Build Your Dreams (BYD) May 2018 Press Release 15
 - 2.6 H2 Aberdeen Hydrogen Bus Project 15
 - 2.7 Analysis of Supply Chain Opportunities for Fuel Cell Buses..... 16
- 3 Identifying Major Supply Chain Issues 16**
 - 3.1 Questionnaire on Fuel Cell Electric Bus Supply Chain..... 16
 - 3.2 Transit Authority Interviews 20
 - 3.3 Impact on adoption of fuel cell transit vehicles..... 22
- 4 Identifying Existing and Potential Midwestern Suppliers 22**
- 5 Proposed Strategies for Improving Bus Performance through Supply Chain Support..... 27**

Abstract

This report assimilates and summarizes prior research on bus supply chain for fuel cell electric buses (FCEBs), focusing principally upon those operated by the Stark Area Regional Transit Authority (SARTA) in Canton, Ohio. The scope of services was issued by Midwest Hydrogen Center of Excellence (MHCoE) in support of certain SARTA Federal Transportation Administration (FTA) grants, through the Center for Transportation and the Environment (CTE). Major supply chain issues were identified for fuel cell transit buses and evaluated on their effect on performance and their impact on broad adoption of fuel cell transit vehicles. Surveys and interviews were conducted of Transit Authorities, FCEB manufacturers, and component suppliers for electric propulsion systems, the fuel cell, and other components and/or accessories. Survey and interview feedback are summarized and assessed within this report including feedback on the role suppliers currently take in responding to product problems. The report also identifies major U.S. FCEB and associated component suppliers and stakeholders with a focus on companies located in Ohio and the Midwest. Strategies are proposed and prioritized for resolving supply chain issues that were identified.

Executive Summary

The Stark Area Regional Transit Authority (SARTA) is a pioneer in deploying hydrogen fuel cell electric buses. The agency has operated hydrogen fuel cell electric buses in Canton, OH since 2016. Supply chain challenges leading to bus downtime have been found in the ramp-up phase of the Hydrogen FCEB (Fuel Cell Electric Bus) industry, as might be expected for other start-up technologies. As of September 2019, there were 71 FCEB's in operation in the U.S., 5 of them at SARTA.¹ The FCEB industry has been able to capitalize on the knowledge and technology improvements in fuel cell components developed for other applications, such as automotive, lift trucks, heavy duty trucks, and stationary power generation. Nevertheless, most of the fuel cell electric bus components are “next generation,” and provide manufacturers with challenges in timely replacing parts. This study was undertaken to identify the most significant challenges incurred, especially by SARTA, and to identify strategies for resolving those challenges.

Past Practices Review: Assimilating Prior Research on Bus Supply Chain

Two recent investigations into bus supply chain are instructive: the “Transit Bus Technology Forum,”² which was a workshop held in Columbus, Ohio on November 6-7, 2019; and the National Renewable Energy Laboratory's (NREL) “Zero Emissions Bus Evaluation Results” for SARTA,³ published in October 2019. According to a recently completed national survey of transit agencies, the results for which were presented at the Columbus bus technology forum, fuel cell electric buses are in 11 transit authorities in the U.S., with anticipated growth projected to be greatest in California in response to zero emission bus procurement mandates. As of September 2019, 2,184 battery electric buses and 71 hydrogen fuel cell buses were in operation nationwide.⁴

The NREL study of SARTA's experience operating a fleet of five FCEBs -- over a one-year period from February 2018 to January 2019 — provided insight on the testing programs and current technology for these types of buses, as well as actual field test results. The NREL report compared evaluation results for the five FCEBs operated by SARTA to a baseline of four compressed natural gas (CNG) buses in similar service for the Canton, OH transit agency. The key supply chain and performance areas covered in the NREL evaluation for SARTA, done in collaboration with FTA for vehicles deployed through that agency's Low or No (Lo-No) Emission Deployment and National Fuel Cell Bus Program (NFCBP) programs, were as follows:

¹ https://calstart.org/wp-content/uploads/2019/10/Zeroing_In_on_ZEBs_Final_10182018-10.21.19.pdf

² <https://calstart.org/wp-content/uploads/2019/11/Transit-Bus-Component-Tech-Forum-Slides.pdf>

³ 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

⁴ See fn 1, *supra*.

maintenance manpower, technology issues, air filter quality, heating-ventilation-air conditioning, downtime for non-technology related issues, energy consumption, planned vs actual days running, compressor, work order maintenance cost, propulsion, manufacturer partners, hydrogen station, common issues, and insights from the operations lead.

NREL has been evaluating all FTA-funded advanced technology transit buses using a standard data collection and analysis protocol originally developed for U.S. Department of Energy (DOE) heavy duty vehicle applications. Based on the data presented by NREL, it appears that FCEBs have not yet achieved the desired level of performance in important areas such as reliability compared to conventional diesel and natural gas buses. With an expedited focus on addressing the issues of performance and cost, FCEBs will be a viable choice in the transit market as they will be needed to meet both range and zero emission transit goals.

Identifying Major Supply Chain Issues for Fuel Cell Transit

When issues occur with buses, this generates downtime and reduces overall operational efficiency, often impacting bus schedules and rider satisfaction. Downtime can include the following: time to diagnose the problem with internal or outside technicians; time to order the replacement part; time to acquire the replacement part or repair existing part; time to ship parts; customs time, if parts are coming from outside the US; and time to replace part on bus and verify problem has been resolved.

To understand the key drivers of supply chain performance, a questionnaire was developed to gain feedback from fuel cell bus OEMs and key systems and component suppliers. The following questions were posed to key supply chain participants:

1. What level of capacity can you provide with current technology and minimal Capex?
2. Are there any technical or manufacturing barriers?
3. What systems do you have in place to support your customers when issues arise?
4. What do you see as issues in the supply for Tier 1, Tier 2, and or Tier 3?⁵
5. Do the issues materially affect performance of the FCEB?
6. Would additional supply chain be beneficial?

⁵ Supply chain tiers are defined as follows: Example: Tier 1 suppliers sell directly to the OEMs, Tier 2 company would supply the metal stampings to Tier 1 company, and Tier 3 company would be the supplier of the metal to the Tier 2 company.

7. Are you getting sufficient feedback on issues from FCEBs in operation?
8. Is the hydrogen supply and dispensing components and infrastructure acceptable?

An interview was also conducted with the SARTA Chief Operations Officer and Service Manager to identify and understand supply chain issues, the process and timing for acquiring replacement parts, incident and warranty reporting, and the comparative experience that other transit agencies have described.

Identifying Major Suppliers and Stakeholders in the Supply Chain

The role that suppliers take to resolve transit bus component problems was found to be dependent on the experiences and expectations from current diverse customers. They feel they are getting sufficient feedback from FCEBs in operation. Recommended next steps are in the report.

A list of major suppliers was developed using OFCC and Greentree Consulting supply chain databases plus other sources such as the November 7, 2019 Transit Bus Component Technology Forum attendees (please refer to pages 24 to 27 of this report). Of the listed companies, 73 are US-based, with 39 of those located in Ohio. Additionally, seven companies listed are outside of the US and considered key players in the FCEB supply chain. Based upon research conducted by Greentree Consulting and OFCC, Ohio maintains the highest concentration of FCEB suppliers, which are generally located near the existing automotive industry. The state would likely benefit from the addition of a FCEB assembly plant to make best use of the Ohio and Midwest concentration of FCEB suppliers.

Proposed Strategies for Resolving Supply Chain Issues

A list of 12 strategies was developed for identifying, tracking, and resolving supply chain issues. They are listed in order of recommended priority. The strategies are the result of group feedback at the November 7, 2019 Transit Bus Component Technology Forum and knowledge/experiences of best practices from the automotive industry. They are as follows:

1. Develop an industry-wide incident reporting and corrective action system between operators, bus OEMs, and component suppliers, similar to today's automotive industry.
2. Develop a standardized testing process to improve the definition and documentation of component performance and durability.
3. Develop effective data collection and disbursement systems which could improve overall FCEB performance.

4. Provide additional resources within existing suppliers to help with improvement in reliability and cost reduction.
5. Achieve greater economies of scale to decrease cost and improve performance.
6. Develop pre-heating/pre-cooling for FCEB passenger area using alternate electric power source such as plug in electric for heating and cooling, versus hydrogen on board.
7. Develop cold and hot weather optional packages.
8. Optimize the watts through the correct balance of infrastructure, battery technologies, heating & cooling, braking, power steering, and education for operators and maintenance technicians.
9. Power density improvement challenge (current compressed hydrogen is 68,000 BTU per cubic ft or 2533 megajoule/cubic meter per U.S. DOE EERE).
10. Maximize mileage by increasing pressure vessel rating (e.g. going from 5,000 to 10,000 psi) through technological improvement to obtain more kg of hydrogen on board.
11. Improve electric motor technical reliability.
12. Develop infrastructure to get “fuel” (i.e. stored energy) to the buses



1 Introduction.

The Stark Area Regional Transit Authority (SARTA) is a pioneer in deploying hydrogen fuel cell electric buses. The agency has operated hydrogen fuel cell electric buses in Canton, OH since 2016. Supply chain challenges leading to bus downtime have been found in the ramp-up phase of the Hydrogen FCEB (Fuel Cell Electric Bus) industry, as might be expected for other start-up technologies. As of September 2019, there were 71 FCEB's in operation in the U.S., 5 of them at SARTA. The FCEB industry has been able to capitalize on the knowledge and technology improvements in fuel cell components developed for other applications, such as automotive, lift trucks, heavy duty trucks, and stationary power generation. Nevertheless, most of the fuel cell electric bus components are "next generation," and provide manufacturers with challenges in timely replacing parts. This study was undertaken to identify the most significant challenges incurred, especially by SARTA, and to identify strategies for resolving those challenges.

2 Literature Review

The following section assimilates some of the most recent and relevant research on the market and supply chain for fuel cell electric buses (FCEBs).

2.1 Transit Bus Component Technology Forum

This forum was hosted in November 2019 by Calstart at Transportation Research Center, Inc.,⁶ an independent vehicle test facility located near Columbus, Ohio, in November 2019. It provided a platform for information exchange on the latest advancements in component offerings and testing centers for low and no emission buses, in partnership with the Federal Transit Administration's (FTA) Transit Vehicle Innovation Deployment Centers.⁷ The goal of the forum was to examine and highlight the capabilities of the FTA's Low and No-Emission Component Assessment Program (LoNo-CAP) centers and have a thorough vetting of the component technology needs of LoNo buses going forward.

The following reports and websites were referenced during the Forum program:

- **Transit Bus Technology Forum**, November 7, 2019

Author: F. Silver and various other presenters.

This forum gathered industry leaders to exchange ideas and information to advance low and no-emission buses at the component level and beyond. Also unveiled was the new FTA Low and No-emission Bus Component Assessment Program (Lo-No CAP) and introduced the new centers and the subsidized services they can provide to prove out components for the industry.

⁶ <https://www.trcpg.com/about-us/>

⁷ See footnote 2, *supra*.

Report link: <https://calstart.org/wp-content/uploads/2019/11/Transit-Bus-Component-Tech-Forum-Slides.pdf>

- **Ready for Work Full Report**

Author: Union of Concerned Scientist

This report provides a breakdown of all zero-emission buses, categorized by battery electric buses and hydrogen fuel cell buses, for every state in the US. A list of transit agencies who are actively operating, ordering, or have received funding for ZEBs is shown.

Report link: <https://www.ucsusa.org/sites/default/files/2019-12/ReadyforWorkFullReport.pdf>

- **Low and No-Emission Component Assessment Program (LoNo-CAP)**

Sponsor: Federal Transit Authority

On September 29, 2016, FTA announced the opportunity for eligible institutions of higher education to apply for funding to conduct testing, evaluation, and analysis of low or no emission (LoNo) components intended for use in LoNo transit buses used to provide public transportation. In January 2017, FTA [announced](#) the selection of The Ohio State University and Auburn University to receive research funds under the Fiscal Year 2016 LoNo-CAP funding opportunity.

Program link: <https://www.transit.dot.gov/research-innovation/lonocap>

- **Energy Flow Charts**

Author: Lawrence Livermore National Lab

This site provides a flowchart of the proportional amount of energy consumed for the transportation sector by energy resource.. Energy resources included solar, nuclear, hydroelectric, wind, geothermal, natural gas, coal, biomass, and petroleum. Energy flow diagrams change over time as new technologies are developed and as priorities change. This website allows users to see the changing mix of energy resources used by the transportation sector over time as well as how this mix varies by country and by U.S. state.

Report link: <https://flowcharts.llnl.gov/commodities/energy>

As of September 27th, 2019, Calstart estimates the following number of zero-emission buses in operation or on order:

- Battery Electric Buses (BEBs): 2184
- Hydrogen Fuel Cell Buses (FCBs): 71
- Total Zero-emission Buses (ZEBs): 2255

Zero-emission buses nationally have grown to over 2000 buses on the road or on order, an increase of 36 percent over the last calendar year. The region of the country with the most buses was the West Coast (Washington, Oregon, and California), with over half in that region alone. California had the highest number of ZEBs with over 1000. The median number of ZEBs per transit agency nationwide was six, while the median number in California was nine. In total, there were 202 transit agencies that had ZEBs in operation or on order in the United States. Of those 202, 56 were in California. Over 60 new transit agencies across the country added zero-emission buses to their current fleets during this time from 2018 to 2019. States that added zero-emission buses for the first time include Arizona, Kansas, Maine, Mississippi, Rhode Island, and Wyoming.⁸

The following number of FCEBs were in operation in the United States as of late 2019:

- 1 in Arkansas
- 52 in California
- 2 in Hawaii
- 1 in Idaho
- 1 in Maine
- 1 in Michigan
- 12 in Ohio

The forum also provided an opportunity for major system and component suppliers, as well as system integrators and transit agencies, to highlight the barriers that remain for wider FCEB adoption:

- New Flyer – Barrier is infrastructure to get the power to the buses
- New Flyer – Motor technical reliability
- Cummins – Power density challenge
- BAE – Infrastructure, battery technologies, hunting for watts to optimize heating & cooling, power steering, education
- SARTA – Ability to take buses out as long as you want; need to go from 5,000 to 10,000 psi pressure in vessels to get from 250 to 400 mile range; all buses are designed and built for California weather; a cold weather package is needed.
- Chicago Transit –Need electric companies more involved, fuel cells versus battery – price & value

⁸ See fn 2, *supra*.

- Cummins – Higher conversions if price of hydrogen goes down to \$4/kg with larger volume
- Economies of scale improve cost
- Battery Electric buses are heavy by 5,000 lbs versus, Fuel Cell (43,420 lb) and CNG buses (41,600 lb)
- SARTA – 10-minute fueling, 1 MW charging is 45 – 60 minutes, \$1,000/kW cost of chargers
- Electrify America at 350 kW (Adding fast power recharging stations with 350kW power)
- New Flyer – running fuel cell at steady state 25 kWhr

2.2 FTA Zero-Emission Bus Evaluation Results for SARTA

This report summarizes the experience and results from a demonstration of five fuel cell electric buses compared to four CNG electric buses operated by Stark Area Regional Transit Authority (SARTA), in Canton, OH.⁹ FTA collaborated with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to conduct in-service evaluations of advanced technology buses developed under its programs. The FCEBs were 40-foot Eldorado National-California (ENC) buses with BAE Systems hybrid electric propulsion systems powered by Ballard's FCvelocity-HD6 150-kW fuel cells. NREL collected data on a fleet of four Gillig compressed natural gas (CNG) buses as the primary baseline comparison.

The focus of the analysis was on the most recent year of service, from February 2018 through January 2019. SARTA collaborated with CALSTART to analyze acceptance of the technology within the agency. CALSTART conducted surveys of the operators and maintenance technicians at SARTA. Survey analysis results are available in the report.

Key points from the report

- The overall average availability for the FCEB fleet was 68%, and the overall availability for the CNG baseline fleet was 76%. Most unavailable days for the FCEBs were due to general bus issues, followed by preventive maintenance. The overall availability of the fuel cell system was 94%.
- Bus reliability, measured as miles between road call (MBRC), for the FCEBs shows a slow but steady climb from the beginning of the demonstration to an overall bus

⁹ <https://www.transit.dot.gov/research-innovation/zero-emission-bus-evaluation-results-stark-area-regional-transit-authority-sarta>

MBRC of 3,737 at the end of the data period, nearing the ultimate target of 4,000. The overall fuel-cell-system-related MBRC, at more than 26,000, surpassed the DOE/DOT ultimate target.

Issues and lessons learned on components and operation

SARTA had two maintenance technicians trained to service FCEBS and was training a third during the evaluation period. The agency plans to train additional technicians each year as its FCEB fleet grows. These technicians handle preventive maintenance, general bus repairs, and troubleshooting and repair of propulsion system issues with help from the manufacturer partners. SARTA's manufacturer partners are available for troubleshooting issues over the phone and travel to the site for repairs as needed.

There were a few issues with the fuel cell and hybrid drive systems during the evaluation period. The fuel cell issues were not related to the stack itself, but rather to the peripheral components that supply hydrogen and air, including a failed hydrogen recirculation blower and an air compressor controller. Hybrid system issues included a problem with a low voltage connector in the electronics that was not properly seated; the problem was intermittent and therefore took extra time to diagnose.

SARTA replaced an air filter with one from a manufacturer that was different from the OEM-specified part for the FCEB. The new filter was listed as a substitute for the original part. Although the non-OEM filter fit, the quality was not the same—the filter allowed water to enter the vent air filter housing, which corroded the wiring for the vent fan, causing premature failure of the fan.

SARTA experienced some issues with the electrically driven air conditioning on the FCEBs due to failing evaporative and condenser motors. The local technician for the component supplier was not familiar with the model, which added to the time to troubleshoot the issue. The failed part had quality issues in the manufacturing process, and the component supplier has addressed the issue. The buses also had early issues with getting sufficient heat to the interior on extremely cold days (e.g. below 15° F). The agency elected to keep the buses out of service on these coldest days. The manufacturer addressed this issue by widening the setpoint limits for heating and insulating the components of the HVAC system that were outside the cabin area. These changes have resulted in better heating inside the bus without affecting the bus efficiency.

During the February 2018 through January 2019 evaluation period, there were two incidents in which a bus was out of service for an extended period that were not due to an

issue with the technology. In one instance, the internal process for SARTA to issue a part order took longer than expected. In the second instance, a part request was not received by the supplier. These circumstances are not expected to reoccur.

The following is a list of issues and findings experienced on SARTA's FCEB's:

- **Commonly reported issues** – Respondents cited that buses were often unable to reach highway speeds and had multiple component failures
- **HVAC and energy consumption** – Respondents stated that running heating and cooling systems limited bus range due to the energy needed to run those systems.
- **Data Collection** – NREL has been evaluating advanced technology transit buses using a standard data collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations
- **Planned days 1,427** – off 85 days for fuel cell system/engine servicing; 66 days for propulsion issues; 96 days PM.
- **Unscheduled Maintenance Costs** – Higher costs in August 2018 resulted from the extra labor to troubleshoot issues and replace several low-voltage batteries while higher costs in October 2018 were due to a high-cost part (air compressor controller) that was not covered under warranty.
- **Work Order Maintenance Cost per mile by System** – Propulsion related (\$0.154 or 46%); Preventative maintenance (\$0.075 or 22%); Cab, body, accessories (\$0.058 or 17%); HVAC (\$0.016 or 5%); Frame, steering and suspension (\$0.015 or 5%). The other systems which include brakes, lighting, general air system repairs, axles, wheels, drive shaft, and tires were less than 1% each.
- **Propulsion** – Propulsion related vehicle systems at 46% of total maintenance cost include the exhaust, fuel, engine, fuel cell system, battery modules, electric propulsion, air intake, cooling, non-lighting electrical, transmission, and hydraulic systems.
- **Experience** – SARTA reports that it has had a positive experience with the technology and that its manufacturer partners have provided excellent support for the buses.
- **Hydrogen Station** – Hydrogen station has proven to be reliable, with no loss of service due to station downtime

According to an interview with SARTA's operations lead, two heating units went out during the demonstration.¹⁰ Heating affected mileage efficiency. Some drivers were able to get better mileage by turning the heater off when possible. The range, forecasted for 250 miles, was in reality closer to 215 miles. SARTA's drivers had range anxiety due to a lack of gauges showing remaining mileage. The operations lead recommended that next generation buses include instrumentation indicating the distance to an empty hydrogen tank. There were no reported safety issues associated with the bus, except that it was so quiet that pedestrians reported that they could not hear it coming.

The fuel cell bus received a generally good rating from both drivers and maintenance technicians. Although both drivers and technicians reported several issues with the bus, most stated that their opinions of the bus improved over time as they gained more experience driving and working on it. This suggests that drivers and maintenance technicians are more likely to accept the fuel cell bus and adopt it over time if the manufacturer works with them to resolve issues quickly and to improve bus design as feedback is provided.

As noted, common issues with the fuel cell bus included a reportedly faulty back door, a slow kneeler, uncomfortable and low seats, slow acceleration, an inability to reach highway speeds, multiple component failures, inconsistencies in the manufacturing quality of buses delivered to SARTA, and poor fuel economy. In terms of vehicle performance, both drivers and technicians agreed on how the bus performed in terms of initial launch, acceleration, coasting/ deceleration, and braking behavior. In 2018, both groups rated the fuel cell bus either the same or better on these measures when compared to a conventional bus. Drivers and technicians also agreed on their operational ratings for cold start and inside and outside noise level. In 2018, both rated these measures the same as or better than that of conventional buses. All in all, the fuel cell bus seemed to perform best on the measures of inside and outside noise level, reportedly much quieter than conventional buses, and it seemed to perform worst in terms of productivity.

2.3 California Fuel Cell Partnership 2019 Bus Road Map

In 2013, the California Fuel Cell Partnership (CaFCP) released "A Road Map for Fuel Cell Electric Buses in California: A zero-emission solution for public transit."¹¹ CaFCP's updated 2019 road map, "Fuel Cell Electric Buses Enable 100% Zero Emission Bus Procurement by 2029" (2019 Road Map), builds on the first report and is directed to multiple stakeholders,

¹⁰ 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

¹¹ https://cafcp.org/sites/default/files/A_Roadmap_for_Fuel_Cell_Electric_Buses_in_California.pdf

including transit agencies, policy makers and others who make decisions that affect millions of transit riders.¹² The focus of this strategy document is the California transit community. However, California's policy and funding leadership, coupled with the size of its vehicle markets, offers opportunities to other U.S. states. The 2019 Road Map counted 15 fuel cell electric buses in operation in California, 13 with Alameda-Contra Costa Transit District (AC Transit) in the San Francisco East Bay, and two with SunLine Transit Agency (SunLine) in Southern California's Coachella Valley. Today, 25 fuel cell buses are on the road with these and other agencies, including the University of Irvine and Orange County Transportation Authority (OCTA), and 21 more buses are expected shortly.

Summary on issues and lessons learned on components and operation

Challenges remain and will require continued collaboration among stakeholders, including private industry and government. These challenges include:

- Hydrogen fueling infrastructure for large fleets
- Fueling infrastructure cost for small fleets
- Federal and state funding for fueling infrastructure
- Supply of parts
- Cost of components

A lower cost of hydrogen competitive with diesel will be reached when produced at scale, including low carbon hydrogen from renewable sources.

2.4 How Can California Transit Agencies Access Hydrogen Fuel?

Nicolas Pocard, Director of Marketing at Ballard Power Systems, has reported on several areas that impact the growth of hydrogen technology, including accessibility of fuel and economies of scale.¹³ Some of his analysis is discussed below with regard to accessing hydrogen.

Key Points

When evaluating fuel cell electric buses against battery electric buses, the issue of fueling/charging is a big one, especially at fleet scale. If a transit agency decides to go for FCEBs, how can it get a sufficient volume of hydrogen fuel that is competitively priced? First, a number of transit agencies within the same area would each need to commit to

¹² <https://cafcp.org/sites/default/files/2019-CaFCP-FCEB-Road-Map.pdf>

¹³ Hydrogen at Scale for Fuel Cell Electric Buses: <https://info.ballard.com/hydrogen-at-scale-for-fuel-cell-electric-buses>

scaling up their fleets to around 50+ FCEBs over time. This would provide minimum hydrogen volume commitment to fuel service providers. Once there is sufficient demand for renewable hydrogen from local transit authorities, green hydrogen production, storage, and distribution facilities would likely be built using renewable electricity from wind and solar farms. SunLine Transit provides a useful lesson in this regard. This Southern California transit agency is currently constructing a 1.5 MW PEM electrolyzer that will enable onsite fuel generation via solar power for what will be the largest renewable hydrogen fueling facility in the U.S. to support a growing fleet of FCEBs.¹⁴

Moving to zero-emission transit is important in order to reduce air pollution. To significantly reduce greenhouse gas emissions, the carbon intensity of the transit fuel—whether it be electricity or hydrogen—is very important. Using green hydrogen locally produced from renewable electricity via wind and solar provides the fastest path to a complete decarbonization. This path is also relatively more economical than alternatives.

Since the cost of hydrogen is on a per kilogram basis, transit operators can budget for annual operating costs, and price generally will improve with volume. In contrast, battery electric buses (BEBs) rely on grid electricity, the costs of which are more unpredictable and complex. The price of grid electricity varies greatly, depending on the time of day, and day of the year. As BEB fleet volumes increase, electric utilities make upgrades so that they have the capacity to provide all the power a transit agency could possibly need at any given time, with the costs for these upgrades being passed on to the agency. The uncertainty surrounding these costs makes it difficult for transit operators with BEBs to accurately budget for yearly electricity costs.

Fuel cells themselves have also progressed in the market. In addition to transport sales, stationary systems, many using natural gas to hydrogen, have seen shipments rise. In addition to increasing shipment, major progress was made in 2018 in the development of the supply chain underpinning fuel cell sales and service. Costs are coming down and investment is flowing into the industry, with big companies staking out positions. For example, established automotive supply-chain players such as ElringKlinger, Michelin, Bosch and Plastic Omnium are continuing to quietly and steadily develop capacity, while fuel cell companies like Plug Power, Ceres Power, Hydrogenics and FuelCell Energy are seeing tens of millions of dollars of investment from public markets or industrial partners.¹⁵

¹⁴ <https://www.metro-magazine.com/sustainability/news/722133/sunline-transit-receives-12-5m-grant-for-hydrogen-fuel-cell-fleet>

¹⁵ <https://www.californiahydrogen.org/wp-content/uploads/2019/01/TheFuelCellIndustryReview2018.pdf>

2.5 Build Your Dreams (BYD) May 2018 Press Release

BYD (Build Your Dreams), the largest electric bus manufacturer in North America and the largest electric vehicle company in the world, announced in 2018 that it was teaming with US Hybrid Corporation, a 20-year industry leader in fuel cell engines, to develop a hydrogen fuel cell battery-electric bus.¹⁶ This bus, the first of its kind, will serve Honolulu's Daniel K. Inouye International Airport, one of the busiest airports in the United States with more than 21 million passengers per year.

The new bus is being developed as part of Hawaii's Clean Energy Initiative (HCEI) to meet sustainable energy objectives of decreasing dependency on imported oil and reducing greenhouse gas emissions. The initiative is a central component of the state's goal to be powered 100% by renewable energy by 2045. Robert's Hawaii, the state's largest employee-owned tour and transportation company, will serve as the bus operator, shuttling passengers between the airport's terminal and car rental facility. The bus will fuse BYD's battery-electric platform with US Hybrid's fuel cell technology to eliminate operational dependency on charging.

2.6 H2 Aberdeen Hydrogen Bus Project

The Aberdeen Hydrogen Bus Project in Aberdeen Scotland has been developed from two separate European funded projects, High V.LO-City and HyTransit.¹⁷ These two projects, which funded a total of ten fuel cell buses and one hydrogen refueling station, were supported by the Fuel Cells and Hydrogen Joint Undertaking, a public-private partnership that includes the European Commission, fuel cell and hydrogen industries represented by Hydrogen Europe, and the research community represented by Hydrogen Europe Research. Both the High V.LO-City and HyTransit projects finished operations in December 2018.

Altogether, the Aberdeen Bus Project delivered:

- production of hydrogen from a 1MW electrolyzer, supplied by Hydrogenics;
- a state-of-the-art hydrogen refueling station, which was Scotland's first commercial-scale hydrogen production and bus refueling station;
- deployment of a fleet of 10 hydrogen buses which have been operated by First Group and Stagecoach; and
- development of a hydrogen-safe bus maintenance facility.

¹⁶ <https://en.byd.com/news-posts/press-release-byd-us-hybrid-develop-first-ever-hydrogen-electric-bus/>

¹⁷ <http://www.h2aberdeen.com/home/H2-Aberdeen-hydrogen-bus.aspx>

2.7 Analysis of Supply Chain Opportunities for Fuel Cell Buses

This report, jointly authored by the Energy Policy Center and the Center for Economic Development at Cleveland State University's Maxine Goodman Levin College of Urban Affairs, and sponsored by SARTA, examined supply chain opportunities for fuel cell buses using industrial classifications.¹⁸ This study catalogued where various companies producing fuel cell buses fit within the various NAICS codes, in what industries and sectors they are primarily concentrated, and the relative cost importance of various sectors to the total cost of the fuel cell bus. This report is a useful baseline for measuring future supply chain growth.

3 Identifying Major Supply Chain Issues

When issues occur with buses, this generates downtime and reduces overall operational efficiency, often impacting bus schedules and rider satisfaction. Downtime can include the following: time to diagnose with internal technicians or calling in outside help to resolve problems; time to order, acquire, and install replacement parts; time to repair existing parts; time to ship parts; customs time if outside the U.S.; and the time to verify problem resolution once parts have been repaired or replaced.

3.1 Questionnaire on Fuel Cell Electric Bus Supply Chain

To understand the key drivers of performance, issue resolution, and feedback throughout the supply chain, a questionnaire was developed and submitted to one FCEB OEM and three key systems /component suppliers.

The following are the 10 questions that were asked along with a summary of responses:

1. **What category best represents your system?**

Summary: The following are the categories of suppliers that responded.

- FCEB manufacturer
- Electric propulsion system
- Fuel Cell
- Electric energy storage
- Hydrogen storage vessels
- Other accessories (e.g. Heating and Cooling)

2. **Do you supply product to any of the following sectors (check all that apply)**

¹⁸ https://engagedscholarship.csuohio.edu/cgi/viewcontent.cgi?article=2467&context=urban_facpub

Summary: All the suppliers had a diverse customer base with the integration of their products in multiple sectors.

- Auto transportation (selected by 2 companies)
- Material handling
- Light duty delivery van
- Heavy duty truck transport
- Stationary power for grid connections
- Transit (selected by 2 companies)

3. What level of capacity can you provide with current technology and minimal Capex?

Summary: One supplier had the capability of supplying 21 to 100 units per year.¹⁹ Others could supply greater than 200 units per year.

- 10 to 20 units per year
- 21 to 100 units per year (selected by 1 company)
- 101 to 200 units per year
- Other (selected by 3 companies)

4. Are there any technical or manufacturing barriers?

Summary: Technical and manufacturing barriers exist in the near and long terms. This is not unusual for a new and growing industry. It is important to get the barriers identified and establish corrective actions.²⁰

- Near Term 1 - 2 years (selected by 3 companies)
- Long Term 3 -5+ years (selected by 1 company)

5. What systems do you have in place to support your customers when issues arise?

Summary: The responses from 4 suppliers are quite varied. The types of responses are most often driven by experiences and expectations from current diverse customers. Development of a transit bus industry-wide incident reporting and corrective action system between operators, bus OEM's, and component suppliers with a 24-hour response time window would be beneficial. Some examples of supplier responses to this question are as follows:

Company A – *“We have service centers worldwide to support customer vehicle set up and ongoing running as well as technical support. We have a formal 8D resolution*

¹⁹ Unit is defined as one transit bus or one component part

²⁰ The barriers identified here are the same as those enumerated at the November 2019 Transit Bus Component Technology Forum in Columbus, OH.

process²¹ for quality related issues to be contained and permanently resolved as quickly as possible. We have reliability teams, warranty and service management teams and continuation improvement teams who specifically review customer requirements, feedback and in-field performance data to improve our existing and future products to meet customer requirements. We have a formal Voice of Customer (VOC) process to capture customer requirements at the start of a project and ensure we can meet these targets and negotiate changes to customer requirements where we know we are unable to meet these targets.”

Company B – *“Dedicated aftermarket support team”.*

Company C – *“Active customer specific service program”.*

Company D – *“Dedicated engineering services, regional sales and service managers, 200 Dealer locations in North America”.*

6. What do you see as issues in the supply - Tier 1, Tier 2, and or Tier 3?

Example: Tier 1 suppliers sell directly to the OEMs, Tier 2 company would supply the metal stampings to Tier 1 company, and Tier 3 company would be the supplier of the metal to the Tier 2 company.

Summary: Technology, capacity, reliability, and cost are all issues in the supply chain. Cost is the most prominent followed by technology and reliability. Priority should be given to the resolution of those issues of most importance to the end Customer.

- Technology (selected by 2 companies)
- Capacity (selected by 1 company)
- Reliability (selected by 2 companies)
- Cost (selected by 3 companies)
- Other (selected by 1 company)

7. Do the issues affect performance of the FCEB?

If yes, can they be fixed for next generation within a year?

Summary: As one supplier stated, meeting component reliability, combined with technology limitations that affect FCEB performance, is an ongoing challenge in meeting current agreed upon customer requirements. However, these problems can be fixed within a year. Ultimate customer performance and lifetime targets will take 3-5 years to achieve due to technology, capacity, reliability, and cost limitations within the supply chain for components. One supplier felt its product was at maturity level. Although it

²¹ The eight disciplines (8D) model is a problem-solving approach typically employed by quality engineers or other professionals and is most commonly used by the automotive industry.

could be questioned if there is variability (in volume and or purity) in the hydrogen electric power generation source. Some examples of supplier responses to this question are as follows:

Company A – *“Component reliability and technology limitations affect FCEB performance and is an ongoing challenge to meet the current agreed customer requirements, but these can be fixed within a year for current performance targets. The ultimate customer performance and lifetime targets will take 3-5 years to be able to achieve due to technological, capacity, reliability and cost limitations within the supply chain for components”.*

Company B – *“NA”*

Company C – *“No”.*

Company D – *“All Electric HVAC systems are already at a maturity level to support the FCEB”.*

8. **Would additional supply chain be beneficial?**

Summary: The combination of additional supplies and additional resources within the existing suppliers would be most beneficial. Some examples of supplier responses to this question are as follows:

Company A – *“Additional supply chain resource is always beneficial but additional resources within the existing suppliers would also help with improvement in reliability and cost reduction”.*

Company B – *“Most Likely”.*

Company C – *“Yes, with focus on investment”.*

Company D – *“Not applicable”.*

9. **Are you getting sufficient feedback on issues from FCEBs in operation?**

Summary: All suppliers feel they are getting sufficient feedback from FCEBs in operation. Having the time and resources to effectively analyze the data and improve is the challenge. Developing the most effective data collection and disbursement of data could produce a larger overall FCEB improvement. Examples of supplier responses to this question are as follows:

Company A – *“Yes, we are getting sufficient feedback on issues from product in the field; this is a lot of data and the challenge is having time and resources to analyze this data and be able to turn this into information for our internal reliability and product development teams and to provide back to the supply chain for inclusion into their lessons learned for next generation components”.*

Company B – *“Yes. We garner the data for our system through data loggers on the vehicle”.*

Company C – *“Yes, review the NREL FCEB reports”.*

Company D – *“Yes, from vehicles”.*

10. Is the hydrogen supply and dispensing components and infrastructure acceptable?

Summary: The current state of dispensing components and infrastructure is not acceptable, although it is improving slowly with the move to standardization over the next 1-2 generations and the engagement of large automotive tier 1 suppliers that is in process now. Responses to this question are as follows:

Company A – *“No, but it is getting better. The FCEB market requirements have not yet standardized so this drives division into the supply chain on component design and manufacture, which in turn leads to few supply options for the component technologies needed and a lack of large automotive tier-1 suppliers designing and making components to the quality, reliability and cost [specifications] required for the FCEB market. There are signs of standardization within the next one to two generations of design. Automotive Tier 1 suppliers are now starting to design components to meet the FCEB marketplace, but these are still two to three years away from launch”.*

Company B – *“NA”*

Company C – *“No”*

Company D – *“NA”*

3.2 Transit Authority Interviews

To get feedback from transit authorities on supply chain issues, the Study Team interviewed SARTA’s Chief Operations Officer and Service Manager, and also with Champaign-Urbana Mass Transit District’s (MTD’s) Grant Manager. The responses from MTD were limited as that agency had not yet taken delivery of its two 60-foot FCEBs that were on order. The following responses to questions posed during this interview process illustrate the supply chain challenges facing these Midwest transit agencies.

SARTA

1. Have you had any supply chain issues to date you can share?

“Yes, the industry is young with only 100 buses in the nation and issues are anticipated until maturity and reaching volume. Thermo King introduced a new technology (3 phase electric) cooling and heating system across all bus line and for the initial SARTA fuel cell

buses. The regional Thermo King service support group did not have the training nor access to service parts”.

- 2. Are you working with the bus OEM and or key component suppliers to identify the most important replacement parts to have? Will you have them on site or have a set number of days to have them shipped?**

“We have started the process of identifying key components and getting them on consignment. We had a recent issue with bus windows, and it took 16 weeks to replace. We also had an issue with fuel tank valves where replacement parts were not in stock. On a fuel cell stack replacement with Ballard, sending the old one back for repair you need to go through customs (which takes approximately 1 week), then wait 3 to 4 weeks for the rebuild, and then wait another week for the install”.

- 3. What kind of incident / warranty reporting and repair system do you plan to use?**

“We use the standard warranty with EIDorado, Ballard, and BAE.”²²

- 4. On the FCEB, does SARTA have replacement parts on hand or is a supplier on contract to ship parts directly to SARTA? And in what time frame?**

“No replacement parts are on hand. There is very little if any stock in the supply chain with the low volume of buses. Once production volume is up, we anticipate more stock for replacement parts. The average time frame for replacement parts is two weeks.”

- 5. Have you had any discussions with other U.S. transit agencies operating FCEBs on their supply chain issues or replacement parts?**

SARTA’s COO has talked with SunLine, Thousand Palms CA, since they also have EIDorado buses and they share supply chain experiences.

- 6. What FCEB service parts on order are still outstanding?**

“There are no outstanding orders at this time. It did take 8 – 10 weeks to receive a leaking fuel tank valve.”

- 7. What kind of incident / warranty reporting system is in place at SARTA?**

“We utilize the existing EIDorado and Ballard systems. They should be maintaining records for the life of buses.”

Champaign-Urbana Mass Transit District

- 1. Have you had any supply chain issues to date that you can share?**

²² SARTA thought that the EIDorado warranty was similar to the one offered by other FCEB manufacturers in the U.S. market.

“Yes, we have had issues with lead time on proprietary parts from New Flyer”.

- 2. Are you working with the bus OEM and or key component suppliers to identify the most important replacement parts to have? Will you have them on site or have a set number of days to have them shipped?**

“We have no key component list and no terms or guarantees for shipping. We have not pursued the stock guarantee programs with New Flyer because we prefer to have the ability to get competitive pricing and these programs lock in the pricing.”

- 3. What kind of incident / warranty reporting system is in place at Champaign-Urbana Mass Transit District?**

“We use New Flyer’s online “iWarranty” program. The OEM will do maintenance for specialty equipment (fuel cell, etc.). We will do standard repairs in-house and receive reimbursement from New Flyer.”

3.3 Impact on adoption of fuel cell transit vehicles.

NREL has been evaluating all FTA-funded advanced technology transit buses using a standard data collection and analysis protocol originally developed for DOE heavy-duty vehicle applications.²³ NREL is using the CNG and diesel buses as the baseline and comparing the fuel cell electric buses to them. The FCEBs evaluated to date have not achieved the performance level of the other buses, although they are making steady improvements with supply chain support and continued education of technicians and drivers. With an expeditious focus on addressing the issues of performance and cost, FCEBs will likely be a viable force in the transit market as they are needed for meeting zero emissions targets.

4 Identifying Existing and Potential Midwestern Suppliers

The following list was developed using OFCC and Greentree Consulting supply chain databases, plus other sources such as the November 2019 Transit Bus Component Technology Forum attendees.

73 companies are US based with 39 of those located in Ohio. Additionally, seven companies are listed outside of the US that are considered key players in the FCEB supply chain. Ohio has the highest concentration of FCEB suppliers in the country. Ohio suppliers also are located in close proximity to the automotive industry. Ohio could benefit from the addition of a FCEB assembly plant to make best use of the Ohio and Midwest concentration of FCEB suppliers.

²³ See <https://www.nrel.gov/hydrogen/fuel-cell-bus-evaluation.html>

Fuel Cell Electric Bus Supply Chain Research and Support Initiative

Component	Company Name	City	State	Country	Web
Bus Chassis	Complete Coach Works	Riverside	CA	US	http://www.completecoach.com
Bus Chassis	Ebus	Downey	CA	US	http://www.ebus.com
Bus Chassis	ElDorado National	Riverside	CA	US	https://www.ElDorado-ca.com
Bus Chassis	Gillig LLC	Livermore	CA	US	https://www.gillig.com
Bus Chassis	GreenPower Motor Company	Rancho Cucamonga	CA	US	http://www.greenpowerbuses.com
Hydrogen Fuel Cells	Hydrogenics USA	Carlsbad	CA	US	https://www.hydrogenics.com
Hydrogen Tanks	Luxfer-Dynetek	Riverside	CA	US	https://www.luxfercylinders.com/
Bus Chassis	Motiv Power Systems	Foster City	CA	US	https://www.motivps.com
Battery	Octillion Power Systems	Hayward	CA	US	https://www.octillion.us
Hydrogen Tanks	Quantum Fuel Systems	Lake Forrest	CA	US	http://www.qtw.com/
Battery Systems	Romeo Power	Vernon	CA	US	https://romeopower.com
Electric Drive System	US Hybrid	Torrance	CA	US	https://www.ushybrid.com
Electric Drive System	Siemens Industry Inc	Alpharetta	GA	US	http://www.siemens.com
Air Purifier Systems	Blueair Cabin Air AB	Chicago	IL	US	https://www.blueair.com/us/
Electric Drive System	Allison Transmission	Indianapolis	IN	US	https://www.allisontransmission.com
Bus Chassis	ARBOC Specialty Vehicles	Middlebury	IN	US	https://www.arbocsv.com
Hydrogen Fuel Cells	Cummins	Columbus	IN	US	https://www.cummins.com/
Aluminum bodies	Morgan Olson	Wolcottville	IN	US	http://www.morganolson.com
Electric Drive System	XL Fleet	Boston	MA	US	https://www.xlfleet.com
Battery Systems	A123 Systems	Novi	MI	US	www.a123systems.com
Battery Systems	AKASOL Inc.	Detroit	MI	US	https://www.akasol.com/en

Fuel Cell Electric Bus Supply Chain Research and Support Initiative

Component	Company Name	City	State	Country	Web
Thermal Management Systems	Engineered Machined Products	Escanaba	MI	US	https://www.emp-corp.com
Powertrain Technology	e-Traction	Southfield	MI	US	https://www.e-traction.com
Battery	LG Chem	Holland	MI	US	https://www.lgchem.com
Drivetrain, mobility, braking	Meritor	Troy	MI	US	http://www.meritor.com
Bus Chassis	Navistar	Rochester Hills	MI	US	www.nav-international.com
Battery Systems	Samsung SDI	Auburn Hills	MI	US	https://www.samsungsdi.com
Transport Refrigeration Units	Thermo King Corporation	Minneapolis	MN	US	www.thermoking.com
Hydrogen Tanks	Hexagon Lincoln	Lincoln	NE	US	https://www.hexagonlincoln.com
Electric vehicle conversion kits	EVAmerica	Wolfeboro	NH	US	www.evamerica.com
Metal forming and coating	Malico	Raymond	NH	US	http://www.malico.com
Battery	Panasonic	Sparks	NV	US	https://industrial.panasonic.com/
Electric Drive System	BAE Systems	Endicott	NY	US	https://www.baesystems.com
Bus Chassis	BYD (Build Your Dreams)	Troy	NY	US	http://www.byd.com.cn
Machining and Prototyping	AIMMRO	Miamiville	OH	US	http://aimmro.com
Pressure Vessels	American Tank and Fabrication	Orville	OH	US	https://www.atfco.com
Custom Metal Fabrication	Anchor Fabricators	Clayton	OH	US	https://www.anchorfab.com
Refractory Ceramics	CerCo LLC	Shreve	OH	US	https://cercocorp.com
Fuel Cell Standards	CSA	Independence	OH	US	https://www.csagroup.org
Bipolar Plates	Dana Corp	Maumee	OH	US	http://www.dana.com
Electrodes and Catalysts	De Nora Tech	Concord	OH	US	https://www.denora.com
Metal Stamping	Die-Matic Corp.	Brooklyn Heights	OH	US	https://www.die-matic.com

Fuel Cell Electric Bus Supply Chain Research and Support Initiative

Component	Company Name	City	State	Country	Web
Materials Joining	Edison Welding Institute	Columbus	OH	US	https://ewi.org
Scalable Hydrogen	Energy Technologies, Inc.	Mansfield	OH	US	https://ecoenergyinternational.com
Surface Finishing and Coatings	Faraday Technologies	Clayton	OH	US	http://www.faradaytechnology.com
Engineering	Gem City Engineering	Dayton	OH	US	http://gemcity.com
Pumps	Gorman Rupp	Mansfield	OH	US	https://www.grpumps.com
Bipolar Plates	GrafTech	Brooklyn Heights	OH	US	https://www.graftech.com/
Carbon Fiber Tanks	Hexagon Purus	Heath	OH	US	https://www.hexagonxperion.com
Brazing, Thermal Proc., Welding	HI-Tech Metals	Cleveland	OH	US	http://htgmetals.com
Catalysts/Heat Exchangers	Johnson Matthey Process Tech.	Ravenna	OH	US	http://www.catacel.com
Precision Machining	Kalt Manufacturing	North Ridgeville	OH	US	https://www.kaltmfg.com
Smart Power Industrial Devices	Micropyretics Heaters Intl.	Cincinnati	OH	US	https://mhi-inc.com
Electrolyzers/Fueling Infrastructure	Millennium Reign Energy	Dayton	OH	US	https://www.mreh2.com
Testing/Monitoring Equipment	Mound Technical Solutions	Miamisburg	OH	US	https://www.moundtech.com
Ceramic Materials/Sensors	Nexceris	Lewis Center	OH	US	https://nexceris.com
Advanced Manufacturing	Ohio Energy & Adv. Mfg Center	Lima	OH	US	http://oeamc.org
Fueling Nozzles	OPW	Hamilton	OH	US	https://www.opwglobal.com
Catalyst and Carbon Materials	pH Matter, LLC	Columbus	OH	US	https://www.phmatter.com
Controls	Rockwell Automation	Twinsburg	OH	US	https://www.rockwellautomation.com

Fuel Cell Electric Bus Supply Chain Research and Support Initiative

Component	Company Name	City	State	Country	Web
Fasteners/Valves/Hoses	Swagelok	Solon	OH	US	https://www.swagelok.com
Graphite and fuel cell plates	TDM	Ashtabula	OH	US	https://www.tdmfuelcellstore.com
Specialty Metals	United Performance Metals	Hamilton	OH	US	https://www.upmet.com
Battery monitoring and analysis	Vanner	Hilliard	OH	US	https://www.vanner.com/
Battery Systems (resistors)	EBG Resistors LLC	Middletown	PA	US	https://www.ebg-resistors.com
HVAC systems	Mobile Climate Control	York	PA	US	https://www.mcc-hvac.com
Bus Chassis	Proterra	Greenville	SC	US	http://www.proterra.com
Battery Systems	Valence Technology	Austin	TX	US	https://lithiumwerks.com/power-cells/
Bus Chassis	New Flyer of America Inc.	Mercer Island	WA	US	https://www.newflyer.com
Bipolar Plates	Schunk Carbon Technology	Menomonee Falls	WI	US	https://www.schunk-carbontechnology.com
Membrane electrode assembly	Dupont	various		US	https://www.dupont.com
MEA	Gore	various		US	https://www.gore.com/fuel-cells
Electric Drive System	Zf North America Inc.	various		US	https://www.zf.com/
Bus Chassis	Van Hool	Koningshooikt		Belgium	https://www.vanhool.be
Hydrogen Fuel Cells	Ballard Power System	Burnaby	BC	Canada	http://www.ballard.com
Bipolar Plates	Borit	Herzogenrath		Germany	http://www.borit.de/
Hydrogen Fuel Cells	Daimler	Stuttgart		Germany	https://www.daimler.com
Electrical auxiliary heaters	Eberspächer catem	Herxheim		Germany	https://www.eberspaecher.com
Bipolar Plate (Catalyst)	Bac2	Southampton		UK	http://www.bac2.co.uk/
Battery	Johnson Matthey Battery Systems	London		UK	jmbatterysystems.com

5 Proposed Strategies for Improving Bus Performance through Supply Chain Support

The following is a list of 12 strategies for identifying, tracking, and resolving supply chain issues. They are listed in recommended priority but can be adjusted. The strategies are the result of collecting group feedback from the November 2019 Transit Bus Component Technology Forum and current best practices from the automotive industry.

1. **Develop an industry-wide incident reporting and corrective action system between operators, bus OEMs, and component suppliers.** A 24-hour initial response time window and corrective action within 72 hours is recommended. Best practices from the automotive industry should be applied.
2. **Develop a standardized testing process to improve the definition and documentation of component performance and durability.** Today the buses themselves are functioning as the test bed for many of the systems and components.
3. **Develop effective data collection and disbursement systems which could improve overall FCEB performance.** Fuel cell bus industry could be best served by collaborating with the automotive industry on best practices.
4. **Provide additional resources within existing suppliers to help with improvement in reliability and cost reduction.** One option would be for suppliers to leverage universities and technical colleges for support.
5. **Improve economies of scale to decrease cost and improve performance.** Hydrogen at a dispensed cost of less than \$4/kg is needed. At higher FCEB production and usage volumes, more suppliers would become engaged and decrease cost.
6. **Develop pre-heating/pre-cooling for FCEB passenger area using alternate electric power source for heating and cooling, versus hydrogen on board.** Apply the lessons learned in the airport industry with quick connects for electric and HVAC as at the airport gate. SARTA, for example, will have electrically heated driver seats and a stand-alone electric heating system for the cabin in its next generation fuel cell buses. These units could be powered from another electrical source or hydrogen.
7. **Develop cold and hot weather optional packages.** The initial FCEBs have been designed for the CA market and its weather. The Midwest and Northeast have colder and wetter climates.
8. **Optimize the watts through the correct balance of infrastructure, battery technologies, heating & cooling, braking, power steering, and education for operators**

and maintenance technicians. Consider conducting an engineering study to determine optimum balance for power distribution.

9. **Power density improvement challenge.** As stated by one participant at the Nov. 6, 2019 forum, *“We have seen gradual improvement over the past years. It would be nice to see a leap in technology to improve power density.”*
10. **Maximize mileage by optimizing pressure vessel rating (going from 5,000 to 10,000 psi) to obtain more kg of hydrogen on board, and/or increase quantity of vessels per bus.**
11. **Improve electric motor technical reliability.**
12. **Develop infrastructure to get power to the buses.** Continued improvement is needed at hydrogen refueling stations and with alternate electric supply and connections on buses.