SARTA Fuel Cell Bus Performance and Data Collection

Summary Report

Prepared for: Stark Area Regional Transit Authority
In Support of the Renewable Hydrogen Fuel Cell Collaborative
Prepared by: CALSTART, Inc.

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E. EXECUTIVE SUMMARY

CALSTART, under funding provided by Stark Area Regional Transit Authority (SARTA), performed this study to provide the transit community and its stakeholders real world knowledge on the state of fuel cell electric bus (FCEB) performance and identify improvements for next generation FCEBs. This study analyzed usage and performance data from six model year 2016 (MY16) second generation FCEBs owned and operated by SARTA, located in Canton, Ohio.

It is important to note that this project was initially meant to analyze and compare data from MY16 and MY18 buses. Due to reduced ridership resulting from the COVID-19 pandemic, however, the MY18 buses were delayed in their deployment and no data was collected. Additionally, one of SARTA's MY16 FCEBs was not included in the analysis because of its limited use throughout the data collection period due to technical issues.

SARTA received funding for these buses from the Federal Transportation Authority (FTA) under their Low or No Emission grant program. The six buses in this study were manufactured by El Dorado and powered by BAE's hybrid electric propulsion system and Ballard's FCvelocity-HD6 150kW fuel cells. Data was collected between January 2019 and January 2020 to analyze the environmental, financial, and operational benefits of fuel cell electric SARTA buses relative to conventional diesel buses.

The data collected and analyzed was used to investigate bus mileage, operational costs, and the relationship between the two, with specific regard to the ambient temperature's effect on cost per mile. Each month, the fuel cell buses drove an average of 2,446 miles and averaged $1.15/mile. The buses operated an average of 156 days per year, with a minimum of 115 days and a maximum of 201 days. It also explored fuel usage of the buses and the emissions reductions from using FCEBs rather than conventional diesel buses. The buses consumed $2,750 worth of fuel monthly and averaged 0.19 kg H_2/mi. In total, all six buses avoided 80,000 kg of CO_2 from a total of 337,976 kg that six conventional diesel buses would have emitted. SARTA's plans to produce on-site hydrogen will decrease the carbon intensity of the hydrogen used, further increasing the carbon dioxide offset.

A comparison of days in operation and causes for downtime for both SARTA diesel and fuel cell buses was also conducted. Overall, 1,791 days and 1,858 days of diesel and fuel cell buses were analyzed, respectively. The six diesel buses analyzed were in operation 1,426 days and the six fuel cell buses were in operation 901 days. On days where the buses were not operating, the buses were either undergoing general maintenance and performance maintenance inspections, unplanned maintenance, not used, or experienced a "support a bus" activity. A support a bus activity occurred a total of 69 days among the fuel cell buses, or 8% of days in operation, in which either unusually high or low temperatures led the air conditioning or heater to draw enough energy that the fuel cell buses lacked enough hydrogen to complete their route.

The main technical issues that led to days not in service differed for fuel cell and diesel buses. For fuel cell buses, complications with the fuel cell system, fuel leaks, performance maintenance inspections, and air conditioning and Thermoking heater unit issues were the primary culprit. For diesel buses, engine issues and performance and maintenance inspections were responsible for the vast majority of days not in service. It should be noted that while fuel cell buses experienced 125 days out of service due to fuel leaks, this all occurred in one vehicle and was not a consistent problem among the fleet. One of the fundamental focuses of this report was the effect of outside ambient temperature on parasitic loads and their effects on bus efficiency. Bus efficiency and cost per mile throughout the year were analyzed with respect to local outside ambient temperature to provide insights on energy draw from the air conditioning and heater.

The analysis showed that the parasitic load from the heater resulted in the winter months reaching the highest cost per mile value of $1.30/mile. An estimated 252 kg of hydrogen, for approximately $1,511, were consumed to power the heater in each bus between November and April. Summer months also experienced an increased average cost per mile value of about $1.15/mile. Between June and September, each bus consumed approximately 88 kg of hydrogen for an estimated $528. Spring and fall experienced more moderate temperatures, averaging a cost per mile value of about $1.00/mile.

CALSTART was also able to engage with two key SARTA employees that interact directly with the FCEBs. A maintenance manager who is responsible for preventive maintenance, general bus repairs, and repairs of the propulsion system shared in detail the differences in his experience with maintaining FCEBs compared to conventional diesel buses. In his experience, the FCEBs needed to be operated at least once every five to seven days or they would experience issues with pumps, fans, or other parts. He also noted that fuel cell bus parts took longer to arrive when ordered, likely due to the small but growing market size, which left them out of operation longer. Still, he saw improvements since the last iteration of FCEBs and was optimistic that the zero-emission buses would soon be cheaper and out-performing diesel buses.

A bus operator of both SARTA FCEBs and diesel buses detailed his views on the pros and cons of each bus type and proposed potential improvements to future iterations of the FCEBs. Like the maintenance manager, he was proud that SARTA was operating zero-emission technology. He saw the FCEB pros as being practically silent in motion, "softer" to drive, and more convenient for persons with disabilities due to its lower ride height and having a better device to help them board the bus. His main criticism of the zero-emission buses was that they were sometimes unable to complete the 16-hour shifts that SARTA buses normally operate, due to a refueling requirement. As noted above, this occurred in 8% of rides, and unusually occurred when high or low ambient temperatures drew large amounts of energy to maintain a comfortable cabin temperature. He recommended that OEMs increase the range in future iterations, and also recommended increasing the speed of the back door opening and closing

SARTA's investment in fuel cell technology extends far beyond these six buses, with Model Year 2018 (MY18) buses nearly ready to be deployed and the transit agency exploring its options for on-site hydrogen production. This leadership provides multiple benefits: the local community is now breathing cleaner air, the riders are experiencing a smoother bus ride, and the significant emissions reductions as a result of adopting these zero-emission buses assist in the fight against climate change. Furthermore, by demonstrating the viability of this advanced technology, SARTA has pioneered a path for other transit agencies. The performance data from this report will help the fuel cell bus industry improve bus reliability and decrease costs and will help transit agencies develop best operational practices.

1. PROJECT OVERVIEW

1.1 INTRODUCTION

The Stark Area Regional Transit Authority (SARTA) in Canton, Ohio received funding for four projects from the Federal Transit Administration's "Low or No Emission Grant Program" in 2019. This report details the data collection and analysis for Project 3: Performance Analysis for New SARTA Hydrogen Buses. For this project, CALSTART examined the performance of six model year 16 (MY16) second generation fuel cell electric buses.

Data was collected over the course of a 12-month period to analyze the environmental, financial, and operational benefits of fuel cell electric SARTA buses relative to conventional diesel buses. This report aims to provide SARTA and other transit agencies across the United States data-driven insight into the current state of fuel cell bus technology. It also suggests key improvements for the next generation of buses in an effort to improve the technology and increase the viability of more transit agencies transitioning to zero-emission fuel cell buses.

1.2 BACKGROUND

Fuel cell electric buses have many benefits for the transit agency, the public, and the environment. The most salient benefits include zero tailpipe emissions, leading to better air quality locally and lessening the contribution to climate change while supporting the region's growing hydrogen economy. Based on a 2017 hydrogen roadmap report, an estimated 65,000 new jobs could be created in a timeframe of 15 years. Many other benefits exist as well, including less noise pollution due to the FCEB's near silent operation and simplified maintenance due to fewer moving parts.

While fuel cell technology has existed for decades, notably being utilized by NASA as part of the space program, transit agencies have been among the first fuel cell electric vehicle adopters.[1] Transit buses are an excellent platform for fuel cell technology because of the several hundred mile range that they can provide, rapid fueling, and relatively minimal amount of space required for fueling infrastructure. Capitalizing on this opportunity, transit bus manufacturers are entering the market all across the globe with hydrogen powered vehicles. In order to facilitate uptake, government agencies are supporting the research, development, and demonstration of this zero-emission vehicle technology. The Federal Transit Administration (FTA) alone has funded this and numerous other transit bus development projects.

FCEBs are a critical part of the electric bus market which continues to make positive strides with increased production volumes that, in turn, further drive down costs as the technology continues to improve with each new model year. Globally, China currently dominates the electric bus market with 99% of the world's 385,000 total electric buses.[2] In the United States, there are currently about 1,650 battery and fuel cell electric transit buses deployed or soon to be deployed.

[1] FuelCellToday, 2020. http://www.fuelcelltoday.com/history. Accessed August 2020.
[2] Poon, L. *How China Took Charge of the Electric Bus Revolution*, May 2018. https://www.citylab.com/transportation/2018/05/how-china-charged-into-the-electric-bus-revolution/559571/ Accessed October 2018.

More than 140 transit agencies around the United States have committed to moving away from fossil fuel powered buses.[3] Five of these transit agencies, including SARTA, are working with the National Renewable Energy Lab (NREL) to demonstrate FCEB technology (SARTA is the only one located outside of California).[4] **Error! Reference source not found.** below highlights the number of zero-emission buses, including both battery electric and fuel cell electric buses, in each state. The figure was taken from CALSTART's 2019 "Zeroing in on ZEBs" report which tracks the 2,000 zero-emission buses adopted around the country and may act as a resource for other transit agencies to inform their future zero-emission investments.

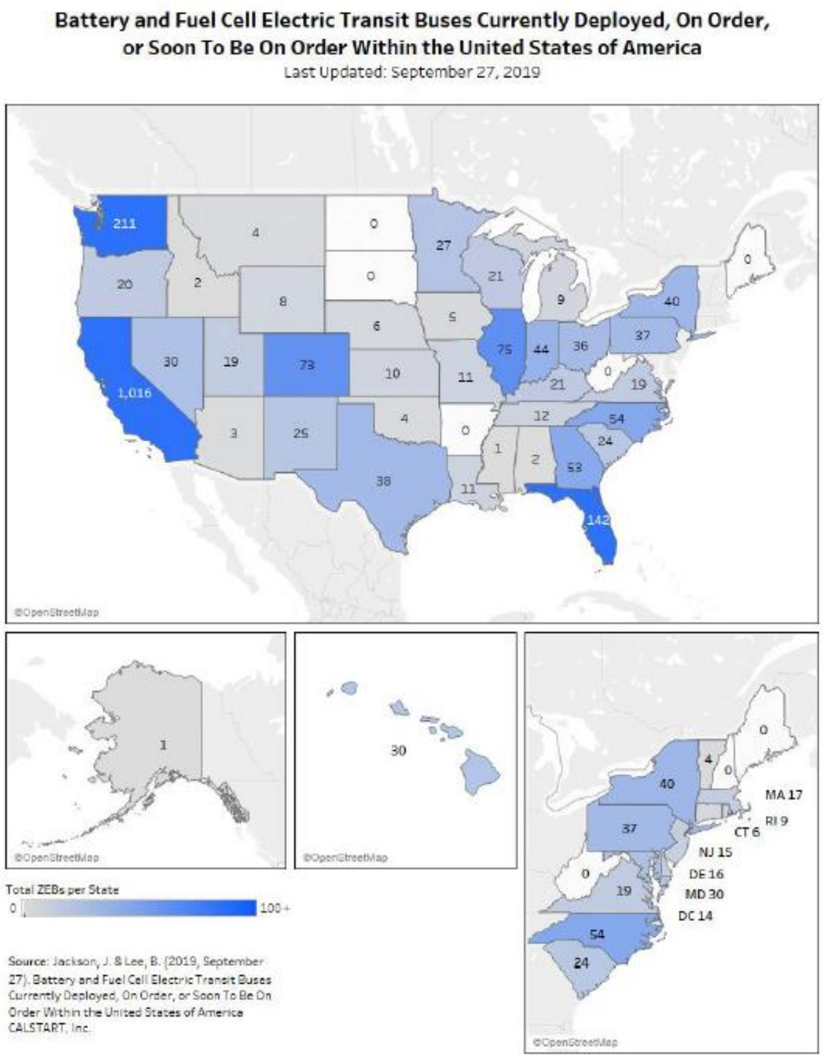

Figure 1: Zero-emission buses across the United States by state in 2019.[5]

[3] Popel, J. *A Survey of Zero Emission Buses Across America*, August 2018. https://calstart.org/wp-content/uploads/2018/11/Breathing-Easy-August-2018.pdf Accessed July 2020

[4] Eudy, L. *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018*, December 2018. https://www.nrel.gov/docs/fy19osti/72208.pdf Accessed May 2020.

[5] Silver, F. *Zeroing in on ZEBs*, October 2019. https://calstart.org/zeroing-in-on-zebs-2019/ Accessed July 2020.

As of August 2020, SARTA had operating or in delivery a total of 13 FCEBs. The fleet of buses is fueled daily, typically with 30 to 35 kg of hydrogen per fueling using H35 (350 bar or 5,000 psi) nozzles on two available dispensers. The fueling takes place within ten minutes per fill with liquid hydrogen (LH_2) delivered by Air Liquide and stored on site in a 2,400 kg hydrogen tank. The refuel island with two fueling dispensers is being expanded to contain four dispensers (4 refuel positions for FCEBs) and a separate dispenser that could host a H70 (700 bar or 10,000 psi) nozzle.

SARTA, committed to adopting clean fuel buses, is looking to expand its current hydrogen fueling station to increase capacity and is exploring the possibilities of transitioning to renewable hydrogen. This hydrogen could be created by an electrolyzer powered by a solar panel or purchased wind electricity. Another possibility is a stationary steam methane reformer (SMR) powered by renewable natural gas sourced from a biodigester located at a nearby Water Reclamation Facility or from a local landfill. These opportunities are explored in more detail in a 2020 report prepared by CALSTART titled "Expansion of Stark Area Regional Transportation Authority Hydrogen Refueling Capabilities."[6]

The following table provides an August 2020 snapshot of SARTA's fleet by fuel type, which includes CNG, diesel, hybrid electric diesel, and hydrogen.

Table 1: Active SARTA fleet vehicles by fuel type as of August 2020

	CNG	Diesel	Hybrid Electric Diesel	Hydrogen	Total
Fixed Route	18	15	3	13	49
Paratransit	28	25	-	*	53
Total	46	40	3	13	102

* *SARTA will soon receive the nation's first commercial hydrogen paratransit buses*

1.3 PROJECT GOALS

The deployment of SARTA FCEBs presents an opportunity for a field test of advanced fuel cell electric bus technology in a real-world transit application. SARTA's bus deployment, located in Canton, Ohio, provides a great opportunity to understand the impact of climate on performance and efficiencies as SARTA buses experience all four seasons with especially long and cold, sub-freezing winters, adding a unique variable for investigation. As such, this study aims to better understand vehicle performance and the effects of parasitic loads such as heating and air conditioning on fuel cell electric buses across a variety of climatic conditions and seasons.

SARTA's mission statement reads:

"SARTA is committed to enhancing the quality of life for our community by providing efficient, affordable and sustainable mobility options for Stark County."

This project was initially intended to analyze data from both six MY16 buses and five MY18 buses. Reduced ridership due to the COVID-19 pandemic resulted in the delayed deployment of the MY18 buses. As a result, no data was collected on MY18 buses and only MY16 buses are included in this analysis.

[6] Cole, J. "Expansion of Stark Area Regional Transportation Authority Hydrogen Refueling Capabilities," April 2020. http://www.midwesthydrogen.org/site/assets/files/1413/sarta_expansion_hydrogen_refueling_capabilities_final.pdf. Accessed September 2020.

CALSTART collected data on the six MY16 buses over the course of a 12 month period to analyze the environmental, financial, and operational benefits of fuel cell electric SARTA buses relative to conventional diesel buses. CALSTART also recommends herewith improvements to be shared with the fuel cell bus industry for the next generation of fuel cell electric buses.

This report summarizes the methodology and conclusions of CALSTART's analysis. It includes a comparison of mileage and operational costs between fuel cell and diesel buses and summarizes hydrogen fuel usage and emissions reductions. It also compares the causes and amount of downtime of SARTA fuel cell and diesel buses. Finally, it investigates a variety of bus performance metrics and their effect on vehicle efficiency with special consideration for climatic conditions throughout the year. This report aims to provide SARTA and other transit agencies data-driven insight into how fuel cell technology can best be integrated into their fleet.

1.4 PROJECT TEAM

Stark Area Regional Transit Authority (SARTA) provides public sector transit for over 2.8 million riders annually in Canton, Alliance, and Massillon, Ohio. SARTA has been a leader in clean transit for over a decade, previously utilizing diesel electric hybrid buses, CNG buses, and most recently hydrogen buses. SARTA's efforts have reduced emissions for hundreds of thousands of nearby residents, and its innovative solutions have made it a national leader in alternative vehicle deployment.

BAE Systems is a major international company working in aerospace, information security, and advanced electric solutions, among other industries. With over 170 patents in electric and hybrid technology and 8,000 systems operating across the globe, BAE Systems is an international leader advancing transit technology and systems integration. It has deployed over 20 FCEBs across the nation. Acting as a systems integrator and manufacturer for SARTA's fuel cell buses, BAE Systems provided data to help analyze the performance of the FCEBs.

CALSTART is North America's leading advanced transportation technologies consortium; a member-supported non-profit organization of more than 250 organizations, fleets, and agencies worldwide dedicated to supporting the growth of the high-tech, clean transportation industry. CALSTART has been working as an effective catalyst for the global advanced transportation technology industry for almost three decades, supporting public-private partnership and implementation strategies in the advanced transportation industry. CALSTART was contracted as a neutral third party to manage and execute this project with the primary responsibilities of collecting and analyzing data and writing this report.

2. DATA COLLECTION

2.1 METHODOLOGY

To evaluate the performance of the FCEBs and achieve the project goals, CALSTART managed multiple data streams. There were three main sources of data collected by collaborating organizations (outlined in Table 2 below) that provided a comprehensive view into how the buses were regularly used.

Table 2: List of different data streams analyzed for this project and their sources.

DATA STREAM	DATA SOURCE	ORGANIZATION
Bus Operational Data	SARTA Staff	SARTA and NREL
Performance Data	On-board Data Logger	BAE
Operator and Maintenance Data	SARTA Staff	CALSTART

In total, six of seven MY16 El Dorado FCEBs, using BAE's hybrid electric propulsion system and Ballard's fuel cells, were included in the analysis. SARTA provided the usage and operational data on the buses that was either provided to them by NREL or collected as part of its daily operations. SARTA staff also provided feedback on the overall operation and maintenance of the vehicles. BAE provided performance data on the buses.

Although data from the seventh bus was reported, it was left out of the analysis because of its limited use throughout the data collection period. According to the maintenance team, this bus (1610) was waiting for its fare collection system to be prepped for service when a leak in the fuel tank valve developed. These complications left bus 1610 largely out of operation during the survey period, and, as a result, only the buses listed in Table 3 were included in the analysis.

Table 3: Hydrogen fuel cell buses included in data analysis.

	BUS ID NUMBERS
MY16 Buses	1611, 1712, 1713, 1714, 1715, 1716

As noted in the Project Goals section above, this project was initially intended to compare the performance of the MY16 and MY18 buses. Due to several unplanned events, this project was rescoped to a 12 month analysis of solely the MY16 buses. In mid-March 2020, SARTA discovered mechanical issues relating to the front sway bars of the MY16 buses. All MY16 buses were taken out of operation in mid-March for further inspection and repair.

At the same time, the nation began its active response to the COVID-19 pandemic. Electrical work was required to upgrade the MY18 bus chargers. This work could not be performed due to the COVID-19 pandemic, thus delaying their deployment. MY18 bus data was therefore not collected. Five MY18 FCEBs have been delivered to SARTA and will begin operating in the near future. Even with all the unplanned events, 12 months' worth of MY16 bus data from January 2019 to January 2020 was still collected and analyzed. The following table displays specifications for SARTA's MY16 buses.

Table 4: Vehicle specifications for MY16 fuel cell buses deployed at SARTA

Model Year	MY16
Length (ft)	40
Number of buses in evaluation	6
Gross Vehicle Weight Rating (lb)	43,420
Fuel Cell	Ballard Fcvelocity-HD6, 150 kW
Bus Manufacturer	El Dorado National - California
Propulsion System	BAE Systems Series hybrid propulsion system, HDS 200, 200 kW peak

Model Year	MY16
Energy Storage	A123 NanoPhosphate Li-ion, 200 kW, 11.2 kWh
Fuel Capacity	Gaseous hydrogen, 8 Luxfer-Dynetek cylinders, 50 kg at 350 bar, 2100 Liters, 5000 psi

The fuel cell system is composed of a variety of components. These include the fuel cell itself, an air compressor, the air compressor controller, the air intake, and the electronic fuel cell control. The propulsion system includes the system control unit, Lithium-ion battery modules, a traction motor, the propulsion control system, auxiliary power, system cooling, and the fuel storage system.

2.2 BUS OPERATIONAL DATA

Operational data on fuel cell electric bus usage was collected by both SARTA and NREL and submitted monthly to CALSTART. Data from January 2019 through January 2020 was analyzed for this report. These monthly reports included information on the parameters found below in Table 5.

Table 5: Parameters from NREL and SARTA monthly reports

PSI DATA	MILEAGE DATA	TEMPERATURE DATA
Date	Date	Date
Begin PSI	Mileage	PSI
End PSI	Miles	Fueling Temperature
H_2 Consumed (kg)	Hour Meter	0430am PSI
GGE (gal)	Hours	0430am Temperature
Begin Fueling H_2 (kg)	GGE	PSI Difference
End Fueling H_2 (kg)	Cost ($)	Vehicle ID
Total H_2 Fueled (kg)	Vehicle ID	
Fueling Cost ($)		
Vehicle ID		

Data collection is a part of SARTA's standard daily operations. Monday through Friday, SARTA buses are fueled between 8 pm and 11 pm. At the time of fueling, the pressure in PSI is manually recorded both before and after fueling with the use of a fueling manifold on the bus. The outside temperature at the time of fueling is also recorded with use of an employee's cellphone. These PSI values are used to calculate the amount of fuel dispensed in kg for each bus. Every morning at 4:30 am Monday through Friday, the outdoor temperature and the PSI of each bus are recorded before the vehicles are put into operation at 5 am. In the morning, the outdoor temperature is recorded manually from the reading on an outdoor thermometer located near the garage where the buses are parked.

Mileage data and the hours in service are manually recorded from the odometer and hour meter, respectively. The odometer is located on the dashboard and the hour meter is located by the fuel cell at the roadside rear of the bus and records hours in use. The fueling cost is calculated by multiplying the mass (kg) consumed by the average price of delivered hydrogen for SARTA, which was an estimated $6/kg. These parameters were all recorded and reported by SARTA to CALSTART for use in this report.

2.3 PERFORMANCE DATA

BAE, the hybrid electric propulsion system provider, was contracted as part of this project to provide performance data for the FCEBs. This data was collected directly from its on-board system and sent to CALSTART for use in this report. The SARTA and NREL data provided insight into cost per mile and fuel consumption rates, while the BAE data provided insight into the internal operation of the buses. The parameters provided by BAE on the MY16 FCEBs that were evaluated can be found in the table below.

Table 6: Parameters included in BAE MY16 fuel cell bus performance data

PARAMETER	UNITS
Timestamp	-
Driving time	-
Average vehicle speed (mph)	mph
Average battery pack cell temperature	˚F
Total distance	miles
Max power	kW
Fuel cell output	kWh created from H_2 output
Energy regenerated (kWh)	kWh
UNIDI 28VDC Energy	kWh
API 230VAC Energy	kWh
ACTM propulsion energy	kWh

The following table provides definitions for the main sources of energy flows within the fuel cell bus system.

Table 7: Definitions of three main sources of energy draw on the fuel cell buses included in the data analysis.

ENERGY OUT SOURCE (kWh)	DEFINITION
UNIDI 28VDC Energy	Powers the bus Dynex system, headlights, taillights, running lights and other lights, front driver fan, the GPS system, farebox system installed by customers, Amerex systems, and power to the PCS, SCU, hydrogen storage, and battery management system.
API 230VAC Energy	Powers the vehicle air compressor, air conditioning, and power steering.
ACTM Propulsion Energy	Energy used to propel the vehicle.

It should be noted that energy data related to the fuel cell bus heating system was not made available. Instead, the following equations were used to analyze the captured data and estimate the energy draw from the heater in the winter months.

Eq. 1 $$Energy\ In\ [kWh] = Fuel\ Cell\ Energy + Regenerated\ Energy$$

Eq. 2 $$Enegy\ Out\ [kWh] = UNIDI\ 28VDC + API\ 230VAC + ACTM\ Propulsion\ Power + (heat + losses)$$

3. ANALYSIS

This section presents the results of the analysis and works to put the data into context. It begins by exploring fuel cell bus usage and, more specifically, mileage and operational costs (3.1.1), fuel usage and emissions reductions (3.1.2), and a time usage analysis (3.1.3). Then, it explores bus performance data with a focus on vehicle efficiency (3.2.1) and a cost per mile analysis (3.2.2). Finally, it concludes with a summary of the interviews of a SARTA maintenance manager (3.3.1) and bus operator (3.3.2).

3.1 BUS USAGE ANALYSIS

3.1.1 MILEAGE AND OPERATIONAL COSTS

Over the course of the 12-month period, the six FCEBs accumulated 153,169 miles across more than 901 total days in operation. The tables below provide a detailed breakdown of cost and miles driven on a monthly and cumulative average basis. On average, each bus cost $733 to fuel weekly and drove an average of 646.2 miles. The buses operated an average of 3.9 days per week and drove 163 miles daily.

On average, each bus cost $2,749 to fuel and drove 2,446 miles monthly. The buses operated an average of 13.4 days per month as found in Table 8 below.

Table 8: Monthly summary of fuel cell bus fuel costs and miles driven.

Vehicle ID	Avg Fueling Cost ($)	Max Fueling Cost ($)	Avg Miles (mi)	Max Miles (mi)	Avg. Days in Use	Avg. Fuel Cost per Mile ($/mi)
1712	$3,312.31	$4,999.26	2,827.1	4,698.0	16.4	1.03
1713	$2,595.70	$3,903.60	2,230.8	3,678.0	13.4	1.13
1714	$2,553.08	$4,074.42	3,022.7	3,935.0	17.4	1.13
1715	$2,709.43	$3,902.04	2,322.4	3,524.0	13.4	1.20
1716	$3,357.82	$4,903.56	2,625.8	3,944.0	15.6	1.36
1611	$2,131.78	$4,217.34	1,957.0	3,580.0	13.4	1.09
Average	$2,749.29	$4,333.37	2445.8	4,698.0	14.7	1.15

As shown in Table 9 below, between January 2019 and January 2020, the six FCEBs cost an average of $29,330 for fuel and drove an average of 25,528 miles each. This equates to an annual cost of $175,980 to fuel all six FCEBs for a total of 153,160 miles, or \$1.15/mile (\$1.1489) driven. Over this 12-month period, the FCEBs each ran for an average of 3,270 hours and consumed an average of 4,313 gallons of diesel equivalent (DGE). Cumulatively, this amounts to 19,618 hours and 25,877 DGE annually.

The fuel cell buses averaged a 4.6 miles per diesel gallon equivalent (MPDGe) value over the course of the year. This was calculated with the following equation.

$$MPDGe = \frac{miles\ driven}{kg_{H_2}} * DGE$$

DGE is calculated as the kg of H2 times 0.882 according to the Department of Energy's Fuel Conversion Factors.[7] The following table details the MPDGe per bus as well as a variety of other cumulative performance parameters.

Table 9: Cumulative summary of fuel cell bus parameters from January 2019 to January 2020.

Vehicle ID	Days of Operation	Fueling Cost (\$)	Miles Driven (mi)	Final Odometer (mi)	Cumulative DGE (gal)	MPDGe	Average Daily Miles Driven	kg/mi	\$/mi
1712	115	\$23,186.16	19,790.0	50,739.0	3,409.3	4.5	172.1	0.20	1.17
1713	144	\$27,778.68	23,477.0	63,201.0	4,084.6	4.5	161.9	0.20	1.18
1714	169	\$30,007.56	27,659.0	60,525.0	4,412.4	4.9	163.7	0.18	1.08
1715	174	\$33,319.26	29,919.0	59,487.0	4,899.3	4.8	171.9	0.19	1.11
1716	201	\$40,370.93	32,754.0	58,244.0	5,936.2	4.3	163.0	0.20	1.23
1611	134	\$21,317.82	19,570.0	35,286.0	3,134.6	4.9	146.0	0.18	1.08
Average	156	\$29,330.07	25,528.2	54,580.3	4,312.7	4.6	163.1	0.19	1.14
Sum	937	\$175,980.41	153,169.0	327,482.0	25,876.5		978.6		

The FCEBs consumed approximately 0.19 kg/mi, or about one kg of hydrogen every five miles. The buses operated at an average fuel cost of \$1.14/mi. In a 2019 report comparing SARTA fuel cell and CNG buses, the fuel costs per mile were calculated at \$1.06/mi for the FCEBs and \$0.45/mi for the CNG buses. The variation in FCEB costs can be attributed to a difference in hydrogen costs. In the 2019 report, hydrogen was priced at \$5.27/kg and this report assumes a \$6/kg value as advised by a SARTA maintenance manager.[8]

[7] *Fuel Conversion Factors to Gasoline Gallon Equivalents*. https://epact.energy.gov/fuel-conversion-factors. Accessed September 2020.

[8] Eudy, L. *Zero-Emission Bus Evaluation Results: Stark Area Regional Transit Authority Fuel Cell Electric Buses*, October 2019. 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 Accessed August 2020.

ViriCiti recently published its E-Bus Performance report concluding that for battery electric buses operating within normal temperatures, battery electric buses of this size (40 ft) consume 1.85 kWh/mi on average.[9] Using this value and the local electricity rate, a comparable battery electric bus would cost approximately $0.18 / mile to fuel.[10] This is about 6.5x less expensive than the cost of fueling a FCEB, although Ohio's climate is more severe than average so a battery-electric bus would likely cost more.[11] While this is significantly less expensive than the calculated fueling cost per mile for the fuel cell buses, a few additional factors should be noted.

A primary benefit of fuel cell buses is the additional range they offer with respect to battery electric buses. According to figures provided by ViriCiti, a 40 ft battery electric bus with 300 kWh of battery capacity can, in perfect conditions, drive 233 miles on a full battery. On a winter day, this range can be as low as 75 miles if the bus is electrically heated.[12] For comparison, SARTA fuel cell buses reached more than 280 miles on a full tank in the best conditions, and still averaged no lower than 140 miles per day throughout the entire year based on the assigned routes. As an upgrade to future iterations, the fuel cell buses can incorporate an advanced HVAC system and heat pump technology to significantly increase range and passenger comfort in the winter months.

Additionally, the fueling procedure for FCEBs is another major advantage. Fuel cell buses refuel similarly to diesel buses with roughly 10 minute fill-ups at a pump. Battery electric buses require significantly more time to charge. At Foothill Transit Agency, for example, their battery electric buses in 2016 averaged a runtime of 13.2 hours per day with an average of 13 daily charges with 20 kWh of energy per charge.[13] Coordinating the necessary downtime to charge each bus for hours adds complexity to route planning and may require transit agencies to purchase additional battery electric buses and to deploy more drivers to account for this downtime.

Further, dozens of fuel cell buses can be fueled at a limited number of pumps. SARTA is planning to fuel over 10 FCEBs and numerous fuel cell paratransit vehicles with four pumps. In the same way that a gas station can serve more vehicles by simply increasing the size of the fuel storage tank, scaling up the number or FCEBs will not require much additional space designated for fueling. Alternatively, commercial battery electric vehicles often receive individualized charging infrastructure. As transit agencies expand the number of zero-emission vehicles in their fleet, they must consider if they have the space required to fuel or charge all their vehicles efficiently.

Finally, costs of electricity and electricity infrastructure for entire fleet of electric buses may be costly. A fleet of battery electric bus charging stations will require a significant upgrade in transit depot infrastructure, including possibly a substation and transmission interconnect. Moreover, electricity prices are often more expensive during the day due to demand charges. Some transit agencies may choose to charge all buses at night. In this case, each bus would require its own charging infrastructure, adding costs and space requirements to each bus.

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[9] *ViriCitiReport E-Bus Performance*, July 2020. https://viriciti.com/wp-content/uploads/2020/07/ViriCiti-E-Bus-Performance-Report-July2020.pdf Accessed August 2020.

[10] Energy Information Administration, June 2020. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a Accessed August 2020.

[11] Henning, M. "An Analysis of the Association Between Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses," https://www.sartaonline.com/Content/uploads/FourSeasonFINALPDF-938.pdf. Accessed September 2020.

[12] Electric bus range, focus on electricity consumption. A sum-up, March 2020. https://www.sustainable-bus.com/news/electric-bus-range-focus-on-electricity-consumption-a-sum-up/ Accessed September 2020.

[13] Eudy, L. *Foothill Transit Battery Electric Bus Demonstration Results*, January 2016. https://afdc.energy.gov/files/u/publication/foothill_transit_beb_demo_results.pdf Accessed August 2020.

Each fuel type for transit buses comes with its own benefits and limitations. Transit agencies would benefit from exploring in depth which fuel type offers the best solution to the agency's individual requirements for bus range, downtime, and fueling/charging infrastructure.

3.1.2 FUEL USAGE AND EMISSIONS REDUCTIONS

On average, each bus consumed about 31 kg of H_2 per day with a max consumption of about 46 kg in a day. Table 10 may be useful in coordinating the amount of hydrogen required for fueling as SARTA scales up its fuel cell vehicle operations. Over the course of a year, each bus consumed an average of 833 kg for a total of 4,312 kg.

Table 10: Daily, weekly, and monthly fuel consumption averages and max values per bus.

Vehicle ID	Avg Daily (kg)	Max Daily (kg)	Avg Weekly (kg)	Max Weekly (kg)	Avg Monthly (kg)	Max Monthly (kg)
1712	33.6	46.5	143.1	222.2	483.0	833.2
1713	31.9	44.8	125.1	204.7	420.9	650.6
1714	29.6	48.1	108.7	212.5	416.8	676.5
1715	31.2	45.3	127.7	217.9	436.2	598.9
1716	33.3	48.2	142.4	235.1	563.4	813.0
1611	26.7	42.5	93.5	186.3	323.0	739.4
Average	31.1	45.9	121.9	235.1	441.9	833.2
Sum	186.3	275.4	740.5	1,278.6	2,643.3	4,311.6

Table 11 shows each bus was in operation an average of 156 days and consumed an average of 4,888 kg of hydrogen over a one year span. 29,330 kg of hydrogen were consumed to fuel all six buses. This corresponds with approximately 36,469 gallons of diesel that would have been consumed by six diesel buses. Diesel consumption was calculated by dividing the total miles driven by 4.2 miles per DGE, NREL's reported value for the diesel gallon equivalent of conventional diesel buses.[14]

[14]National Renewable Energy Lab, *NREL Fuel Cell Bus Analysis Finds Fuel Economy to be 1.4 Times Higher than Diesel*, December 2016. https://www.nrel.gov/news/program/2016/nrel-fuel-cell-bus-analysis-finds-fuel-economy-to-be-14-times-higher-than-diesel.html#:~:text=NREL%20has%20published%20a%20new,times%20higher%20than%20compressed%20natural. Accessed August 2020.

Table 11: Days in operation, cumulative hydrogen and equivalent diesel consumption, and emissions produced from hydrogen and equivalent diesel consumption between January 2019 and January 2020

Vehicle ID	Days of Operation	Cumulative H_2 Consumption (kg)	CO_2 Emissions Produced from H_2 (kg CO_2)	CO_2 Emissions Produced from equivalent diesel (kg CO_2)	CO_2 Emissions Offset (kg CO_2)
1712	115	3,864.4	34,045.0	44,529.8	10,484.8
1713	144	4,629.8	40,788.4	53,349.9	12,561.5
1714	169	5,001.3	44,061.1	57,630.5	13,569.4
1715	174	5,553.2	48,923.8	63,990.7	15,066.9
1716	201	6,728.5	59,278.0	77,533.7	18,255.7
1611	134	3,553.0	31,301.7	40,941.6	9,639.9
Average	156	4,888.3	43,066.3	56,329.3	13,263.0
Sum	937	29,330.1	258,397.9	337,976.1	79,578.2

The term "well to tank" is used to express the average of emissions released into the atmosphere from the production, processing, and delivery of a fuel.[15] Similarly, the term "tank to wheels" is used to define the average emissions produced from the point where fuel enters the vehicle through the fuel's combustion or utilization. Finally, the term "well to wheels" defines the total average emissions produced from fuel production, processing, delivery, and combustion or utilization.

An estimated 8.8 kg CO_2 / kg H_2 well to wheels was used for SARTA's FCEBs based upon Argonne National Lab's GREET Model. This value corresponds with hydrogen produced from natural gas without CO_2 sequestration. The well to tank diesel emissions were estimated at 1.7 kg CO_2 / gal conventional diesel from crude oil for US refineries.[16] The well to tank emissions were combined with an estimated tank to wheels value of 10.2 kg CO_2 / gal diesel, totaling a well to wheels value of 11.9 kg CO_2 / gal diesel.[17] The well to wheels diesel value was multiplied by the diesel displaced to approximate diesel CO_2 emissions from a conventional bus. Overall, this amounts to approximately 1.7 kg CO_2 / mi for fuel cell buses and 2.73 kg CO_2 / mi for diesel buses, a 38% decrease in emissions for SARTA.

As displayed in the table above, an estimated 13,263 kg CO_2 were offset by each fuel cell bus between January 2019 and January 2020 relative to a conventional diesel bus. In total, the six FCEBs offset nearly 80,000 kg of CO_2

[15] "Well-to-Tank Factors." https://www.lowcvp.org.uk/Hubs/leb/TestingandAccreditation/WTTFactors.htm. Accessed September 2020.

[16] Argonne National Laboratory, *GREET Model*, 2020. https://greet.es.anl.gov/ Accessed July 2020.

[17] Energy Information Administration, *How Much Carbon Dioxide is Produced by Burning Gasoline and Diesel Fuel?* May 2014. http://www.patagoniaalliance.org/wp-content/uploads/2014/08/How-much-carbon-dioxide-is-produced-by-burning-gasoline-and-diesel-fuel-FAQ-U.S.-Energy-Information-Administration-EIA.pdf Accessed July 2020.

over the one year span. This is equivalent to 87.7 tons of CO_2, or the emissions produced from powering nearly 12 US households for a year.[18] Over the six buses assumed lifetime of 14 years, the total savings will be close to 1,114 metric tonnes of CO2, or enough to power the annual electricity use for 189 homes.[19]

While these emissions savings are significant, they also shed light on the importance of reducing emissions from fuel production and distribution. Currently, SARTA is purchasing hydrogen produced from natural gas that is trucked in from Canada. The transit agency has committed to producing hydrogen on-site and is exploring different options including the use of an electrolyzer or a steam methane reformer using renewable natural gas or carbon sequestration.

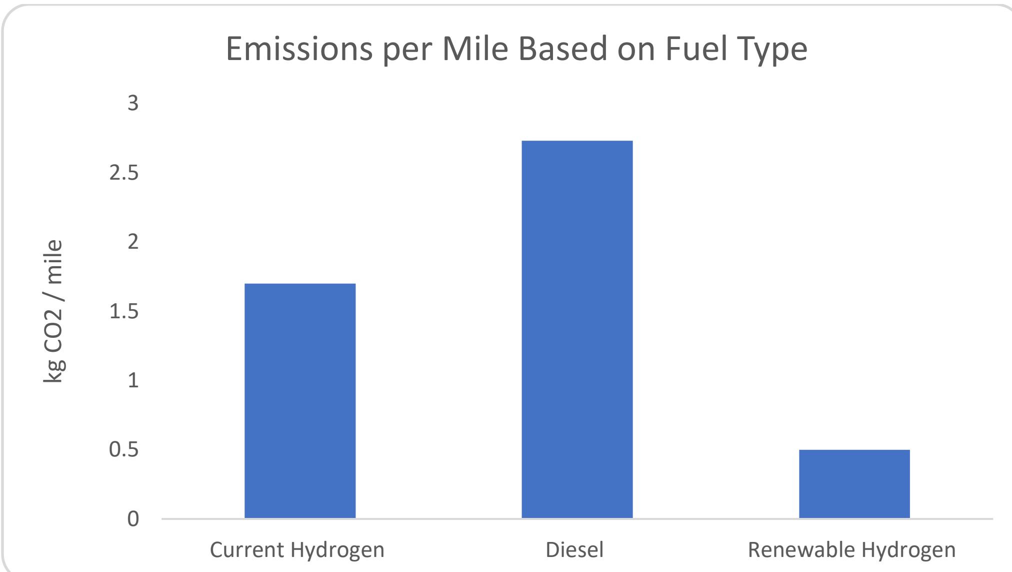

Figure 2: Kg CO2 emitted per mile from current hydrogen, diesel, and renewable hydrogen that may soon be utilized.

If the hydrogen in use was produced renewably, the emissions offset could be more than 4x greater. The figure above helps display the difference in kg of CO_2 produced per mile driven from diesel buses, current FCEBs, and potentially future FCEBs running on renewable hydrogen. The renewable hydrogen value comes from the GREET model for gaseous hydrogen from electrolysis. If renewable hydrogen was used, about 260,000 kg of CO2 would be offset annually from the six buses. The figure below helps visually display the difference in emissions produced over the lifetime of one bus with respect to its fuel source.

[18] Forest Preserves Champaign County https://www.ccfpd.org/Portals/0/Assets/PDF/Facts_Chart.pdf Accessed July 2020.

[19] O'dea J, *California Gets one Step Closer to Zero-Emission Transit Buses*, Union of Concerned Scientists, https://blog.ucsusa.org/jimmy-odea/california-gets-one-step-closer-to-zero-emission-transit-buses#:~:text=Given%20transit%20buses%20are%20typically,the%20road%20across%20all%20agencies. Accessed September 2020.
Greenhouse Gas Equivalencies Calculator, March 2020. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator. Accessed September 2020.

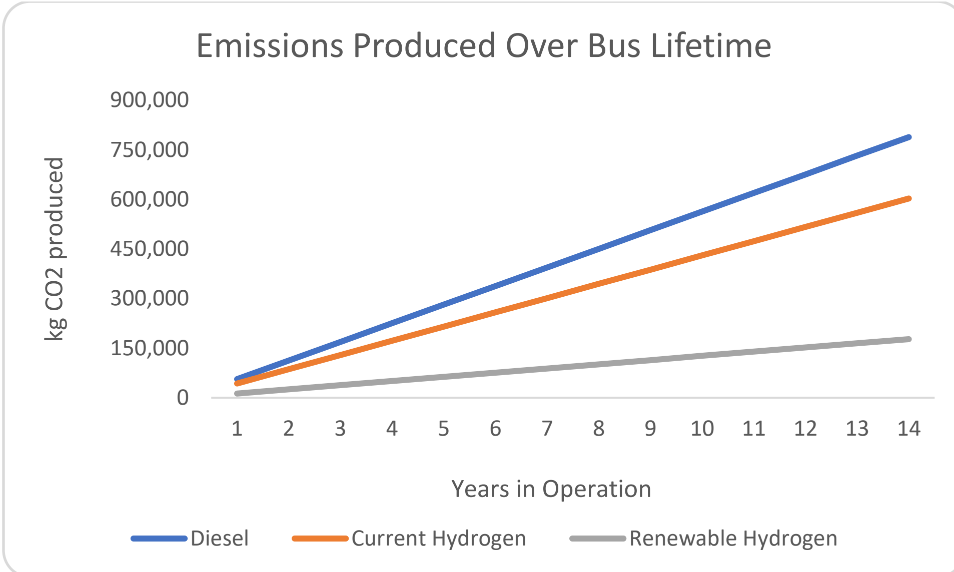

Figure 3: Emissions produced by one diesel or hydrogen bus over its lifetime depending on the carbon intensity of the fuel.

As shown in Figure 3, using renewable hydrogen would drastically reduce the emissions produced over the lifetime of a fuel cell bus. Although hydrogen produces zero tailpipe emissions, the method in which it is produced and distributed can produce drastic difference on the fuel's well to wheels emissions. Converting to renewable hydrogen would compound the benefits of operating fuel cell vehicles and further solidify SARTA as a national leader in sustainable transit.

As SARTA prepares to deploy its new MY18 hydrogen FCEBs and nearly double its fleet of buses that produce zero tailpipe emissions, the transit agency is simultaneously working to minimize its fuel emissions from hydrogen generation. These forward-thinking investments serve to benefit SARTA riders, the local community, and the fight to reduce emissions in the face of climate change.

3.1.3 TIME USAGE ANALYSIS

SARTA maintains daily records of how each bus, both fuel cell and diesel, were used. These logs were analyzed to provide insight into operational, downtime, and other key differences. In total, data was collected on the fuel cell and diesel buses for 1,858 and 1,791 days, respectively. The figure below shows the average daily use of the fuel cell and diesel buses.

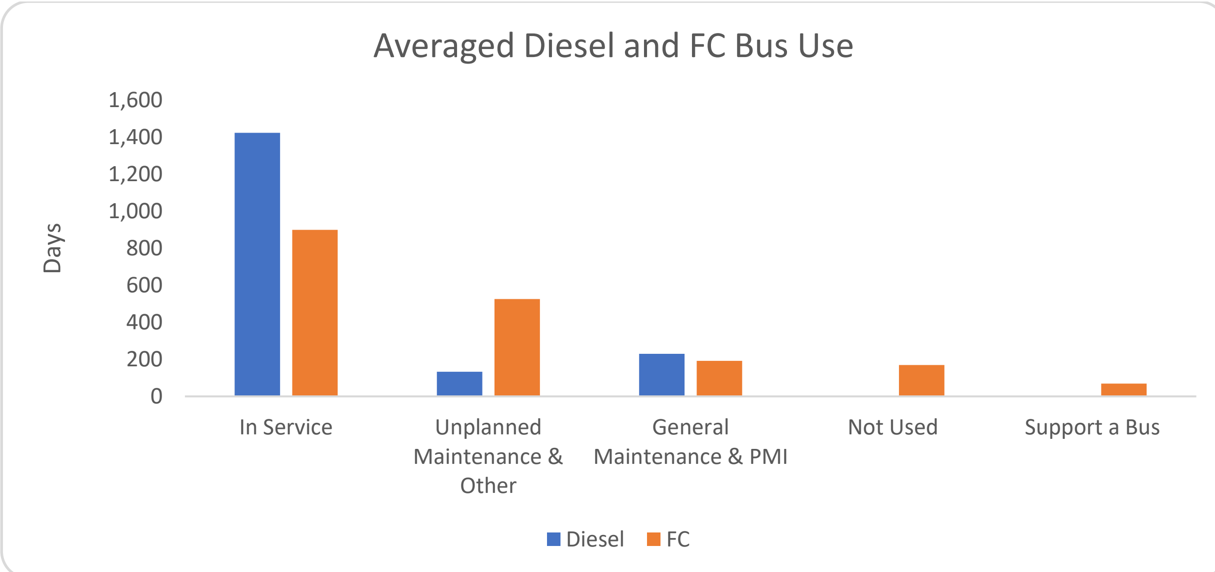

Figure 4: Comparison of average daily use of six diesel and six fuel cell buses.

Fuel cell buses experienced two activities that the diesel buses did not. As discussed in Section 3.3.2, the fuel cell buses occasionally run low on fuel during their shift and require a second bus to meet them on their route. These "Support a Bus" days occurred a total of 69 days out of a total 901 fuel cell bus in-use days, or about 8% of the time. The fuel cell buses also experienced days where they were ready to be operated but were not utilized. This occurred on 170 days, or about 9% of the time, but did not occur with the diesel buses.

Overall, the diesel buses were in service more often than the fuel cell buses. Diesel buses operated 1,426 days and fuel cell buses operated 901 days over the data collection period. Unplanned maintenance was the biggest contributor to this discrepancy. It should be noted that nearly 20% of unplanned maintenance for FCEBs was due to a single bus having a fuel leak. This was not the same bus that was excluded from the study due to a prolonged 163 day fuel leak. As discussed in Section 3.3.1, the maintenance team experienced longer waiting periods to receive custom parts for the fuel cell buses, leaving them out of service. This is being addressed by allowing the customer to procure an inventory of replacement parts, including fuel tank valves, such that any additional hydrogen fuel leaks can be addressed in a more efficient manner moving forward. In the future, replacement times will decrease as the fuel cell electric bus market grows and parts become more common.

By reducing the amount of fuel cell bus downtime and utilizing fuel cell buses when they are ready to be operated, SARTA can ensure they are maximizing their FCEB use. Figure 4 shows the diesel buses requiring slightly more time for "General Maintenance," indicating that with future iterations of fuel cell buses requiring less unplanned maintenance, larger part inventories that reduce waiting time, and fewer days where operational buses are not utilized, fuel cell buses may be able to achieve the promise of less maintenance as is often assumed. The figure below examines the major causes for buses being out of service.

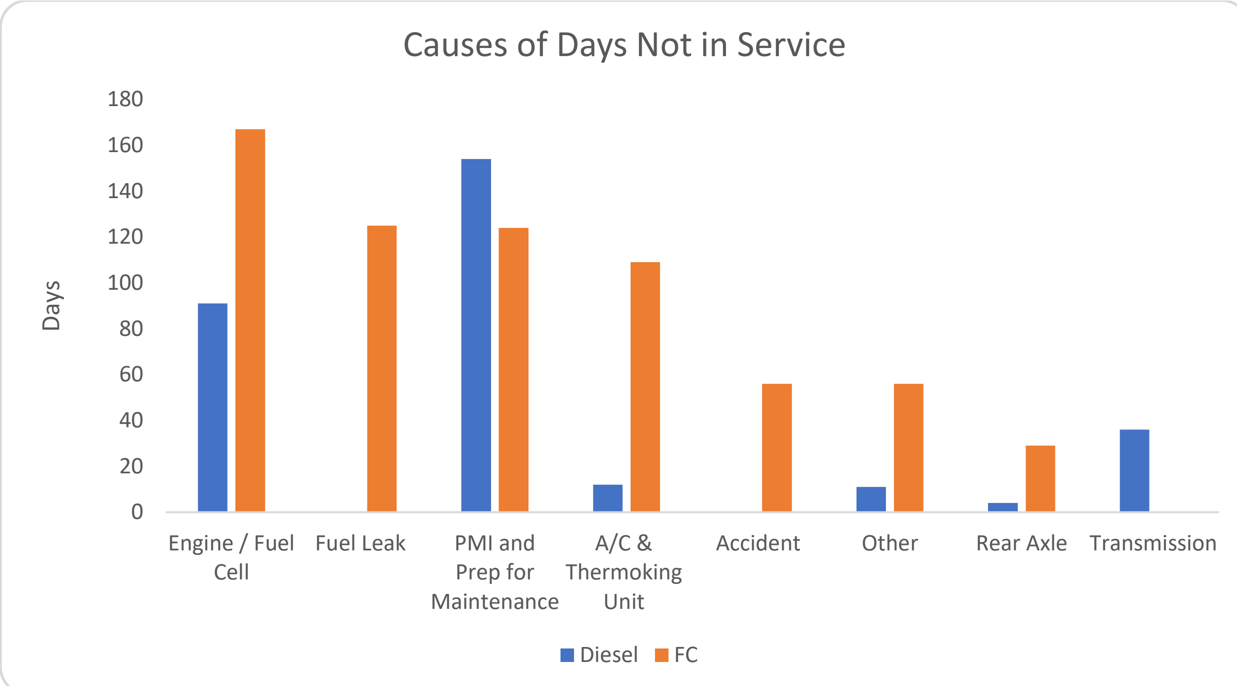

Figure 5: Major technical causes of six diesel and six fuel cell buses being out of service.

According to Figure 5, the major technical causes for diesel and fuel cell buses being out of services differed. Nearly 50% of days when diesel buses were out of service was due to PMI (Preventative Maintenance and Inspection) and Prep for Maintenance. Unplanned maintenance is less of an issue for the diesel buses as the maintenance team appears to have learned how to avoid it with preventative inspections and maintenance. The second and third leading causes of days not in service for the diesel buses are engine (30%) and transmission (12%) related issues, respectively. Altogether, these three causes are responsible for over 90% of diesel days not in service.

The fuel cell buses experienced a more diverse set of causes for days not in service. Fuel cell problems were responsible for 25% of days not in service. Even so, fuel cell issues were responsible for a smaller percentage of days out of service than from diesel engine issues. It should be noted that the fuel cell issues were not solely related to the fuel cell stack, but rather the peripheral components that supply hydrogen and air, including a failed hydrogen recirculation blower and air compressor controller. In total, diesel and fuel cell buses were out of operation due to technical issues for 308 and 666 days, respectively. One bus included in the study experienced a fuel leak that left it out of commission for 125 days. However, it appears that hydrogen fuel leaks were not a fleet-wide issue, since there was only one other instance.

The air conditioning and Thermoking unit was responsible for about 16% of days not in service for the fuel cell buses. Specifically, SARTA experienced some issues with the electrically-driven air conditioner on the FCEBs due to quality issues in the manufacturing process that led to failing evaporative and condenser motors. The local technician for the component supplier was not familiar with the model, which added time to troubleshooting the issue. Understanding the problem now will help prevent this issue from occurring in future fuel cell bus models.

Among the "other" events that left the buses out of service are trainings, special events, and complications with the side window, outside windshield, sway bar links, and EMP pump. Accidents, issues with the rear axle, and other issues were responsible for the other 21% of fuel cell bus downtime. As future iterations of the buses resolve these issues and the maintenance team learns the best methods of preventative maintenance and establishing a helpful inventory of parts, the transit agency will maximize the number of days these fuel cell buses are in operation.

3.2 BUS PERFORMANCE DATA

3.2.1 AUXILARY LOAD ANALYSIS

Weather plays a significant role in the efficiency of SARTA's fuel cell buses. To ensure passenger comfort and safety, the winter months require buses to run the heater and summer months require buses to use air conditioning, resulting in variations in energy demand. The table below displays the average energy demands, miles driven, energy produced in the fuel cell, and vehicle efficiency all broken down monthly.

As defined in Table 7, the UNIDI 28VDC line powers all the bus lights as well as a variety of other features that remain relatively constant with changes in temperature. The API 230VAC line, on the other hand, powers the air compressor, power steering, and air conditioning. Finally, the ACTM propulsion line is used to propel the vehicle. Energy data related to the bus heater was not recorded. As a result, efficiency values for winter months in the table above are lower than the true value since energy being drawn by the heater is being counted as wasted energy.

The efficiency values in Table 12 were calculated by dividing the FC Energy, or the energy generated in the fuel cell, by the sum of the UNIDI 28VDC line, API 230VAC line, and ACTM Propulsion line. Between April and October, when the heater would presumably not be needed, efficiency values were over 90%. The drop in efficiency in the colder months indicates the gap in data where the heater drew significant amounts of energy.

Table 12: Average energy draw from each energy source and average miles driven for each month.

Month	Average UNIDI 28VDC Energy Consumption (kWh)	Average API 230VAC Energy Consumption (kWh)	Average ACTM Propulsion Energy Consumption (kWh)	Average Miles Driven (mi)	FC Energy (kWh)
Jan	542.9	258.0	5,465.8	1,960.4	8,127.7
Feb	537.1	267.3	5,349.2	1,937.3	7,730.9
Mar	631.5	291.8	6,633.8	2,355.9	8,931.2
Apr	877.3	464.8	8,620.9	3,150.5	10,954.7
May	691.4	482.1	6,477.6	2,331.5	7,760.9
Jun	790.7	838.2	6,736.6	2,517.2	8,433.2
Jul	753.8	1,210.7	5,632.0	2,150.8	7,854.8
Aug	714.1	1,154.3	5,468.0	2,042.0	7,557.3
Sep	714.8	971.6	5,843.2	2,138.4	7,747.6
Oct	771.9	456.0	6,935.6	2,577.1	8,783.9
Nov	721.1	342.2	6,797.1	2,467.9	9,678.4
Dec	737.6	393.1	6,986.5	2,542.7	10,569.0
Average	707.0	594.2	6,412.2	2,347.7	8,677.5
Sum	8,484.2	7,130.0	76,946.3	28,171.8	104,129.4

The API 230VAC shows the most variation based on temperature, because it powers the air conditioning,. Table 12 shows a spike in API 230VAC demand between June and September. Compared to January, the energy demand from the API 230VAC line in the summer months is between 3 and 4.7 times higher.

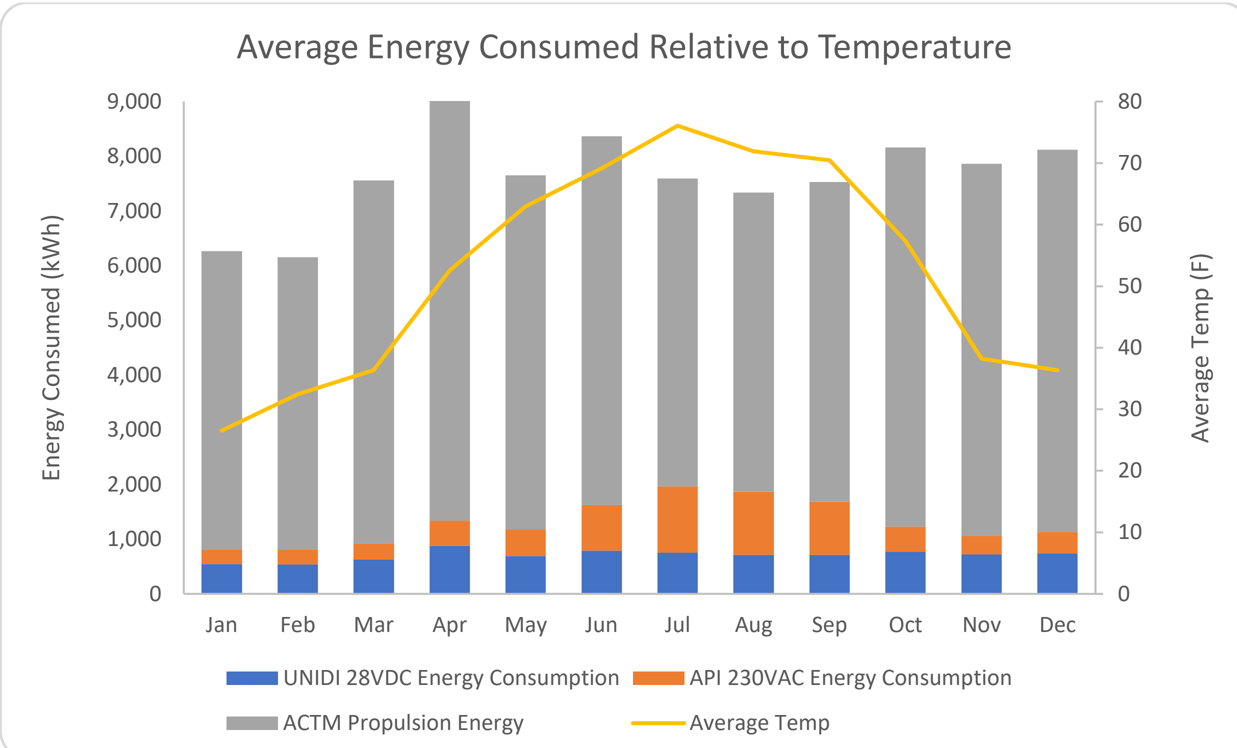

Figure 6: Energy going to each of the three energy draws, excluding heater data, in comparison with average temperature.

Figure 6 above displays the increase in API 230VAC energy draw between June and September as the summer temperatures spike. This figure provides insight into how energy is being consumed, especially in the summer months. Energy drawn by the heater is not included in this figure, which explains why January and February are displayed as having the lowest energy draws. As a result, Figure 6 should only be used to draw conclusions about the energy draw from the air conditioning in the API 230VAC line. A more complete figure would include a fourth energy draw for the heater.

To estimate how much energy the heater drew during winter months on average, the energy balance equation below was used:

Eq. 3 $$heat = (Efficiency * Energy\ In) - UNIDI\ 28VDC - API\ 230VAC - ACTM\ Propulsion$$

The efficiency in Equation 3 was calculated through an iterative process to find the value that resulted in the summer months, where presumably no heater would be used, being as close to zero as possible. This value was 0.97.

Using Equation 3, an estimated average heater draw of 1,399 kWh per month between November and April was calculated with a peak estimated value of 2,135 kWh in December. For comparison, the API 230VAC line averaged 1044 kWh in June through September, where no heater was presumably used, with a max value of 1211 kWh. The 1,399 kWh equates to approximately 42 kg of hydrogen consumed for heating monthly per bus between

November and April, assuming 1 kg contains 33.33 kWh of usable energy.[20] In total, heating a bus between November and April consumed approximately 252 kg of hydrogen, for a cost of $1,511 per bus.

The average cost of heating a bus between November and April was calculated to be $0.11/mi. In contrast, Dr. Knote from Fraunhofer's Institute of Transportation and Infrastructure Systems estimates that a diesel heater on a standard diesel transit bus consumes about 1.7 gal diesel / 100 miles driven.[21] At this rate, a SARTA diesel bus would consume approximately 245 gallons of diesel between November and April. While this is very similar to the calculated 252 kg of hydrogen necessary to heat the bus between November and April, a more accurate comparison of diesel and fuel cell heating efficiencies and costs would require diesel bus data which is outside the scope of this project.

The energy consumed by the FCEB's air conditioning unit was estimated in a similar approach by averaging the energy drawn by the 230VAC line between November and March, where energy consumption values are much lower and consistent, presumably because no air conditioning was used. The average energy used during these months was subtracted from the energy drawn by the 230VAC line in months that used air conditioning to estimate the air conditioning energy. Between June and September, the average monthly energy draw for the air conditioning was 733 kWh, or about 22 kg of hydrogen. In total, providing air conditioning for each bus during the summer months of June through September consumed roughly 88 kg of hydrogen for a cost of $528.

The table below summarizes the calculated estimates for energy demand and costs of running the heater and air conditioning over the course of the year. While the results are only approximations, they correspond with the findings in Section 3.2.2 that running the heater throughout the year costs nearly three times as much as the air conditioning.

Table 13: Calculated estimates for air conditioning and heater fuel consumption and costs per bus.

	Months	Fuel Used (kg)	Cost	Avg. Miles Driven
Air Conditioning	June - September	88	$528	2,018
Heater	November - April	252	$1,511	2,087

3.2.2 COST PER MILE ANALYSIS

The following figure examines the relationship between temperature and average cost per mile for all six FCEBs. The local temperatures were taken from Weather Underground for North Canton, Ohio.[22] The color shading is used to represent the four seasons, with blue representing winter, green representing spring, yellow representing summer, and orange representing fall.

[20] Liquid Hydrogen Outline. https://www.idealhy.eu/index.php?page=lh2_outline#:~:text=1%20kg%20of%20hydrogen%20contains,is%20outperformed%20by%20liquid%20fuels. Accessed August 2020.

[21] Eliptic, *Are buses with a diesel-powered heater true zero-emission buses?* December 2017. https://eliptic-project.eu/news/are-buses-diesel-powered-heater-true-zero-emission-buses. Accessed August 2020.

[22] 22 IBM Cloud, August 2020 https://www.wunderground.com/history/monthly/us/oh/north-canton/KCAK/date/2019-11 Accessed August 2020.

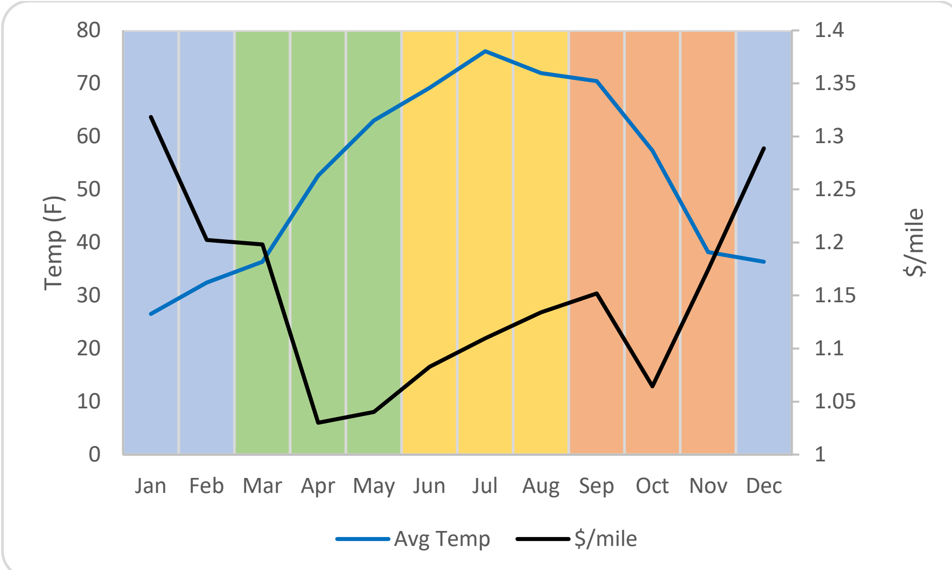

Figure 7: Temperature and cost per mile comparison

According to the figure above, when temperatures decreased below about 55 degrees Fahrenheit, cost per mile increased by about 20%. On the contrary, when the temperatures exceeded about 70 degrees Fahrenheit, the prices became about 10% higher than the optimal 60 degree value. The average cost per mile was highest in the winter months of December through February, presumably as cold temperatures required more energy to heat the bus. Cost per mile continued to drop until mid-April when a minimum cost per mile value of about $1.03/mile was reached.

From mid-April thru August, ambient temperature increased to the point that air conditioning had to be turned on to ensure the comfort of the passengers on board the buses. These costs increased to around $1.15/mile as temperatures reached their warm-weather peak in the summer months, and then began to drop again as temperatures cooled in September and October.

As the end of Fall approached, the temperatures continued to drop through November and into December as the cost per mile increased again to approximately its maximum value of around $1.30/mile. Warm temperatures and the use of air conditioning resulted in higher cost per mile values, but the use of heating in the winter seemed to increase operating costs to their highest value of $1.30/mile. The lowest cost per mile values occurred between late March and early June, with similar values occurring between late September and early November.

3.3 OPERATOR AND MAINTENANCE INTERVIEWS

CALSTART had the opportunity to interview two members of SARTA's staff that interacted with the FCEBs regularly. This included John, Maintenance Manager, and Eric, Bus Operator. The following points are the main takeaways from the interviews. It should be noted that these interviews only represent the views of two SARTA employees and not the transit agency as a whole.

3.3.1 MAINTENANCE MANAGER:

SARTA's maintenance manager, John, is responsible for preventive maintenance, general bus repairs, and repair of propulsion system issues. John shared in detail the differences in maintaining FCEBs in comparison to the conventional diesel buses. In his experience, he noted that the FCEBs are more expensive to maintain than CNG and diesel buses. In large part, this is because parts for FCEBs are much less available due to the industry being in its early stages.

Every 3,000-6,000 miles, the entire fleet of buses at SARTA undergoes regular maintenance as part of its operations. According to John, it takes almost two times as long to perform preventive maintenance on fuel cell vehicles due to the limited availability of new parts, resulting in more downtime. Unplanned maintenance is also very expensive as the wait times to obtain new parts may leave the buses out of operation for a long time. These factors significantly offset the maintenance benefits of FCEBs, such as not requiring oil.

Overall, the current maintenance limitations of FCEBs are consistently improving. John believes that despite current issues with the buses, they are getting better with each new model and that soon the vehicles will be outperforming diesel buses. The first generation of FCEBs at SARTA tended to experience issues with their pumps, fans, and other parts if they were not run at least once every five to seven days. John recommends that FCEB manufactures focus on making future generations of FCEB more durable and less sensitive to water and the environment. He describes them as "robust but delicate."

3.3.2 BUS OPERATOR

Eric, a SARTA bus operator, is responsible for driving the buses as well as the safety and comfort of SARTA's passengers. Eric transports people through local routes, making scheduled stops to pick up and drop off passengers. According to Eric, the FCEBs have a few operational advantages relative to the diesel buses. Among these, the FCEBs have a lower profile and ride much closer to curb height which helps persons with disabilities get on and off the bus. The device installed on the FCEBs to aid persons with disabilities is also much simpler to use than the device installed on diesel buses. The FCEBs have a much "softer" ride and are basically silent in motion. Finally, the mirrors are placed closer to the bus than the diesel bus mirrors, reducing the risk of hitting objects.

Eric also noted a few opportunities for improvement with the MY16 FCEBs. The major limitation of the buses is their range. SARTA buses are operated for two shifts daily for a total of approximately 16 hours and FCEBs are sometimes unable to complete both shifts without having to refill. There are times when the amount of energy needed to run 2 shifts, or 16 hours, between refueling opportunities is greater than the amount of energy available. This typically occurs when there is an unplanned route change due to an emergency situation, or extreme hot or cold temperatures. When this occurs, the operator may run low on fuel and require a trade out situation.

During a trade out situation, the bus operator dispatches back to base and requests a second driver to meet the first driver with a fueled bus at the next transit station on route. The first driver and all passengers must then exit the bus they were on to get on the fueled bus. This is an inconvenience for the drivers who have already adjusted their seat and mirrors to their liking, as well as a hassle for passengers who experience a delay in their ride and may need to carry bags or luggage over to the new bus with them. He recommends increasing the range in future iterations of the buses so they can meet the 16-hour double shifts that buses operate. According to the data, fuel cell buses drive an average of 163 miles per day with a recorded maximum of 282 miles.

It should be noted that SARTA confirmed that switching vehicles due to low fuel is a regular occurrence under certain circumstances. These include cold weather days in winter where the buses can't go the full range due to energy expended heating the buses, as well as especially hot summer days where the Air Conditioning draws significant amounts of energy. While the fuel cell buses are not the only buses that experience bus trading, SARTA did specify that fuel cell bus switching due to low fuel is the most common cause. As noted in Section 3.1.3, bus trading of fuel cell vehicles occurs about 8% of the time.

Additionally, the back doors of the FCEBs open and close slower than the diesel buses. Eric explained that this was a minor issue, but it slowed down the operators and sometimes created confusion among riders. He also noted that the heating system on the FCEBs required more than just the single turn of a knob making it slightly more complex than the diesel buses. Finally, fuel cell operators have been advised to limit the use of the heater while on the freeway to help conserve energy.

Eric noted that the diesel buses are significantly louder and often "stink from the exhaust," but that he currently prefers the diesel buses because of the longer range and a slightly faster "0 to 30." From his experience, passengers have not expressed interest in the bus being zero-emission and that for them, it is solely a method of getting from point A to B.

4. MAJOR FINDINGS

This project provided insight on numerous aspects of the MY16 FCEBs. These findings arose from bus usage and performance data as well as interviews with SARTA staff.

Each month, buses drove an average of 2,446 miles and consumed an average of approximately $2,750 worth of fuel. The buses averaged 0.19 kg H_2/mi and $1.14 / mile. On average, the buses were in operation 156 days per year, with a minimum of 115 days and a maximum of 201 days.

The buses consumed an average of 2,653 kg of hydrogen fuel monthly. A well-to-wheel analysis of the fuel concluded that together, all six hydrogen buses offset 80,000 kg of CO_2 from a total of 337,976 kg that six conventional diesel buses would have produced. SARTA's ongoing plans to produce hydrogen on-site will serve to decrease the carbon intensity of the hydrogen fuel used and further increase the amount of carbon dioxide offset by the FCEBs.

For the months where complete data was available, about 97% of the energy produced by the fuel cell was used by one of the three main energy draws on the bus. In other words, only 3% of energy produced by the fuel cell was wasted before reaching its intended use source. The fuel consumption and associated cost of running the air conditioning in the summer months and heater in the winter months was calculated. From the calculations, an estimated 252 kg of hydrogen for approximately $1,511 was used to power the heater between November and April, and an estimated 88 kg for approximately $528 was used to power the air conditioner between June and September.

Winter operations lead to the highest costs per mile due to having to run the heat for passenger comfort. A comparison of temperature throughout the year and the average cost per mile of the fuel cell vehicles concluded that the winter months reach cost per mile values of $1.30/mile, likely due to the increased fuel used to heat the bus. Spring and fall had the lowest cost per mile values at slightly above $1.00/mile. The summer months showed an increase in costs to $1.15/mile likely due to the use of air conditioning, although this was less significant than the increase due to heating in the winter months.

Having the opportunity to interview two key SARTA employees who work on and operate the FCEBs added unique ground-level insight to the day-to-day operations of the FCEBs. A maintenance manager noted that fuel cell bus parts took longer to deliver than diesel bus parts. He explained that this issue made unplanned downtime last longer than a diesel bus due to long lead times on parts. In his experience, the FCEBs needed to be operated at least once every five to seven days or they would experience issues with pumps, fans, and other parts. Still, he was very glad SARTA is investing in fuel cell technology, optimistic that with new iterations of the buses continually improving, soon the zero-emission buses will be outperforming diesel buses for a fraction of the cost.

The SARTA bus operator was also glad that SARTA is adopting zero-emission technology. He listed the benefits of the FCEBs that include being practically silent in motion, "softer" ride while driving, and aided by the lower ride height of the bus, the FCEBs have a better device to help people with disabilities to get on and off the bus. Because SARTA buses regularly operate 16-hour long double shifts, about 8% of the time the FCEBs are unable to complete both shifts. When this occurs, an additional bus must be delivered for the operator and all passengers to switch to when the fuel runs low. The bus operator described this range limitation as the main roadblock for fuel cell vehicles. He recommends improving the range and increasing the speed of the back door opening and closing.

SARTA's investment in fuel cell technology extends far beyond these six buses, with MY18 nearly ready to be deployed and the transit agency exploring its options for on-site hydrogen production. This leadership provides multiple benefits: the local community is now breathing cleaner air, the riders are experiencing a smoother bus ride, and the significant emissions reductions as a result of adopting these zero-emission buses assist in the fight against climate change. Furthermore, by demonstrating the viability of this advanced technology, SARTA has blazed a path for other transit agencies to begin adopting FCEBs with improved reliability, decreased costs as the market continues to scale, and experienced guidance on best operational practices.