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REPORT
GTI ENERGY PROJECT NUMBER 22339
CARB G16 Demo-02

On-Road Advanced Technology Demonstration: Fast-Track Fuel Cell Truck

Reporting Period:
April 16, 2018 to May 31, 2022

Report Issued:
September 8, 2022
Revision 5, Final

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Acknowledgements

This report was prepared in fulfillment of Grant Number G16 Demo-02- "On-Road Advanced Technology Demonstration Projects-Fast Track Fuel Cell Truck Project". GTI Energy would like to acknowledge the organizations and individuals who contributed efforts to realize the project goals and objectives.

This Project was part of the California Climate Investments (CCI), a statewide program that puts billions of Cap-and-Trade dollars to work reducing GHG and criteria air pollutant emissions, while strengthening the economy and improving public health and the environment, particularly in disadvantaged communities.

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- **Total Transportation Services, Inc. (TTSI)**
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- **Loop Energy**
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- **Hydrogenics**
    - Rob Del Core

Additionally, GTI Energy would like to thank and acknowledge the vehicle drivers, mechanics, managers, and supporting staff members who operated and maintained the advanced technology demonstration vehicles throughout this demonstration Project.

Table of Contents

List of Abbreviations

Acronym	Description
AHJ	Authority Having Jurisdiction
API	Application Programming Interface
APU	Auxiliary Power Unit
AQIP	Air Quality Improvement Program
AQMD	Air Quality Management District
BEV	Battery Electric Vehicle
BST	Bill Signs Trucking
CaFCP	California Fuel Cell Partnership
CAN	Controller Area Network
CARB	California Air Resources Board
CBO	Community Based Organization
CCI	California Climate Investments
CEC	California Energy Commission
CE-CERT	College of Engineering, Center for Environmental Research & Technology
CSE	Center for Sustainable Energy
FCEV	Fuel Cell Electric Vehicle
FMVSS	Federal Motor Vehicle Safety Standards
FTFC	Fast Track Fuel Cell
GGRF	Greenhouse Gas Reduction Fund
GHG	Greenhouse Gas
GTIE	GTI Energy
HVDM	High Voltage Distribution Module
HVJB	High Voltage Junction Box
kW	kilowatt
LFP	Lithium Iron Phosphate
MW	Megawatt
NMC	Nickel-Manganese-Cobalt
NREL	National Renewable Energy Lab
NVH	Noise Vibration and Harshness
OEM	Original Equipment Manufacturer
POLA	Port of Los Angeles
PCAS	Power Control Accessory System
SDPTA	San Diego Port Tenants Association
SOC	State of Charge of Battery / Batteries
SOSS	Station Operational Status System
TCO	Total Cost of Ownership
TTSI	Total Transportation Services, Inc.
VIN	Vehicle Identification Number

Executive Summary

The continued development and demonstration of advanced technologies (zero-emission and near zero-emission) is necessary in order to meet California's long-term GHG emission reduction goals, protect public health, and reach attainment with increasingly more stringent federal air quality standards.

The technology deployed and demonstrated in this project was TransPower's advanced battery-dominant fuel cell-electric truck (hybrid plug-in) platform. The trucks were designed to have a range of 200 miles, extended to 400 miles with a one-hour intraday electrical re-charge and H2 refueling event. The trucks were designed and built in approximately one year, and have been tested over 18 months in various use scenarios. All five vehicles were planned to operate in revenue service with commercial fleets throughout Southern California, however the actual service with fleets was very limited due to numerous reasons described in detail in the report. The primary barriers were: fuel availability, COVID-19 disruptions and technical issues.
The researchers credit the new generations of technologies from major industry stakeholders such as Cummins, Meritor or Peterbilt partially to the lessons learned from the issues encountered by the technical project team.

Local community outreach, education and workforce development workshops were attended by multiple community stakeholders throughout the duration of the project, and generated strong interest in the technology and positive feedback from the participants.

The key findings of this project are:

- Hydrogen Fuel Cell Vehicles are capable of operating in drayage service with 200-300 mile range with a 1-hour electrical recharge and/or 15-minute H2 refueling between shifts

- Based on data collected, current electrical grid emissions and hydrogen carbon intensity, the trucks offer 70% reduction in CO2 emissions compared to diesel

- Hydrogen fueling infrastructure and supply chain need to be more accessible and robust

- Reliability of fuel cells, electric powertrains and associated control systems needs further improvement and long-term pre-commercial demonstrations

- Next generations of technology (fuel cells, e-axles, batteries, integrated controls) developed over the last 5 years have addressed the challenges encountered by the project team

- Data collection from pre-commercial, non-OBD compliant vehicles is challenging and requires dedicated effort

Introduction

Project background and need

On May 19, 2017, solicitation titled On-Road Advanced Technology Demonstration Projects that led to this project was issued under the Assembly Bill 118 (AB 118) Air Quality Improvement Program's (AQIP) Advanced Technology Freight Demonstration Projects and the Low Carbon Transportation Investments with all project funds from the Cap-and-Trade auction proceeds deposited into the Greenhouse Gas Reduction Fund (GGRF) as part of the California Climate Investments (CCI). The project is intended to fund technologies on the cusp of commercialization that further the purposes of AB 32 (Nunez, Chapter 488, Statutes of 2006).

The continued development and demonstration of advanced technologies (zero-emission and near zero-emission) is necessary in order to meet California's long-term Greenhouse Gas (GHG) emission reduction goals, protect public health, and reach attainment with increasingly more stringent federal air quality standards. Projects selected under the aforementioned solicitation were required to demonstrate advanced technologies that should be able to provide a significant reduction in GHG emissions and improve air quality for many affected areas within the State when the technology is fully integrated into the marketplace.

CARB's solicitation indicated that "Zero-emission technology is just now making its way into the Class 8 truck market with one model available. Commercialized zero-emission truck technology is now found in lower weight classes that are primarily used in urban delivery and transit bus applications, with multiple vehicle manufactures in the market. Those smaller zero-emission trucks are utilizing electric drive systems with on-board energy stored completely in battery packs, or battery packs coupled with fuel cells acting as range extenders". At the time CARB was funding a 43-truck demonstration of zero and near-zero emission Class 8 drayage trucks. No fuel cell / hybrid plug-in trucks were funded under the FY 2014-15 drayage truck solicitation. Therefore, one of the funding categories required a focus on fuel-cells being demonstrated in short and regional haul trucks to push the development of zero-emission technologies in the heavier truck categories with longer ranges than found in purely battery plug-in zero-emission trucks.

In 2018 TransPower had reported that it had recently expanded its competitive advantage by initiating road testing of its first fuel cell truck. The team believed this was the only fuel cell-powered Class 8 truck in the world that has made intercity trips on its own power and that is suitable for regular commercial use. Indeed, by the time the Fast-Track Fuel Cell Truck project ("Fast Track") started, this and a second truck of the same design would be in everyday use and would have accumulated thousands of miles of operation. By building directly on this technology, it was believed that TransPower has a much better chance than any competing technology provider at deploying functional fuel cell trucks capable of driving 400 miles per day, within the limited time available for this project.

Team structure and capabilities

GTI Energy and its team proposed a lean, rapidly-paced "Fast Track" project that set the extraordinary challenge of completing a practical hybrid plug-in heavy duty truck demonstration. Team members, capabilities and planned responsibilities are outlined below:

GTI Energy: GTI Energy was the prime contractor with the ARB and was responsible for overall project planning, scheduling, reporting, billing, and for meeting the project goals and deliverables. GTI Energy has managed large, advanced vehicle demonstration projects like this and regularly collaborated with its network of technology partners to bring emerging technologies to commercialization.

Transportation Power, Inc. (TransPower): Transportation Power, Inc., is a California-based corporation that designs, builds, and tests zero emission trucks. TransPower has successfully deployed more working, zero-emission trucks into actual real-world service in California than any other company as of 2018. Statewide, Class 7 and 8 zero-emission trucks, yard tractors, and school buses using TransPower's technology have accumulated more than 100,000 miles of in-service use. TransPower was acquired by Meritor in January 2020.

Meritor, Inc: Meritor, Inc.,a global leader of drivetrain, mobility, braking, aftermarket and electric powertrain solutions for commercial vehicle and industrial markets. Meritor acquired TransPower in January of 2020.

Hydrogenics: Hydrogenics was a worldwide leader in designing, manufacturing, building and installing industrial and commercial hydrogen generation, fuel cells and MW-scale energy storage solutions. Hydrogenics provided TransPower with the fuel cell power system and related controls for the first three Fast Track trucks and supported TransPower with the integration of the power systems onto the vehicle platforms. Cummins acquired Hydrogenics in 2019.

Cummins, Inc: Cummins Inc., a global power leader, is a corporation of complementary business segments that design, manufacture, distribute and service a broad portfolio of power solutions. The company's products range from diesel, natural gas, electric and hybrid powertrains and powertrain-related components including filtration, aftertreatment, turbochargers, fuel systems, controls systems, air handling systems, automated transmissions, electric power generation systems, batteries, electrified power systems, hydrogen generation and fuel cell products. Cummins announced an intent to acquire Meritor, Inc in February of 2022 with the expected close date of the transaction by the end of 2022.

Loop Energy: Loop Energy is a Vancouver-based company that had developed an advanced fuel cell power system designed specifically for heavy-duty truck and bus applications. Loop Energy's patented "eFlow" technology is a breakthrough in fuel cell design that maximizes power, efficiency, and durability through optimized air flow inside the fuel cell.

Peterbilt Motors Company: Another key contributor to the Fast Track project was Peterbilt Motors. Peterbilt supplied the two new gliders to be equipped with TransPower-Loop Energy fuel cell systems. Based in Denton, Texas, Peterbilt has a global reputation for industry-leading design, innovative engineering, and fuel-efficient solutions. As part of the second phase of the project, the first of these trucks was planned to be driven (not towed on a flatbed truck) to the PACCAR Technical Center in Mount Vernon, Washington for extensive testing.

OneH2, Inc.: OneH2, Inc. was formed in late 2015 by a group of North American based heavy equipment dealers to facilitate the production and distribution of hydrogen fuel to heavy on and off road mobile fuel cell applications. OneH2 focus on the distribution of hydrogen through their investor's dealership network and directly. They rent and maintain hydrogen refueling infrastructure, production equipment, and hydrogen powered equipment to end users while sourcing hydrogen supplies from the most practical and economic means available.

Frontier Energy: Truck performance and fueling station infrastructure data collection and analysis was to be handled by Frontier Energy. Frontier Energy is a consulting firm specializing in the development and management of programs to move new technical practices and technologies from R&D into practical commercial use. The firm's emphasis is on fostering energy efficiency and environmental gains in buildings, power supply, and vehicles. The firm has five offices in California.

Center for Sustainable Energy (CSE): Founded in 1996, CSE is a nonprofit, mission-driven organization whose goals are to transform and advance the market for clean and sustainable energy. CSE role was to provide outreach and education services to local community in the San Diego area and work with Frontier and the other project team members to tie in this project with other clean transportation initiatives in southern California.

The Fast Track project also began with the involvement of two actively engaged fleet operators based in two different regions to provide broad-based benefits throughout Southern California.

Total Transportation Services, Inc. (TTSI), with its new base of operations at Customs House at the Port of Los Angeles (POLA), was to operate three fuel cell trucks. They transport containers between the Ports of Los Angeles and Long Beach and inland destinations beyond the reach of TTSI's pure battery-electric trucks, such as warehouses in Ontario and San

Bernardino. Bill Signs Trucking (BST), operating out of its base in Lakeside, California, was to operate two fuel cell trucks primarily within the San Diego region.

Shortly after the project commenced, however, BST withdrew from the project. **Daylight Transport** expressed significant interest in participating as the deployment partner for the two Phase 2 trucks. Daylight was to operate the trucks out of their Fontana facility and their site had available space and power for the mobile fueler.

Project Goals and Objectives

To achieve a target 12-18 months of field trials, TransPower would leverage their demonstrated experience building and integrating electric and fuel cell vehicle systems. It was hoped that this would reduce development time and minimize the risk of schedule slippage.

To deploy five demonstration trucks, a target investment per demo truck of less than $1M was established. The approach selected was as follows:

- Repurpose three existing battery-electric (plug in) trucks to reduce component and integration costs for Phase 1 fuel cell demonstration,
- Leverage existing Peterbilt-TransPower electric truck design to minimize budget for non-recurring engineering,
- Use Navistar and Peterbilt truck platforms already used for electric propulsion to minimize vehicle integration costs.

To provide sufficient operation range for a 400 miles/day demonstration vehicle in Phase 2, engineering efforts were focused upon a new Loop Energy fuel cell, which appeared to have the potential to deliver 100 kW+ in a more practical (smaller, less expensive) package. The plan was to adopt Nissan high energy nickel metal cobalt cells, which have twice the energy density of truck batteries used to date, and utilize high-power, onboard chargers to reduce charge time. This would enable two shifts of operations per day.

The team has planned to install chargers at the fleet locations, utilize existing fuelers at TTSI location in the POLA and deploy a permanently installed mobile hydrogen fueler at BST / Daylight facility.

To educate various stakeholders, especially truck operators, about the benefits of fuel cell propulsion, and to ensure that the project has a practical impact in terms of stimulating adoption of targeted technologies, the team was planning to involve two major original equipment manufacturers (OEMs), Navistar and Peterbilt, and to involve community organizations such as and San Diego Port Tenants Association (SDPTA) in developing and executing outreach plans.

Technology Design and Build (Task 2)

Phase 1

In Phase 1, three existing Class 8 electric semi-trucks, already proven to operate reliably on battery power, were upgraded by TransPower and Hydrogenics to a fuel cell configuration. Navistar electric trucks that had done demonstration service were repurposed by adding hydrogen storage and a pair of Hydrogenics fuel cells integrated into an auxiliary power unit (APU). This allowed the Fast Track team to eliminate most of the risk of technology schedule delays that accompanies the integration of new and untested technologies. A photograph of the three fabricated Phase 1 fuel cell trucks developed in this project is provided in Figure 1. The trucks were designated FC3, FC4 and FC5 (from left to right) and were referred to as Red, Barney and Blue. The numbering scheme for the trucks omits FC1 and FC2 as they were built by TransPower and used for a different project, and Fast Track project team chose to start the numbering with FC3 to avoid confusion. A side view of the fuel cell system installed is most visible on the red truck in Figure 1.

Figure 1 - Phase 1 Fuel Cell Trucks 3, 4 and 5 (L to R)

The old lithium-iron-phosphate (LFP) batteries were replaced by the latest production batteries based on a Nissan Leaf module. The batteries can be seen in Figure 1, two packs below the door, one aft and two under the drivers' door, for a total of 220kWh rated capacity.

- To consolidate the five battery cables to connect to the inverters, the HVJB (High Voltage Junction Box) was added.
- The HVDM (High Voltage Distribution Module) incorporates the battery contactors in a waterproof container replaced an older design.
- Other components of the PCAS (Power Control Accessory System) were retained, including

the inverters. The PCAS was improved by adding shielding from water spray. Adding the fuel system and the fuel cell required a longer truck wheelbase, by over a foot, so the frame rails were cut and extended, with reinforcing C beams. A new drive shaft was fabricated to fit this new longer wheelbase. See Figure 2.

Figure 2 – Extended Frame Rails for Red Phase 1 FTFC truck Before Mounting, Tanks, Hydrogenics System and APU.

This major re-build of the electric drivetrain required, at completion, driving and testing of the electric truck, which was done before adding the tanks and fuel cell system. The tank system was fabricated by an outside vendor, pressure tested and delivered with skins (of 1/8" aluminum) separate. The skins were painted and added to the fuel system following mounting on the trucks. The fuel cell system is unique to these trucks, and complex, hence was fabricated and tested before mounting on the truck. Figure 3 shows the fuel cell system before skins were added. Hydrogenics fuel cells (two, each rated 30kW) are left of a firewall which separates the low and high voltage sides of the system.

Figure 3 - Hydrogenics Fuel Cell System for Phase 1 FCFT Trucks

Following addition of the containment box which protects fuel cell from the weather, and installation of the cooling system atop the fuel cells and inverters (Figure 4) the completed fuel cell system was moved outdoors, connected to the truck electrically and to a separate hydrogen storage. The system was tested by running the fuel cells and charging the truck batteries. This assures easy access to the components for troubleshooting. Following the commissioning of the fuel cell system next to the truck (See Figure 5), each system was added to the truck for driving and commissioning.

Figure 4 - Hydrogenics Fuel Cell System with Containment and Cooling Module

Figure 5 - Commissioning the first fuel cell system. The partially complete fuel cell system for truck FC3 is in the background. (March 2019).

Figure 6 -Tanks shown mounted on the first Phase 1 truck

Commissioning of the Phase 1 truck FC3 fuel cell system was delayed due to unexpected changes the supplier made in the DC-DC conversion module, needed to boost from fuel cell output voltage. Extensive discover effort was required to learn how to operate the module even using the supplier in-house software EPyQ. After a month of attempting to use the new firmware, the decision was made to return to code developed and supplied for early (2017) units. It took almost a month to determine how to wipe the new coding from the system, retrofit with the code that had worked on early fuel cell trucks and to install appropriate parameters to enable operation. Once this was done, commissioning of the first fuel cell system was completed.

During July 2019, a total of 324 miles of commissioning driving was completed TransPower. This included the accumulation of 170 miles of loaded test driving without recharging and with 80% of a tank of hydrogen fuel, suggesting that the initial goal of achieving 200 miles of operating range could be achieved when these trucks enter service. TransPower continued to accumulate miles with FC3 as measurements were being made validating coolant flow and the cooling response to high temperatures in July and August of 2019.

The first of the Fast Track Fuel Cell (FTFC) trucks, FC3, underwent several weeks of test driving until the fleet was taken out of operation on August 20, 2019, pending an on-going review of TransPower's compliance with Federal Motor Vehicle Safety Standards (FMVSS). It was hoped that the certification procedures could be straightened out and approved by the federal government in short time. During August the Red truck was driven 513 miles with a focus on performance as well as on improving the cooling system software so as to achieve more power from the fuel cells. A similar Fuel Cell (FC) truck funded previously by the U.S. Department of Energy and South Coast Air Quality Management District (ZECT 2 project) was operating reliably at TTSI prior to the FMVSS stand-down, but its average fuel cell power has been limited, peaking at about 50% of rated power. For long range driving on freeways it is important to achieve more fuel cell power so as to better maintain battery state of charge. At the same time TransPower reached out to Hydrogenics staff to discuss the limitations to the fuel cell operating temperature and hence the power output from the fuel cells.

During the commissioning/testing of Phase 1 vehicles, drivers began reporting that the vehicles experienced a shift quality issue, which was intermittent and difficult to investigate. On December 20, 2019, TransPower delivered the first truck FC3 (Red) to TTSI and TTSI began installation of their telematics system. Delivery of vehicles FC4 and FC5 was postponed until the shift quality issue identified earlier had been resolved. A baseline survey, operator training and acceptance was scheduled for January 2020, while TTSI was also working on registering the truck with Department of Motor Vehicles (DMV) and the POLA as part of the Clean Truck program to ensure the Licensed Motor Carriers confirm their concession status and maintain accurate truck data in the Ports Drayage Truck Registry.

Around January 2020, TransPower reported that Meritor had acquired the outstanding shares of TransPower and had become the sole owner. GTI Energy immediately scheduled a visit to TransPower to meet with the new leadership, discuss the project status and potential impacts of the transition on project timeline. No issues were identified at that time.

Truck FC4 was delivered to TTSI in March 2020 but was returned to TransPower for shift quality issue investigation alongside truck FC5. The root cause has been narrowed down to a resonance between the two traction motors and inverters, and required inverter firmware improvements. EPC, the inverter manufacturer, requested dynamic current and voltage measurements from TransPower. However, the measurements require extensive instrumentation and TransPower was not successful in acquiring the data. Simultaneously, TransPower had initiated testing of torque limiting software to see if reduction of the power level can reduce the shudder effects at least enough to allow commissioning testing. At the same time, TTSI observed a reduction in freight volumes at the POLA due to an outbreak of COVID-19 in Asia, which pretty quickly spread in the US and decimated the cargo traffic at the ports. TTSI was unable to operate the vehicles due to shipping business coming to a halt. Anecdotal reports suggested that container volume was reduced to a mere 3% of the typical volumes (50 versus 1700/day).

By May 2020, the shift quality issues have been resolved and the trucks were waiting for TTSI to resume operations and accept the trucks. Truck FC4 and FC5 were exhibiting a drivetrain vibration issue and TransPower performed driveline alignment. That improved the symptoms to a point where truck FC4 drivability was acceptable with a part-loaded trailer. The vehicle was driven for 450 miles to gain confidence with the durability. A further improvement was suggested by driveline experts which required adding an inertia disc to the driveline that may dampen the vibration, however the solution was not pursued.

By the third quarter of 2020, TTSI was not ready to start the truck operations due to ongoing COVID-19 disruptions and limited fueling options around the POLA, while trucks FC4 and FC5 had seen very limited operation at TransPower as they worked to resolve technical issues. FC4 was troubled by intermittent communication issues between the components, which were traced to failed low-temperature coolant pump vibration isolators, putting stress on the electrical connector. Truck FC5 underwent further drivetrain alignment efforts to mitigate the vibration, however the improvement was limited. FC5 was also found to need new vibration isolators for the coolant pump. With the port operations significantly diminished and trucks suffering from reliability issues, the team decided to shift all vehicle testing to TransPower, requiring hiring of additional drivers and making fueling arrangements in San Diego area. The mileage accumulation started ramping up slowly through Q4 2020 and peaked in Q1-Q2 2021.

In May 2021, Truck FC3 (Red) was attempted to resume revenue service at TTSI, but it went down due to a failed Hydrogenics fuel cell, and the team recommended to stop supporting the truck due to increasing costs of support and decreasing reliability. Trucks FC4 (Blue) has been accumulating test miles at a healthy pace despite a couple issues: telematics datalogger required repair and radiator was found leaking which required a new drain plug. FC5 has been suffering from intermittent battery dropout issues and the fuel cells have lost power. The root causes needed investigation, but the TransPower resources were allocated to Phase 2 vehicle work. The decision has been made to stop the Phase 1 operations and keep the effort focused on Phase 2 trucks.

Phase 2

The Phase 2 trucks were planned to have a fuel cells by Loop Energy with novel cell channel technology and new on-board inverter-charger units (ICUs).

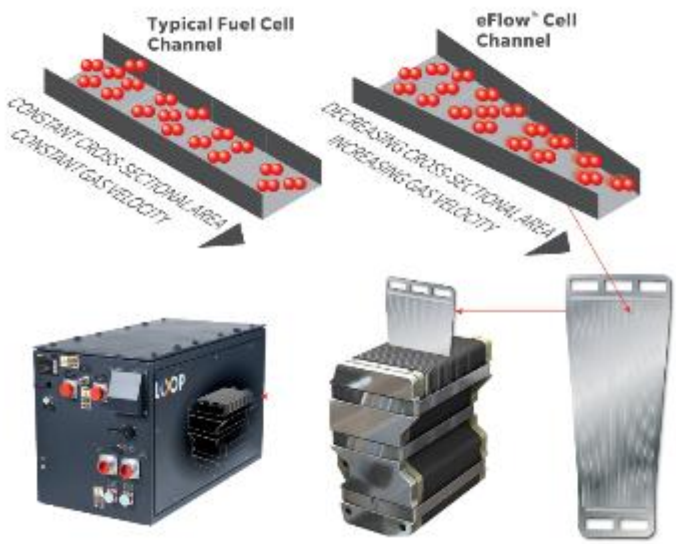

Figure 7 - Loop eFlow Cell Channel

The plan was that Phase 2 trucks would be operated through the end of the project, for approximately 9-12 months. At the start of the grant, BST had agreed to accept the completed Phase 2 trucks and operate them throughout the San Diego and Los Angeles regions. However, shortly into the project, BST withdrew its commitment, and the team secured a commitment from Daylight Transport to operate the trucks out of their Fontana facility.

Two Peterbilt Model 579 truck gliders were purchased to be built into Phase 2 trucks. The Phase 2 truck gliders were ordered in July 2019, delivered in September 2019. Concurrently, 2 of the 4 fuel cells were delivered by Loop in July 2019, while the remaining 2 units were on backorder.

Figure 8 - The first of the Phase 2 trucks, on the production line in Texas.

Both Peterbilt chassis (FC6 and FC7) had been assembled and commissioned in Battery Electric Vehicle (BEV) configuration by January 2020. Installation of fuel cells and hydrogen tanks was delayed until March 2020 due to an Electronic Stability Control (ESC) harness required from Peterbilt, that was held up at their manufacturing facility in Mexico. The harness needed to be installed before the tanks and fuel cell modules. At the same time, the ESC control modules had to be sent to the manufacturer in Ohio for reprogramming, to account for change in vehicle dynamics due to the new components (batteries, tanks, fuel cells).

The vehicle testing has been on hold due to FMVSS compliance review by TransPower. Normally FMVSS certification would not be required by the end user as this is completed by the vehicle manufacturer and registered with the Vehicle Identification Number (VIN). In this case, the trucks manufactured by Peterbilt were considered "gliders", or unfinished vehicles, and a VIN was never produced. FMVSS compliance, overseen by the Federal Highway Administration, regulates the design, construction, performance, and durability of the vehicles to ensure overall vehicle safety and is required of all vehicle manufacturers. Since critical components were excluded from the "gliders" like the powertrain which also provides the power for the steering and braking systems, TransPower was required to declare compliance with FMVSS upon finishing the installation of the Hybrid Electric Powertrain, and to apply for a VIN as the vehicle manufacturer. This process was not initially scoped into the program and required additional non-budgeted TransPower resources. This ultimately caused a delay in clearing the vehicles for registration and on-road operation until April 2020. The truck began on-road commissioning in May 2020.

The outbreak of COVID-19 forced most of the partners to work remotely starting in March 2020, TransPower was most impacted and laid-off about 50% of their workforce. Their operational capability was significantly diminished. The work on vehicle verification continued, albeit slower than expected.

The original plan was to transport the first completed Phase 2 truck to Peterbilt's PACCAR Technical Center in Mount Vernon, WA, where testing would be performed on the truck to validate its safety, durability, and performance. However, in July 2020 Peterbilt indicated that PACCAR would not be able to support the project. Around the same time, Daylight Transport, a fleet operator that committed to operating the trucks out of Fontana, informed the team that due to the current economic and labor situation they were unable to accept the trucks. Since Phase 1 trucks were not accumulating in-service miles as planned, the team decided to refocus the effort and perform safety, durability, and performance testing on-road, with the test managed and operated by TransPower in San Diego area.

Commissioning and testing of the truck FC6 continued to be paced by development of the control software required by the unique nature of this fuel cell truck. Early testing uncovered cooling system limitations which caused the fuel cells to operate at combined 75kW instead of nominal 100kW. TransPower updated the cooling system with more powerful fans to address the issue.

As January temperatures dropped to below 10° C, the fuel cells did not start. This was a result of limiting commands in the firmware controlling the fuel cells. The constraint was removed for the foreseeable future by reducing the limit to 5°C as the average low for the operating areas are ~8°C and rising as it gets into February. The truck continued commissioning mileage with the fuel cell engines limited to half power until new software is developed to optimize the operation of the fuel cells. This would require some complex control innovations allowing the fuel cells to charge the batteries at half or full power, from either one or both fuel cells, but only when battery voltage is lower than critical start-run thresholds.

In March 2021 truck FC6 had developed a grounding insulation fault, which was narrowed down to coolant contamination causing high conductivity. The system was flushed, and the coolant was sent for analysis to determine root cause of the contamination, which was reported as aluminum ions. Ions are removed from the coolant by de-ionizing filters, and the filters were renewed at the time. The issue returned again in May 2021 and was addressed again via coolant flush and replacement of the de-ionizing filters with a different type of filtering media (also referred to as "resin bed"). The truck was back on test in the last week of April but tripped two fuses. With support from Loop Energy, the team identified a suspect a DC/DC control board, however the replacement did not resolve the issue. During the troubleshooting process a crack in the radiator has been found, which necessitated a replacement of the radiator. The team was unable to secure a replacement radiator as the radiator manufacturer was severely constrained by the supply chains, and TransPower was forced to redesign the cooling system with larger and readily available radiators.

Figure 9 - Old cooling system (left) and redesigned cooling system (right)

Commissioning of Loop fuel cell and installation on Peterbilt glider

The next series of photographs illustrate the process followed to commission the Loop Energy fuel cells with the first Phase 2 truck FC6. Upon delivery of the Loop fuel cell to TransPower, the commissioning team instrumented the equipment for off-truck verification of performance and proper operation (Figure 9). A complete image of the Loop fuel cell that includes the cooling system mounted on the top is shown in Figure 10.

Figure 10 - The Loop fuel cell team commissioning the system for truck FC6

Figure 11 - Loop Fuel Cell System after commissioning

In Figures Figure 11 and Figure 12, the Loop Fuel Cell package is on a skid in preparation for mounting on the glider frame of FC6. Referring to Figure 13, one can see the hydrogen storage skid ready for installation on FC6.

Figure 12 - Loop Fuel Cell System ready for installation on FC6

Figure 13 - Hydrogen storage ready for installation on FC6

Figures Figure 13 and Figure 14 provide an ‘under the hood’ view of the power components mounted on the Peterbilt engine frame of FC6 truck.

Figure 14 - Assembled phase 2 truck FC6-driver side view

Figure 15 - Assembled phase 2 truck FC6-passenger side view

Figure 15 is a photograph of the fully assembled FC6 truck with fuel and hydrogen fuel tanks mounted on the glider with batteries stored below the frame.

Figure 16 - FC6 truck on scales during on-road commissioning. The long wheelbase and additional equipment bring the curb weight to 23,300 lbs

Figure 16 is a photograph of FC6 towing a full test load in preparation for delivery to the partner fleet for commercial service and demonstration testing.

Figure 17 - Truck FC6 towing full test loads

Truck FC7 followed a similar process, however it was delayed due to Loop redesigning the fuel cell modules for the ease of manufacturing. The difference between FC6 and FC7 fuel cells was mostly in the packaging, however it necessitated a redesign of the supporting structure and connecting interfaces. FC7 was also retrofitted with a redesigned cooling package with larger, commonly available radiator. The vehicle assembly was completed in January 2022.

Figure 18 - Fuel Cell Subassembly for Truck FC7

Figure 19 - Commissioning of fuel cells with FC7 (fuel cell modules are off-truck for accessibility)

Figure 20 - Completed FC6 and FC7

Vehicle Specifications

	Phase I	Phase II
Manufacturer	TransPower	TransPower
Chassis/Cab	Navistar ProStar	Peterbilt 579
Propulsion	400V, 320kW peak	400V, 320kW peak
Transmission	Eaton automated manual	Eaton automated manual
Axle	Conventional, tandem	Conventional, tandem
Batteries	220kWh, NMC	220kWh, NMC
Plug-in charging	Yes	Yes
Onboard charger	70kW	70kW

Charging time	3 hrs.	3 hrs.
Battery-only range	35+ miles	35+ miles
APU (Fuel Cell)	2 x 30kW, Hydrogenics HD30	2 x 50kW, Loop Energy
Onboard hydrogen storage	32kg @ 5000 psi (350 bar)	32kg @ 5000 psi (350 bar)
Fill Time	10-15 min	10-15 min
Combined Range	200 miles	200 miles

Hydrogen Fueling

At the time of the solicitation team has planned to utilize existing hydrogen fuelers at TTSI location in the POLA. TTSI was receptive to that plan, however upon the start of demonstration the team was informed by SCAQMD, who funded the fuelers, that the fuelers will not be able to accommodate Fast Track vehicles. TransPower and the team worked with TTSI to determine if a totally separate hydrogen infrastructure can be installed for the three FTFC trucks.
The team has pursued several alternative options:

1) Deploying an additional fueler, however an extensive permitting process and uncertain facility future precluded the option
2) Fueling at local retail stations with 350 bar supply. TTSI was anticipating the new heavy-duty Shell station to be commissioned in Wilmington, however the project was facing delays. The other nearest station in Torrance was too far out of the way for the TTSI operations.
3) On-site fueling also known as “wet-hosing”, where a fuel is delivered to vehicles by a mobile fueler. The solution, although expensive and logistically inconvenient, has been used at TTSI and TransPower several times and provided limited support for the operations.

Early into the project an event[1] on Saturday, June 1, 2019, at a Santa Clara facility owned and operated by the chief hydrogen supplier for the region, Air Products and Chemicals, Inc. led to a hydrogen shortage that affected the hydrogen supply to most of the fueling stations in California. Due to the incident, First Element and Air Products had ceased offering hydrogen at 350 bar from the Del Mar station, which was a sole fuel source for TransPower. The team evaluated multiple options, such as procuring 2000 psi (136 bar) industrial hydrogen and boosting it onsite to 350 bar, however the solution was deemed not practical. To continue the commissioning and development of the trucks TransPower resorted to using six packs of 2000 psi hydrogen in industrial cylinders. Although this solution did not offer full tank fills, it allowed continued testing.

[1] https://h2tools.org/sites/default/files/2021-06/AP_Santa_Clara_Incident_Review_Report_Rev1.pdf

Continued commissioning, including long drives with load, has been made possible by the addition of a hydrogen fuel supply on site, a small trailer which was charged to 350 bar from the PV powered electrolyzer at Cal State University Los Angeles. TransPower had to fuel from this trailer for the remainder of the commissioning testing. (See Figure 21). The trailer was towed from Texas, where it had been used to maintain cell tower fuel cell backup power systems, by the IGX Group, which also is responsible for refueling the trailer as that becomes necessary.

Figure 21 - IGX mobile fueler filling FC5 at TransPower (left) and FC3 at TTSI (right)

For Phase 2 trucks, the team had planned to deploy a permanently-installed mobile hydrogen fueler at Daylight facility in Fontana, manufactured by OneH2 in North Carolina. OneH2 has began the permitting process in 2019, filed a complete permit application with the City of Fontana, and had gone through several reviews and revisions. The permit reviews were delayed by remote operations of the Authorities Having Jurisdiction (AHJs) due to the quarantine requirements, however ultimately the process came to a halt when Daylight indicated they were unable to continue the project due to the overall economic situation in the trucking industry. The team has refocused the efforts on operating the trucks out of TransPower facility in Escondido and fueling at local retail station in Del Mar.

Technology Demonstration (Task 3)

The team has planned to demonstrate the technology with two commercial fleet partners. Phase 1 trucks were to be operated by TTSI in port drayage duty out of POLA and Phase 2 trucks were to be operated by Daylight in Fontana.

Unfortunately, numerous factors prevented an effective demonstration of the technology in revenue service. The factors were:

- Technology issues. The team had difficulties attaining the reliability required for a robust revenue-service demonstration.

- Hydrogen fueling availability. Inconvenient locations, and sometimes unreliable retail infrastructure as well as hydrogen supply chain disruptions have delayed the project progress.
- Change in labor laws and disruption to freight industry caused by COVID-19 prevented the partner fleets from operating the trucks
- Staffing challenges due to COVID-19. TransPower had to lay off 50% of their workforce at one point, and staffing back up has been a challenge.
- Other factors such as the novelty of FMVSS requirements or challenges registering hybrid trucks with the DMV.

Facing the challenges and delays, the team has decided to operate the trucks themselves, and TransPower has sought out to hire an additional driver to start accumulating miles on the trucks to demonstrate the performance and reliability of the trucks.

Overall, the vehicles have accumulated more than 16,000 miles combined, with majority of the testing occurring in the spring of 2021as shown below in Figure 22 and broken down by vehicle in Table 1.

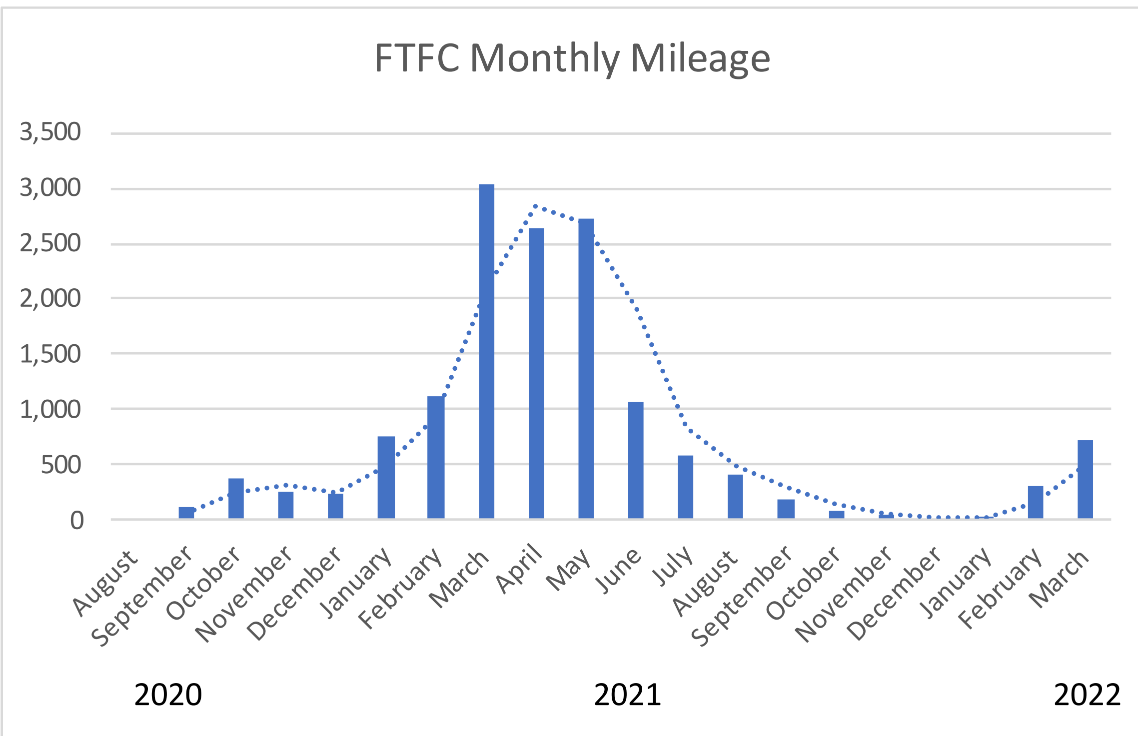

Figure 22 - FTFC Monthly Mileage Accumulation

Phase 1 vehicles have been retired in the summer of 2021 due to deteriorating reliability and increasing costs of maintenance. With the freight industry recovering mid-2021, TTSI has agreed to take the Phase 2 trucks into revenue service, however due to recurring grounding faults on

FC6 and delayed completion of FC7 due to limited resources, the Phase 2 trucks have not accumulated any revenue service miles throughout the duration of the project.

Truck ID	Chassis	Nickname	Odometer	Test Mileage	Revenue Service Miles (at TTSI)
FC3	Navistar	"Red"	7,663*	1,442	426
FC4	Navistar	"Blue"	23,207*	8,512	-
FC5	Navistar	"Barney (Purple)"	19,665*	3,977	-
FC6	Peterbilt	"Eleanor"	2,899	2,899	-
FC7	Peterbilt	TBD	595	595	-

Table 1 - Test Fleet Overview. Trucks FC3, FC4 and FC5

* Trucks FC3, FC4 and FC5 report high odometer readings as they were used prior to start of the project.

Data collection and reporting

The project team had planned to collect several data during the project. The key goal was to acquire and analyze performance and operational data form the vehicles and fueling/charging infrastructure during the operations with the fleets. Frontier Energy has developed an automated data transfer system from TransPower's telematics system by FleetCarma, and developed automated data analytics with a web dashboard, including detection of trips, fueling and charging events. The system was tested with limited data collected during the commissioning, but never fully deployed due to vehicles not operating in reliable, statistically significant duty cycle of revenue service. The system was updated by Frontier to account for acquisition of FleetCarma by GeoTab and then TransPower switching the telematics provider to Viriciti. Each of these changes required re-development of the server backend and analysis algorithms. More issues related to data collection were reported throughout the project, such as missing GPS coordinates, changing Application Programming Interfaces (APIs) and data structures from telematics providers. While the trucks were operated by TransPower, the team continued to monitor and review the data manually, but the duty cycles used for testing were quite inconsistent due to varying loads, routes, and predominantly technical issues. Moreover, the data quality was very inconsistent with key performance parameters "dropping out" for extended periods of time, making them unusable. The team has manually reconstructed as much data as possible, however the final performance analysis relies on some assumptions and interpretations, rather than measured parameters. Fueling data was collected mostly based on fueling station paper receipts collected by TransPower drivers, and later via reports from the fleet fueling cards, however even the fleet card reports were inconsistent with the amount of hydrogen dispensed and required reinterpretation. As shown in Table 2table below, the amount of telematics data collected is much smaller than actual miles traveled (over 16k miles traveled vs 11k miles recorded). Of 11k miles recorded only a small subset was deemed actionable due to data quality or non-representative operation.

Frontier has identified several periods of consistent FC4 operation and analyzed the basic performance attributes of that operation, this data was then given to the CSE for overall emissions analysis. In addition to this the overall summary of each vehicle is below. Note: Table 1 above shows higher mileage than the below analysis due to some loss of telematics data (caused by hardware failures, connectivity issues and poor data quality). See appendix for the detailed usage of each vehicle.

Vehicle	Days Operating	Miles Recorded	kWh Charged	kWh H2	H2 used
FC3	85	424	-565 kWh	56 kWh	68.6 kg
FC4	120	7, 090	-6,262 kWh	1, 722 kWh	378.5 kg
FC5	45	1, 949	-1,912 kWh	530 kWh	146.5 kg
FC6	91	1, 324	-1,394 kWh	566 kWh	80.2 kg
FC7	25	556	-573 kWh	311 kWh	11.2 kg

Table 2 - Summary of Energy Data Collected from Telematics

Analysis for Emissions Reduction Estimate - CSE

The CSE was tasked to analyze and estimate the emissions reduction rate with data support from Frontier Energy for the FTFC Project as part of a CARB grant. For the purpose of this analysis truck FC4 was selected as the data quality and operating profile from that truck was deemed the best candidate for representative analysis at the time. This analysis represents a CO2e emissions reduction of about 70.8% for FC4 that was field tested and compared to a similar diesel-powered combination short-haul truck. Truck performance data was collected and analyzed for over 1,800 miles of travel across twenty-one days including electric energy consumed from the grid and hydrogen (H2) consumed by the onboard fuel cell. It's abundantly clear that there is a significant emissions advantage to this hybrid truck over a standard diesel truck and as explained in the Analysis Results section of this report, there is a varying fuel economy based on which system is prioritized within FC4. Detailed methodology is shown in the Appendices in the section "Deliverable 3.5 Analysis for Estimation of Emissions Rate". Another important takeaway from this analysis is by shifting charging start times from a 3pm start to a 9pm start, an additional reduction of 42.4% in lbs CO2e emissions can be realized for associated electric consumption. This is due to the fact that starting the charging session at 3pm will likely continue charging through the evening peak demand and CO2 emissions associated with the electricity supplied by the grid in California (ref. Figure 23). Starting the charging session at 9pm will avoid the 8pm peak and continue through the night when the CO2 emissions the declining.

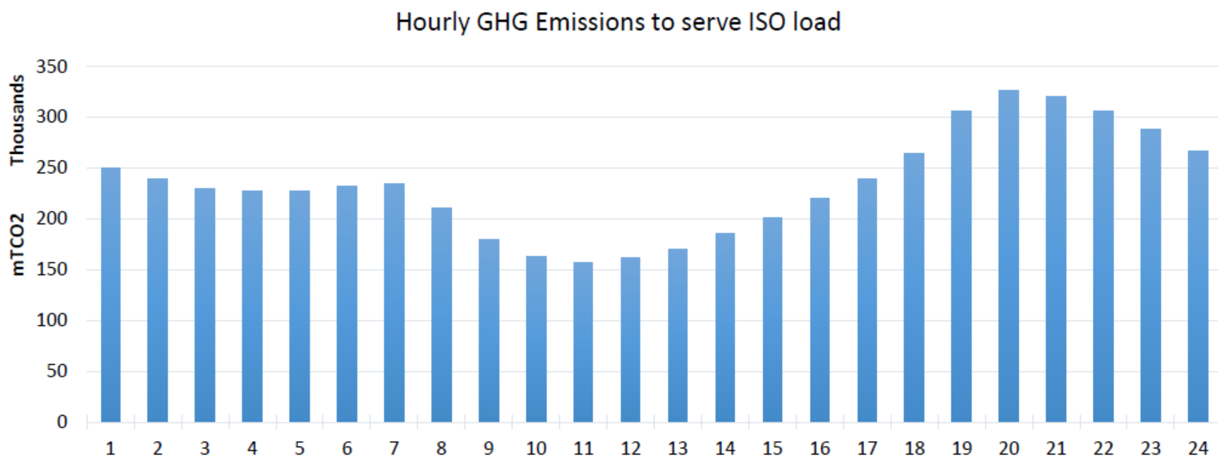

Figure 23 - Total hourly GHG emissions to serve California electrical grid. This figure reflects the hourly sum of GHG emissions serving grid load for the month of August 2021[2]

The main results of this analysis are highlighted in Table 3 below.

Miles Driven	**1,839 Miles (21 Trips)**
Grid Energy Consumed	1,251 kWh
Hydrogen Consumed	58.4 kg
Grid Energy Emissions	1,230.0 lbs CO2e (41.6%)
Hydrogen Emissions	1,724.7 lbs CO2e (58.4%)
Total Elec + H2 Emissions	2,954.7 lbs CO2e
Grid Energy Fuel Economy	0.67 lbs CO2e per Mile
Hydrogen Fuel Economy	0.94 lbs CO2e per Mile[3]
Total Elec + H2 Fuel Economy	1.61 lbs CO2e per Mile
Diesel Fuel Consumed	339.6 Gallons
Diesel Fuel Emissions	10,113.3 lbs CO2e
Diesel Fuel Economy	5.5 CO2e per Mile
Total CO2e Reduction	7,158.6 lbs CO2e (70.8%)
Total Fuel Economy Reduction	3.89 lbs CO2e per Mile

Table 3 - Comparative Analysis Results for All Testing Trip Performance

[2] http://www.caiso.com/Documents/GreenhouseGasEmissions-TrackingReport-Aug2021.pdf
[3] Based on total hydrogen consumed (first six trips only) divided by total miles (all twenty-one trips)

The team had additional plans of collecting driver feedback via mobile app developed by Frontier, however it was never used due to limited commercial operation of the vehicles. The mobile app was intended to capture the overall driver experience with the vehicle that day along with a high level overview of road conditions and any issues encountered.

Frontier attempted to survey the drivers at TTSI and TransPower to measure the expectations associated with the zero-emission vehicles for the first-time operators, however both organizations had drivers already experienced with Zero Emission Vehicles, therefore the survey was abandoned.

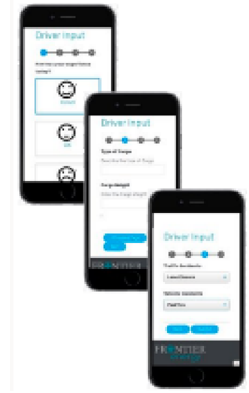

Figure 24 - Frontier Mobile Driver Feedback

Outreach

CSE has performed several tasks with a goal of educating the stakeholders about the benefits of Zero-Emission Vehicles.

The first task was preparation of materials explaining the fuel-cell technology, benefits and career opportunities associated with the new technologies. These materials, shown below in Figure 25, were used later in interactions with the communities and stakeholders.

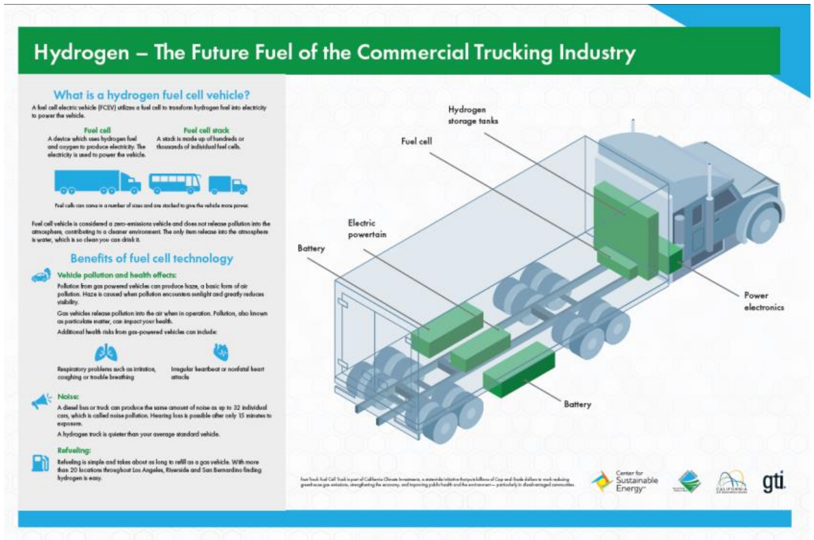

Figure 25 – Outreach Brochures

CSE has conducted two educational workshops in December of 2019: at Mt. San Jacinto Community College Automotive Department (audience of 35-40) and at Santa Rosa Academy Automotive Department (audience of 20-30). Details of the workshops are provided in the Appendix in Deliverable 3.4 Workshop for Local Education CSE.

Shortly after the educational workshops COVID-19 outbreak stopped any outreach activities as the communities and the team were struggling with the quarantine and social distancing requirements. No outreach activities have been performed through 2020, but by Q2 2021 the team started planning work with Community Based Organizations (CBOs) to address the questions and concerns from the residents of areas affected by the freight and port operations. The ebbs and flows of COVID-19 variants have been delaying public event schedules, and by Q3 the team started working on remote listening sessions.
CSE conducted the listening sessions on February 15 and 17, 2022.

Listening sessions

The CSE was tasked to conduct community outreach and education to the most impacted by heavy duty diesel pollution for the FTFC project as part of a CARB grant. These communities are impacted heavily by pollution from the ports / warehouses traffic. Due to the COVID-19 pandemic, CSE was limited by the rules set forth by California Department of Public Health and was unable to conduct any in-person outreach to the community for the duration of the project.

After consulting with our project partners GTI Energy and Frontier Energy, we decided to take a more targeted approach and gather community feedback from the communities. By working with two different CBO’s, CSE was able to conduct two listening sessions with community members from Wilmington and San Bernardino. The main conclusions are summaries in the following:

- Most community members mentioned the **poor air quality in their community**, and they know someone whose **health was impacted by the poor air quality**.
- Community members citing **big rig traffic**, **warehouse buildings**, **ports**, and **refinery** as the four main cause of bad local air quality
- While the community members might be not fully aware with zero emission technology (electric or hydrogen vehicles), all of them identified **zero emission vehicles** as a **key component** to improve the air quality in their community.
- Another key takeaway is not only do most participants want **more education on zero emission technology** in their communities, more importantly they want to see more **programs** and **policies** being **implemented in their communities** to reduce air pollution right now.

The team had also planned a stakeholder workshop in Escondido area involving local fleets, businesses and chamber of commerce, however Omicron variant of COVID-19 forced the team to change the workshop to a virtual format. The workshop was held on February 22, 2022 and was attended by 20 participants out of 28 registered participants.

Results and Discussions

The project was one of the first at the time to attempt the design, build and demonstration of Class 8 hydrogen fuel cell trucks at this scale. The team was well aware of the technology challenges and had a robust plan with a roster of experts with decades of experience working with novel transportation technologies. Although the team was not able to accomplish the objectives as planned, there are numerous lessons that have been learned from the project.

Cost discussion:

The team set out to build five fuel-cell plug-in hybrid vehicles at $1M each, which was unprecedented at the time (and still is to certain extent). 5 years later, “commercially available” fuel cell Class-8 vehicles bear $0.75M-$1M cost, and prototype vehicles are expected to cost in excess of $2M. As all major component and vehicle manufacturers have been working on developing high-volume designs and manufacturing capabilities of electrified powertrains, it is anticipated that the economy of scale and competition will drive the cost down, eventually.

According to National Renewable Energy Lab (NREL) Total Cost of Ownership (TCO) study[4] Fuel Cell Trucks could be cost-competitive with diesel trucks if the 2025 technology scenario assumptions of $258,000 vehicle purchase costs are achieved and hydrogen fuel prices are $4/kg. The team believes that successful execution of this project has contributed to the advancement of technology towards achieving the NREL projections. It should be noted that even if the $258,000 vehicle cost is achieved, it will be twice as expensive as a conventional diesel truck, and will require financial incentives for the commercial fleet operators to adopt them as operational assets.

Design discussion:

Upon initial project conception and scoping, the team set out to utilize existing battery-dominant (plug-in) based test platforms (previously tested reliable technology) to reduce risk and focus on hydrogen fuel cell integration as a form of range extender. Considerations included: available technology at that time, known drayage application duty cycle, peak APU output, and the trade off between the on-vehicle energy storage capacity (electrical vs hydrogen).

In addition to APU and regenerative energy, the vehicle will also use grid power to charge the batteries via an onboard charger. Utilization of this option during vehicle down time, either as overnight or opportunistic charging, would allow for maximum range for the subsequent use. For the near dock and intermediate drayage duty cycles considered for the project (traveling to areas as shown in Figure 26), this combined functionality was expected to provide a full day of usage with one fill up in between shifts.

In the 5 years since the project inception, the industry has made a significant progress in developing fuel cells with higher output (in 100kW and higher), which can be configured in pairs to provide adequate electrical output for fuel cell-dominant configuration, as found in passenger vehicles such as Toyota Mirai or Honda Clarity. Fuel cell-dominant heavy-duty vehicles are expected to be the next step in evolution of zero-emission heavy-duty transportation technology, and manufacturers such as Hino, Hyundai or Symbio are in the early stages of demonstrating Class 8 trucks with combined fuel cell output of 250kW and higher.

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[4] NREL/TP-5400-71796 September 2021, Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks

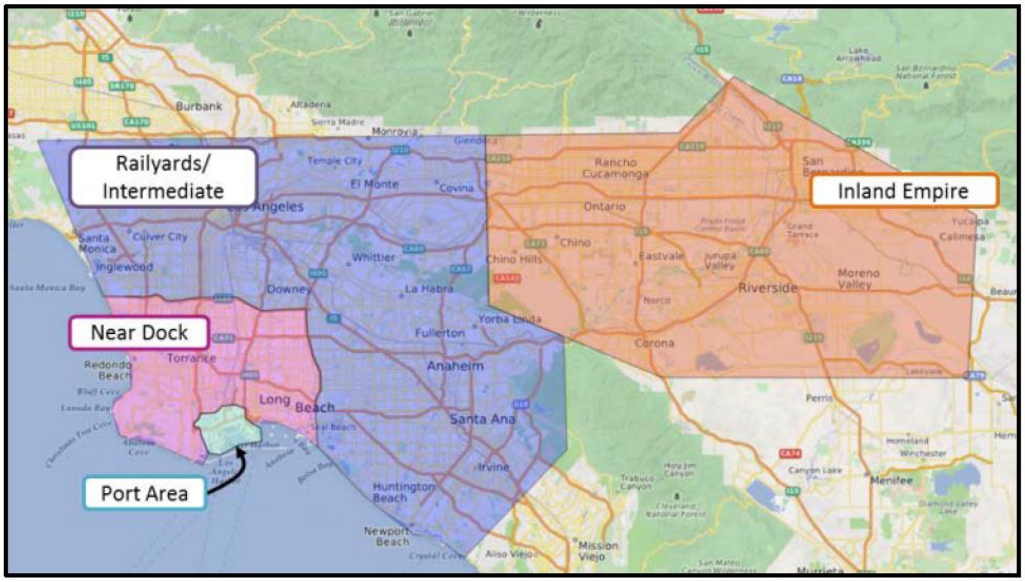

Figure 26 - Drayage Truck Operating Areas

Drivetrain

Tandem electric motors were paired up with a conventional semiautomatic transmission, driveshaft, and tandem axle. This, due to technology constraints at the time, proved to be a technical issue that consumed significant amount of time and resources taken away from the primary objectives of the project. Multiple issues arose with transmission control and vehicle Noise Vibration and Harshness (NVH) due to motor to transmission alignment, driveline alignment, driveshaft balancing and control resonances between the tandem electric motors and inverters. Technology advances from the onset of this project virtually eliminate the powertrain integration issues encountered with the introduction of e-axles.

E-axles provide multiple benefits to EV and hybrid fuel cell-electric vehicles which may assist with widespread industry adoption. Benefits include higher efficiency in power transfer by elimination of conventional gearboxes, integrated power electronics and controls offering reduced complexity and packaging space requirements, improved NVH, and improved reliability over conventional powertrains.

Energy Storage

Total vehicle energy storage targets are set from the end users duty cycle and range expectations for that given application. For traditional fuels like diesel, the considerations are more straight forward they are limited to the total efficiency of the powertrain and size of fuel tank. For a dual energy / fuel like the plug-in hybrid fuel cell-electric vehicles, tradeoffs between the capacities of battery and Hydrogen storage as well as fueling (charging) speeds must be made and looked at carefully to ensure the customer's operational requirements are met. For this drayage application, the team opted for a total gross storage of approximately 1285 kWh onboard (220 kWh battery + 1065 kWh H2[5]) based on the analysis performed to meet the requested 400 mile daily range with one re-fueling event. For the battery solution, the team chose the best in class commercially-available technology at the time, Nissan leaf-based air-cooled Nickel Manganese Cobalt (NMC). The contemplated duty cycle for the vehicle was drayage truck port cycle, where the vehicles would operate in Port Area and Near Dock, with excursions into the Railyards/Intermediate regions as identified in the map developed by NREL[6] as shown in Figure 26.

The batteries, although air cooled, were expected to have enough thermal capacity to adequately handle the low power demands of Port Area and Near Dock, with fuel cells supplying most of the power required for tractive effort and maintaining battery state of charge. However, it became evident that the fleets were very eager to utilize the trucks on longer trips, beyond the Railyards/Intermediate area and into the Inland Empire, which proved to be a challenge for the selected technology. High-speed operation (60mph+) of the vehicles required more power than was available from the fuel cells, which was putting more stress on battery storage and exposing thermal management limitations of the battery packs. The problem was exacerbated by fuel cells being limited in output due to other issues, resulting with deteriorated vehicle performance and range. The team anticipates that a reliable 100kW+ fuel cell power source would have avoided the issue, and when coupled with liquid-cooled battery system, would provide a reliable solution for POLA to Inland Empire trips. The industry has also seen a shift from NMC to Lithium Iron Phosphate (LFP) batteries, which although heavier, offer lower cost and more robust operation.

The hydrogen storage of 32kg is deemed adequate for the application and the fuel system has proven to be trouble-free and reliable.

Performance, efficiency discussion:

Despite the lack of revenue service, the data collected from limited milage the fleet accumulated (~16,000 miles) the overall performance and efficiency of the vehicles has been strongly demonstrated. With the estimated 70% reduction in CO2e based on FC4 vehicle data and relatively low technology based hardware issues. The team was not able to interview the commercial fleet drivers from TTSI, however an extensive feedback has been received from TransPower’s test drivers. The drivers listed the following factors differentiating the vehicles from conventional diesel trucks: better acceleration, lower noise and vibration, improved comfort and lack of exhaust odor.

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[5] Equivalent of 32kg of hydrogen with 33.3 kWh/kg energy content

[6] https://www.nrel.gov/docs/fy16osti/66649.pdf

Route data from FC3, FC4, and FC6 was analyzed for overall vehicle efficiency, but due to data integrity issues the reported results are kept to what was deemed reliable and representative (for example vehicles FC5 and FC7 have not reported reliable data or duty cycles, numerous trips were performed in battery-only mode due to operator errors or fuel unavailability). Vehicle efficiency (kWh/mile) must not be taken as absolute as the data sampling rate was insufficient too accurately determine the tractive and regenerative work. The kWh/mile data presented below in Figure 27 and Table 4 are purely based on the energy consumption from the change in the SOC and the measured FC output, it does not factor in the regenerative braking energy that was recouped and consumed which artificially increases the vehicles efficiency (lowers kWh/mile value). Multiple days for each vehicle were processed manually to account for lapses in data and intermittent fueling events (plug-in charging and hydrogen fills). Similarly, payload information was not available therefore the team was not able to assess the sensitivity to combined vehicle weight. Figure 27 below shows the estimated kWh/mile, calculated Miles per Kg and average speed for each of the runs analyzed. As mentioned above, the vehicle load is not known so no correlation between average speed and H2 consumption can be determined.

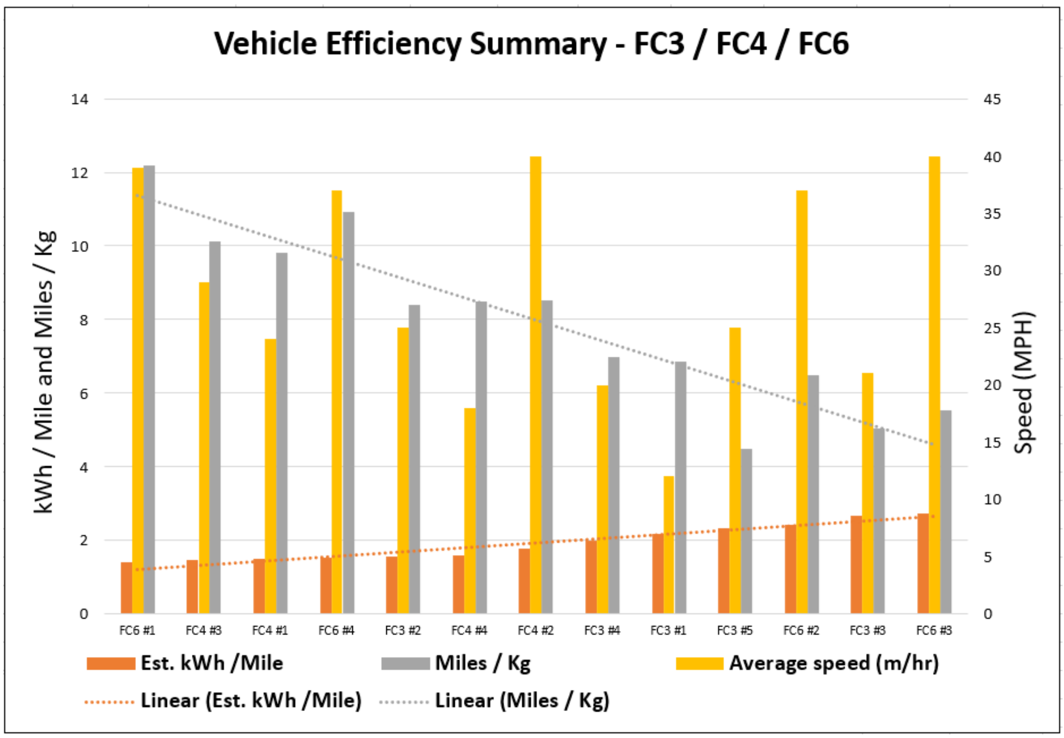

Figure 27 - FC3 / FC4 / FC6 Performance Summary

Vehicle	Miles Driven	Est. kWh /Mile	Miles / Kg	Average speed (m/hr)
FC6 #1	147	1.4	12	39
FC4 #3	213	1.5	10	29
FC4 #1	209	1.5	10	24
FC6 #4	101	1.5	11	37
FC3 #2	53	1.5	8	25
FC4 #4	128	1.6	9	18
FC4 #2	97	1.8	9	40
FC3 #4	79	2.0	7	20
FC3 #1	10	2.2	7	12
FC3 #5	66	2.3	4	25
FC6 #2	133	2.4	7	37
FC3 #3	38	2.7	5	21
FC6 #3	65	2.7	6	40
AVERAGE	135	1.5	10	30

Table 4 Performance Analysis Summary

FC3 operation was limited to in port and near port usage for average trip lengths of 50 miles with the longest of 80. Examples of both routes are shown below. Since FC3 was the only vehicle operated in revenue service, these routes and data are deemed the most representative of drayage operation. The average fuel economy for the 246 miles of operation analyzed was **6.31 Miles / Kg H2**.

The routes were limited to port and near-port operations as shown in figure 28 and 29 below, characterized by low speeds and long idle times, therefore the fuel economy appears lower than data from FC4 and FC6. TTSI has expressed interest in operating the trucks on longer routes extending into Inland Empire, requiring more high-speed freeway operation, however technical issues and fuel unavailability prevented these runs at the time.

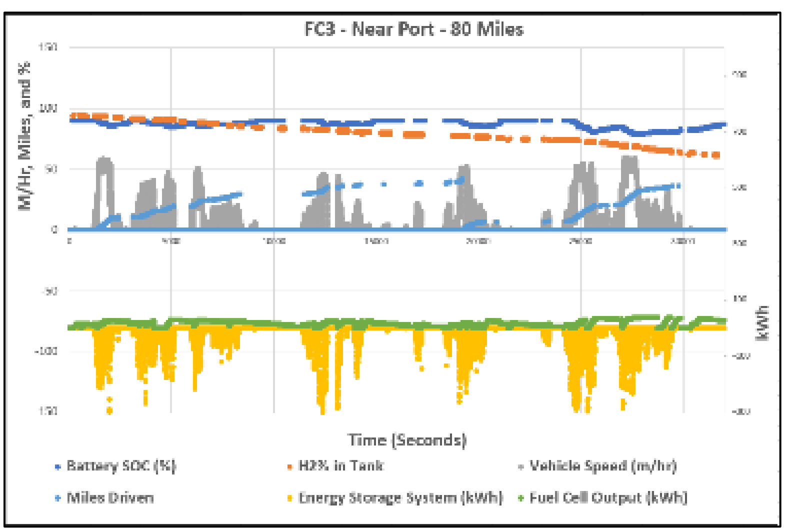

Figure 30 - FC3 Near Port Data Set Example

Figure 29 - FC3 In Port Usage

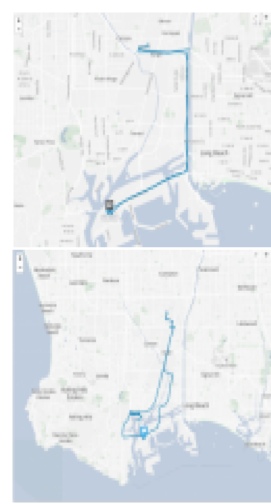

Figure 28 - FC3 Near Port Usage

Trucks FC4 and FC6 were tested by TransPower out of their Escondido facility and focused on evaluating the capabilities on routes including freeway operation. Both trucks were running mostly regional routes allowing for average trips of over 100 miles to be analyzed at a time with the longest trip being 213 miles. Based on those longer runs and assessment of onboard energy usage the team is confident the trucks were capable of 300-mile range. Examples of these routes are shown below in figures 31 and 33. The averaged efficiency for the 647 Miles of operation analyzed for FC4 was **9.46 Miles / Kg H2** while FC6 operated at an average of **9.23 Miles / Kg H2** for the 445 miles analyzed miles. The above efficiency offers 260 mile range on hydrogen alone (28kg usable onboard hydrogen x 9.3 miles/kg) plus 75-mile battery-only range (150kWh usable battery / 2kWh/mile).

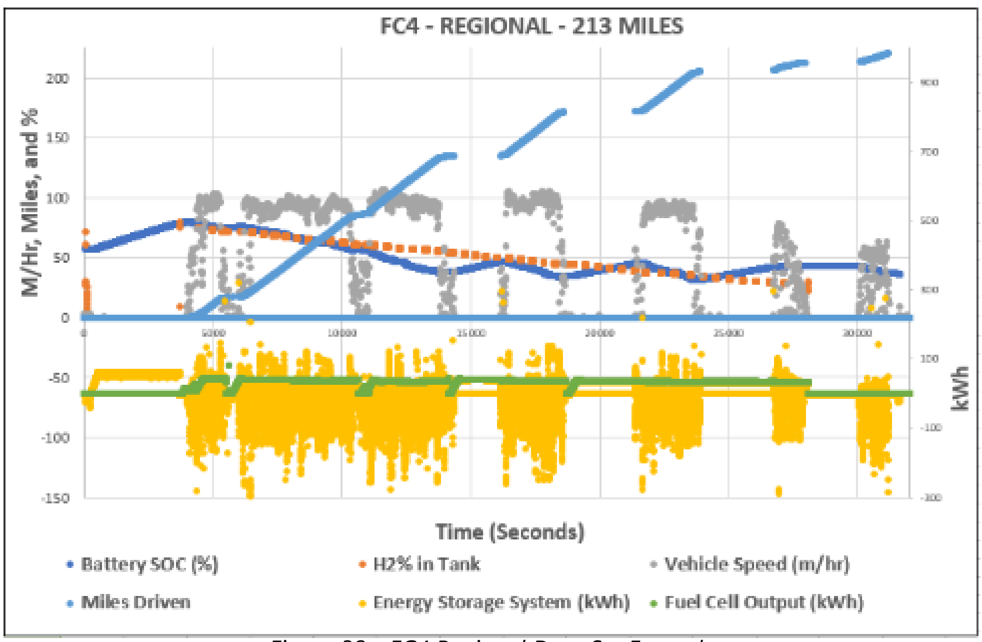

Figure 32 - FC4 Regional Data Set Example

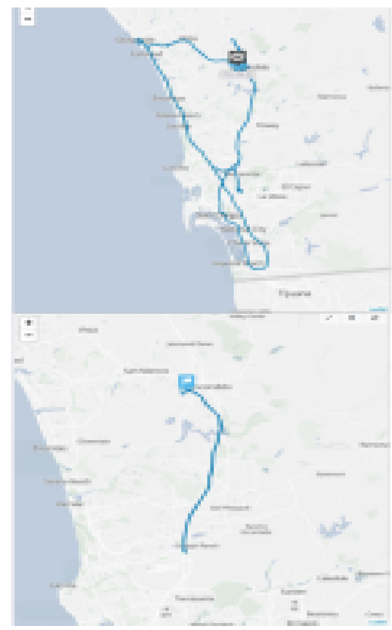

Figure 31 - FC4 Map of Regional Operation

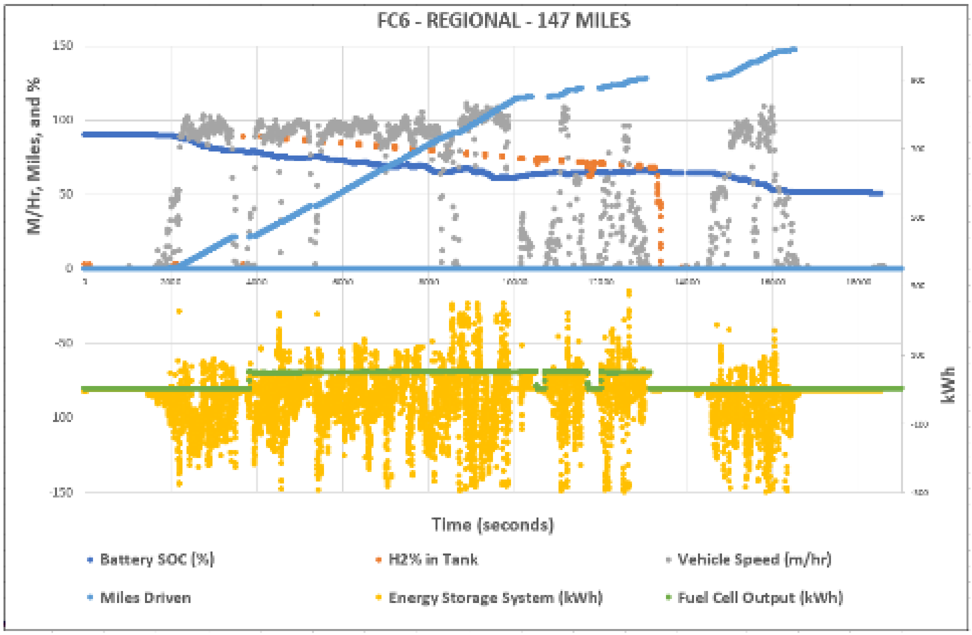

Figure 37 - FC6 Regional Data Set Example

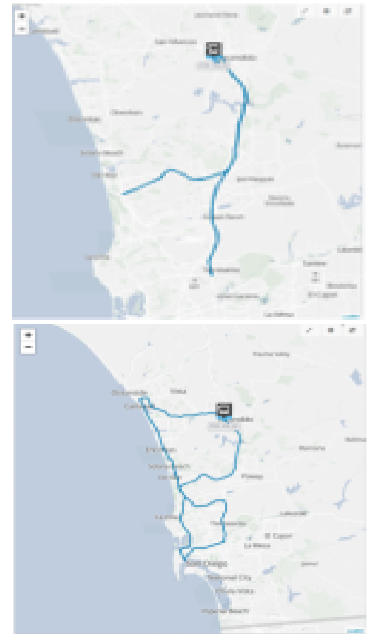

Figure 35 - FC6 Map of Regional Operation

Reliability discussion:

In order to accurately convey the overall reliability of the vehicles, it would be prudent to break down the vehicle into the following systems to look at what issues were a result of conventional technology, adaptation of new technology, or the new technology itself.

Powertrain system - Consisting of 2x160kW (tandem) electric motors, conventional semi-automatic transmission, and tandem axles. Technology Integration issues encountered were misalignment of the electric motor to the conventional transmission causing drivetrain vibration / driver dissatisfaction and shift quality issues due to inverter software and calibration. This was a plaguing issue with units FC3, FC4, and FC5 throughout testing. The use of now commercially available e-axles will eliminate these issues for future projects.

Cooling system – Consisting of electric water pumps and conventional type radiators for cooling of the Fuel Cells. Conventional issues consisted of a cracked radiator and a leaking coolant drain plug both resulting in loss of coolant.

Controls system – Software and controls integration for Hydrogen fuel cell, powertrain, and vehicle communication. One of the most complex technology aspects which has proven to be an area of continuous improvement and numerous delays. Complex interactions between the fuel cells, electric accessories, traction motors, transmission, energy storage system require significant design, coding and validation effort. While "soft" issues are typically reported as nuisance rather than hardware failures, they should be considered a major factor in vehicle design.

High Voltage (HV) system- consisting of batteries, cables, and inverter. Issues encountered included inadequate grounding methods, isolation faults, battery strings “dropping out”, inverter firmware/software, and thermal limitations of the battery cells.

High Pressure Hydrogen fuel system– consisting of storage tanks, tubing, and all valving. Technology Integration issues encountered were multiple false positives from Hydrogen detection sensor used to detect any leaks. This was due to moisture buildup and reading prior to sensor heating up. No other issues were noted with the hydrogen storage, tubing or delivery system.

Hydrogen fuel Cell- Consisting of Fuel Cell and controller. Technology issues encountered were multiple failures of the Hydrogen Recirculation Pump (x8), Fuel Cell leaking coolant (x2), failure of flow sensor (x2), failure of circuit boards (x2), failure of Cathode Blower (x2), multiple Cell rebuilds required (x6), and Fuel Cell coolant contamination causing high conductivity and shutdown was also encountered.

Vehicle Chassis- Consisting of all conventional vehicle chassis components, suspension, etc. No issues encountered

Electric Accessories - Consisting of electric power steering, air compressor and air conditioner. No issues encountered.

Infrastructure and fueling:

Fueling and infrastructure availability / reliability have been long recognized as barriers to a widespread adoption of alternative fuel vehicles such as Compressed Natural Gas (CNG) in the past. Most of the publicly accessible hydrogen stations in California are designed for, and primarily service light duty (passenger) vehicles such as Toyota Mirai, Honda Clarity or Hyundai Nexo. The stations, although often offering both 350 bar fuel supply typical to heavy duty vehicles and 700 bar supply for passenger cars, are not truck-friendly due to narrow lanes, tight turns and limited space.

Figure 38 - Examples of Light-Duty and Heavy-Duty Hydrogen Fueling Stations

The team has encountered situations where 350 bar fuel was turned off to prioritize the hydrogen supply for passenger cars, or the 350 bar fuel availability was limited due to the technical constraints of the station design (compressor size, onsite storage capacity). Since the project inception, thanks to funding from the state agencies, several dedicated heavy-duty stations have been in development, however they were either not ready or too far from the test routes.

The project team has frequently encountered stations out of service due to technical issues or lack of hydrogen, which limited the team's ability to operate the vehicles. It is expected that this type of situation will be a major barrier for commercial fleets to adopt fuel cell vehicles and more investment is needed in developing the fueling infrastructure, so it is reliable and accessible to heavy duty vehicles.

Another potential barrier to adoption observed by the team is a lack of heavy duty fueling standard. The team had received anecdotal reports of incompatible fueling nozzles and inconsistent fueling times at the heavy-duty stations. While the 700 bar (light duty) fueling protocol and nozzle are well defined and standardized by global standard organizations, the 350 bar fueling lacks a unified protocol and nozzles. There are ongoing global efforts to develop and standardized a high-flow fueling protocol for heavy duty vehicles, but the work is still in progress.

In light of the public infrastructure limitations, a temporary onsite fueler is an attractive solution for fleets that seek to deploy the hydrogen-powered vehicles. A fueler typically consists of multiple hydrogen storage tanks housed in an enclosure, often trailer-mounted for mobility (aka. "tube trailer"), along with associated tubing, valves, regulators and safety devices. A dispensing device can be either integrated or separate from the storage module. This solution can be deployed with minimal site work, does not require onsite compressor or cooling, improving reliability and cost of operation. The tradeoffs include: slower flowrates due to thermodynamic limitations of the hydrogen tanks onboard the vehicle and incomplete vehicle fills when the onsite storage is depleted (for example: if the fueler is depleted to 60%, the truck can be filled only to 60%).

Figure 40 - Examples of Temporary and Mobile Hydrogen Fuelers

Currently, majority of hydrogen stations rely on delivery of liquified or compressed hydrogen to site via tanker, rather than producing it onsite. Also, the production and delivery of hydrogen to the majority of stations in California is supplied by a few major producers. This presents certain risks to the robustness of supply chain – as experienced by the project team, an explosion at AirProducts facility has caused a long-lasting disruption to the hydrogen supply chain across the state for months. From early June to early October 2019, the plant that is the source of hydrogen fuel for most Northern California stations went offline. This disruption resulted in limited hydrogen supply and led to several Northern California stations temporarily closing because of lack of fuel.[7]

Moreover, the reliability of stations has been rather intermittent, usually due to equipment failures, such as compressors, chillers, point-of-sale or network issues. To manage the day-to-day fueling, drivers of fuel-cell vehicles have been extensively using online Station Operational Status System (SOSS)[8] developed and maintained by California Fuel Cell Partnership (CaFCP). The website offers near real-time information about station status and hydrogen amount available, helping drivers avoid inoperative stations. Again, the project team largely relied on hydrogen station in Del Mar, and the SOSS system proved to be a valuable resource in planning truck testing.

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[7] https://www.energy.ca.gov/sites/default/files/2021-05/CEC-600-2019-039.pdf

[8] Stations Map | California Fuel Cell Partnership (cafcp.org)

Another lesson learned by the team was a challenge associated with obtaining a permit for installing a hydrogen fueling equipment. The team had planned to deploy a hydrogen fueler at a partner fleet depot, and the permitting process proved to be quite extensive. While the fueler is not necessarily technically complex, presence of hydrogen and general lack of experience with hydrogen by municipal building inspectors and fire marshals makes the permitting process very lengthy. The team has found that the Authorities Having Jurisdiction (AHJs) require certain amount of education to understand the risks and safety requirements of hydrogen and hydrogen-handling equipment, oftentimes prolonging the permitting process. Since the building departments and fire marshals are unique to each municipality, the process varies city-to-city, adding uncertainty to future deployments. A unified permitting guidelines / process across the state would contribute to lowering the barriers to wider adoption of hydrogen as a fuel.

Future Application and Evolution of the Technologies

The team anticipates the following technologies to see significant progress in the next decade:

High-output fuel cells. Class 8 diesel trucks typically utilize engines with output of 350-550hp (260-410 kW). With fuel cells matching this output, the battery storage can be reduced, reclaiming payload capacity lost to the batteries, which can be as much as 7,500 lbs. The challenges will involve development of high-density fuel cell modules, demonstrating the durability expected of a Class 8 vehicle (25,000 hours or 1,000,000 miles), and designing cooling systems capable of managing thermal needs of fuel cells. Both Department of Energy and California Energy Commission regularly offer funding to support the development of next generation of fuel cells.

Increased onboard hydrogen capacity. The current de-facto standard for heavy duty vehicles is 350 bar storage developed for early hydrogen fuel-cell transit buses. 350 bar system, although more cost effective, is limited by fueling flowrates (up to approximately 2kg/minute, depending on ambient conditions and nozzle type) and requires high volume of tanks. Several heavy-duty manufacturers, such as Hyundai, Hino or Symbio have been introducing 700 bar systems evolved from light-duty applications and scaled-up for heavy duty market. 700 bar storage offers 67% more energy storage at the same volume, however the fueling station supporting 700 bar trucks is more complex and expensive to build, as it requires dedicated compression, storage and -40F cooling system. A heavy-duty high-flow filling standard with a flowrate target of 10kg/minute has been in development by a global consortium for a number of years and is expected to reach commercialization stages in 2022-2023 timeframe. The researchers expect the next generation of fuel-cell trucks to introduce demonstrations of 700-bar systems with capacity of approx. 60-70kg, which should offer a range of 500 miles, enabling demonstrations in regional and long-haul duty cycles. A further evolution of the hydrogen storage technologies will introduce cryogenic liquified hydrogen (LH2) offering almost twice the density of 700 bar system, however the applications will be limited to vehicles with continuous, high duty operation. The cryogenic hydrogen is stored at -423F and slowly boils off when not used, therefore it is recommended that the vehicle does not have long dwell times and is refueled frequently. Although transport and fueling of LH2 offer benefits of higher density, easier transport and faster fueling times, the liquefication process is very energy intensive.

Integrated electric powertrain and accessories. Early demonstrations and pre-commercial vehicles have utilized electrified, conventional truck powertrain and drivetrain components, which required a number of compromises and additional interfaces (for example electric motors mated to conventional tandem axle through a conventional transmission). The power electronics, electrified accessories (power steering, air conditioning, air compressor) and control systems were partially integrated, adding complexity and potential failure points. In the last couple of years, the axle manufacturers have begun to offer e-axles where the electric motor, reduction gear and power electronics are integrated into a single unit, reducing complexity, weight and integration time. It is expected that the market will follow with integrated electric accessories and control systems, reducing the cost and complexity, and improving efficiency of these components, often considered as “parasitic”. Furthermore, the researchers expect the industry to keep evolving current hydraulic systems used by vocational trucks, such as cement mixers or waste trucks, to improve the overall system efficiency. This technology evolution will enable zero-emission applications in vocational, off-road, construction and agricultural markets, that rely heavily on hydraulic Power Take-Off (PTO) implements and accessories.

Dedicated tires. Electric vehicles have been reported to wear tires twice as fast as conventional vehicles, unclear whether due to increased weight, torque of electric motors, or both. Tire manufacturers have been developing tires with construction and rubber compounds optimized for the vehicles, with the expected benefit of improved operating cost, lower particulate pollution from tire dust, and up to 5% energy efficiency improvement. The researchers expect to see the evaluations and introductions of these tires in the upcoming years.

Electric powertrain technology improvements. Due to the changing geopolitical situation, the industry has seen a push to reduce the utilization of rare earth metals used in electric motors. Similarly, research and development on improving efficiency of power electronics such as inverters and Direct Current Converters (DC-DC Converters) is ongoing and the researchers expect to see the next generations of these components in demonstrations soon.

Truck skateboard chassis. As successfully demonstrated in the light duty segment, electric powertrains enabled redesign of the vehicle chassis (floor, frame, suspension) away from body-on-frame or unibody, to body-on-skateboard platform, where batteries and other components form a structural floor instead of taking volume away from the cab or payload. It is expected that some truck manufacturers will begin evaluating such architecture, which can be enabled by utilization of integrated e-axles and departure from longitudinal powertrain (engine – transmission – driveshaft – axle) that effectively required the frame and inter-frame space dedicated to the powertrain components. The benefits of body-on-skateboard platform include better component packaging, lower center of gravity and improved aerodynamics, translating to higher efficiency. Development of such platform is a major undertaking and can take 5-7 years, before it reaches high-volume production capability and 1,000,000 mile reliability.

Conclusions and Future Recommendations

The trucking industry is undergoing an unprecedented disruption fueled by the regulations, incentives, corporate environmental stewardship and revolving energy crises. As a result, the transportation technology has been evolving faster than ever. The researchers have been actively participating in various demonstration projects, holding discussions with fleets, technology manufacturers, energy suppliers and utilities. The following are the opinions of the research team following over 10 years of monitoring the industry.

Early investments and push for battery-electric trucks has began to uncover the limitations of the technology and energy supply (grid constraints, utilities slow to respond). With the focus on range, payload and operation efficiency, the fleets and manufacturers are reconsidering alternative fuels such as hydrogen, asAs such, hydrogen is no longer considered a “science project” or a distraction to decarbonized transportation, but an alternative fuel complementary to the battery-electric technology. North American Council for Freight Efficiency coined the term “Messy Middle” indicating the disruption in the marketplace and stakeholders seeking the best solutions for their needs.

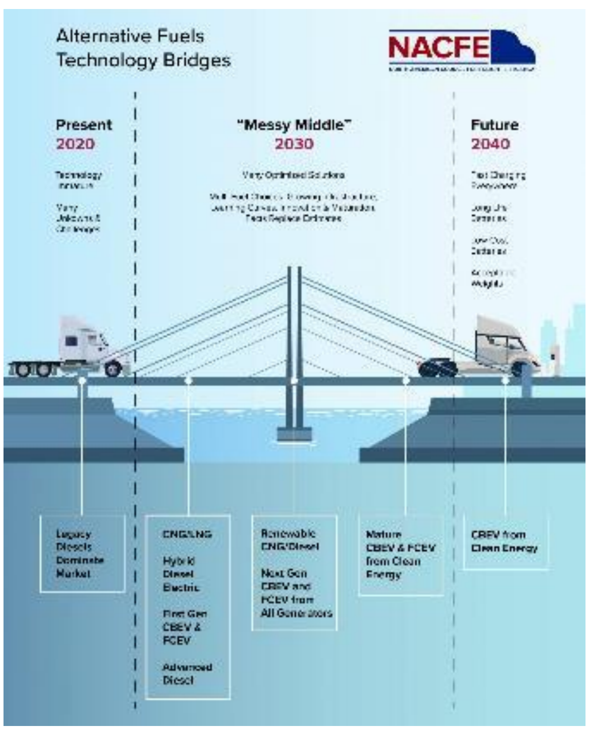

Figure 41 - NACFE "Messy Middle" Infographic[9]

[9] Viable Class 7/8 Electric, Hybrid, and Alternative Fuel Tractors - North American Council for Freight Efficiency (nacfe.org)

It is expected that in the next decade the stakeholders (fleets, energy providers, manufacturers) will converge on several solutions that will be best for their own geographical location, climate, operational needs, fueling infrastructure and total cost of ownership. Likely, battery-electric trucks will perform the best in short-haul, return-to-base and delivery operations, while hydrogen fuel cell trucks will be capable of covering energy-intensive duty cycles, such as high-speed and payload, long haul, or round-the-clock operations that require short fueling times.

Figure 42 - Anticipated Technology Sweet Spots[9]

In closing, the team faced several issues throughout the program which ultimately reduced the amount of miles accumulated in revenue service demonstration. Multiple integration issues (electric motor adaptation to conventional transmission / drive line, calibration, etc.) were the result of hardware selection based on technology that was available at the time. Since then, multiple advances in heavy duty vehicle electrification have been commercialized that offer solutions to the issues seen on this project. In addition to electrified drivetrain improvements, advancements in battery storage and hydrogen fuel cell technology have also been made. Liquid-cooled batteries will enable better battery thermal management control and larger output H2 fuel cells can be utilized to bias more towards a fuel cell-dominant strategy. This could enable a more versatile solution for a broader use in application duty cycles.

A total of 16K miles was accumulated for which 1800 miles of robust data was analyzed and shown to have clear advantage in reduced CO2e emissions by approximately 70% of the diesel equivalent. Although reliability was not demonstrated, the advantages of the technology has been clearly demonstrated to warrant additional studies with focus on the latest generation of hardware and improved data quality. The vehicles, despite the reliability issues and technology limitations, performed on par with diesel counterparts, and were capable of 200-300 mile combined hydrogen/battery range, while offering improved working conditions for the drivers due to the lack of exhaust odor and engine noise/vibration.

The team is of a strong opinion that more demonstrations programs such as the Fast Track Fuel Cell Truck are needed to thoroughly evaluate the efficiency and reliability of all the technology advancements developed in the last 5 years. Robust demonstrations are required to build confidence with commercial fleets, which are very cautious about adopting new technologies with undocumented reliability, as they expect the Class 8 trucks to have a 1,000,000-mile life.

Appendices

Appendix A

Deliverable 3.4 Workshop for Local Education CSE

Appendix A - Deliverable 3.4 Workshop for Local Education CSE

Presentation 1 – December 5, 2019
Location:
Mt. San Jacinto Community College Automotive Department, Room 901
1499 N. State Street
San Jacinto, CA 92583
Automotive Instructor and Department Chair: Robert Pensiero
The presentation was provided by CSE's *Clean Transportation Specialist,* Kevin Wood. Kevin further elaborated on the topics covered on the Fast Track Fuel Cell Project Power Point presentation.

The presentation covered how the fuel cell technologies worked and the importance of reducing air pollution within their communities. Most of the students have a very limited understanding of how internal combustion engines create pollution. However, as the presentation continued, students began to ask additional questions on why we are still using ICE (internal combustion engines) instead of electric or hydrogen vehicles.

Throughout the presentation students became more engaged, along with the professor and his automotive staff. The professors were actively engaged because most of their material was not as up to date as they would have liked. Neither the professor nor class knew much about hydrogen technology. The only thing they really knew about hydrogen was regarding the Hindenburg disaster, which in turn, turned into their first question questioning if hydrogen fuel was dangerous or not.

In speaking with the Department Chair, he stated that he did not have a lot of resources available on fuel cell technologies and was thankful CSE presented these technologies to his class. Robert also mentioned that one of the only known schools outside of traditional ICE automotive programs is Tesla, and Tesla's program only teaches technicians on Tesla vehicles and provides limited education on other electric vehicle manufacturers. He is aware that there are a few schools that that cover clean technologies, but he felt that those programs were still in their infancy. A student also mentioned that her father actually worked for Sunline and stated that he had to go through a comprehensive on the job training process in order to work on their vehicles. In turn, the Sunline employee was in high demand as this was a new technology.

We also spoke with the Education Coordinator for Mt. San Jacinto Community College. She mentioned that the school is interested in incorporating these technologies into their career center curriculum, along with other community colleges across the state.

Overall, the presentation went well and a continued demand to learn more on clean technologies was wanted. The content can include more technical content due to the students being well versed on vehicle mechanics.

Attached are a few pictures from the event:

Kevin Wood, CSE Clean Transportation Specialist (individual in the upper left corner facing the audience in the front, is an ASL interpreter).

The class was packed with about 35-40 students total, eventually standing room only.
Presentation 2- December 6, 2019

Presentation 2 – December 6, 2019
Location:
Santa Rosa Academy
27587 La Piedra Rd,
Menifee CA 92584
Automotive Instructor and Department Chair: Robert Pensiero

The presentation was provided by CSE's *Clean Transportation Specialist,* Kevin Wood. Kevin further elaborated on the topics covered on the Fast Track Fuel Cell Project Power Point presentation.

Santa Rosa Academy is a non-traditional charter school and students are responsible for selecting a career track during their freshman year. The presentation was made to the senior class that were in the engineering track, and teacher, Michael Mays (retired engineer). The class focused on building and creating new technologies along with digital electronics. One student in particular was actually working on a hydrogen vehicle prototype for his end of the year project. The audience was very different from the local community college as they were curious about learning more on clean transportation. Students had a brief understanding of the inner workings of an ICE vehicle, as it was covered at the start of the fall semester. However, their current curriculum did not cover any content on clean transportation.

The students were able to understand the environmental impacts of particulate matter and were very curious as to how their carbon footprint could be reduced. Kevin Wood, CSE's Clean Transportation Specialist did very well with the high school audience and was able to keep them actively engaged. Many students asked about career development and what kind of jobs would be available with their degrees. It was interesting to see how many wanted to be on the cutting edge of technology and were willing to learn more on hydrogen.

Overall Lessons Learned

Initially, the community college students were not as open as the high school students about fuel cell or electric vehicle technologies, due to the current curriculum which only covered internal combustion engines. The community college students seemed fearful of the new technology and thought of it more as a government scam to encourage trucking companies to purchase new vehicles.

However, the high school students were very interested from the beginning and were interested in how their education goals could be tied into training opportunities.

Overall the presentations went well including the time spent with the community college students. There appears to be a continued demand to learn more on clean vehicle technologies. The content should include more technical information because the students are well versed on vehicle mechanics.

Santa Rosa Academy – Grade 12

Introduction by Nicholas Badillo on Hydrogen Technologies

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Appendix B

Deliverable 3.5 Analysis for Estimation of Emissions Rate – CSE

Appendix B - Deliverable 3.5 Analysis for Estimation of Emissions Rate – CSE

Executive Summary

The Center for Sustainable Energy (CSE) was tasked to analyze and estimate the emissions reduction rate with data support from Frontier Energy for the Fast Track Fuel Cell Truck (FTFCT) Project as part of a California Air Resources Board (CARB) grant. This analysis represents a CO2e emissions reduction of about 70.8% for Fuel Cell Truck #4 (FC4) that was field tested and compared to a similar diesel-powered combination short-haul truck. Truck performance data was collected and analyzed for over 1,800 miles of travel across twenty-one days including electric energy consumed from the grid and hydrogen (H2) consumed by the onboard fuel cell. It's abundantly clear that there is a significant emissions advantage to this hybrid truck over a standard diesel truck and as explained in the Analysis Results section of this report, there is a varying fuel economy based on which system is prioritized within FC4. Another important takeaway from this analysis is by shifting charging start times from a 3pm start to a 9pm start, an additional reduction of 42.4% in lbs CO2e emissions can be realized for associated electric consumption. The main results of this analysis are highlighted in the table below.

Miles Driven	**1,839 Miles (21 Trips)**
Grid Energy Consumed	1,251 kWh
Hydrogen Consumed	58.4 kg
Grid Energy Emissions	1,230.0 lbs CO2e (41.6%)
Hydrogen Emissions	1,724.7 lbs CO2e (58.4%)
Total Elec + H2 Emissions	2,954.7 lbs CO2e
Grid Energy Fuel Economy	0.67 lbs CO2e per Mile
Hydrogen Fuel Economy	0.94 lbs CO2e per Mile[10]
Total Elec + H2 Fuel Economy	1.61 lbs CO2e per Mile
Diesel Fuel Consumed	339.6 Gallons
Diesel Fuel Emissions	10,113.3 lbs CO2e
Diesel Fuel Economy	5.5 CO2e per Mile
Total CO2e Reduction	7,158.6 lbs CO2e (70.8%)
Total Fuel Economy Reduction	3.89 lbs CO2e per Mile

Table 5: Comparative Analysis Results for All Testing Trip Performance

Fuel Cell Truck Performance Data

The data provided to CSE for this task included performance data for Fuel Cell Truck #4 (FC4) during the months of June through August of 2021. Onboard metering systems captured several

[10] Based on total hydrogen consumed (first six trips only) divided by total miles (all twenty-one trips)

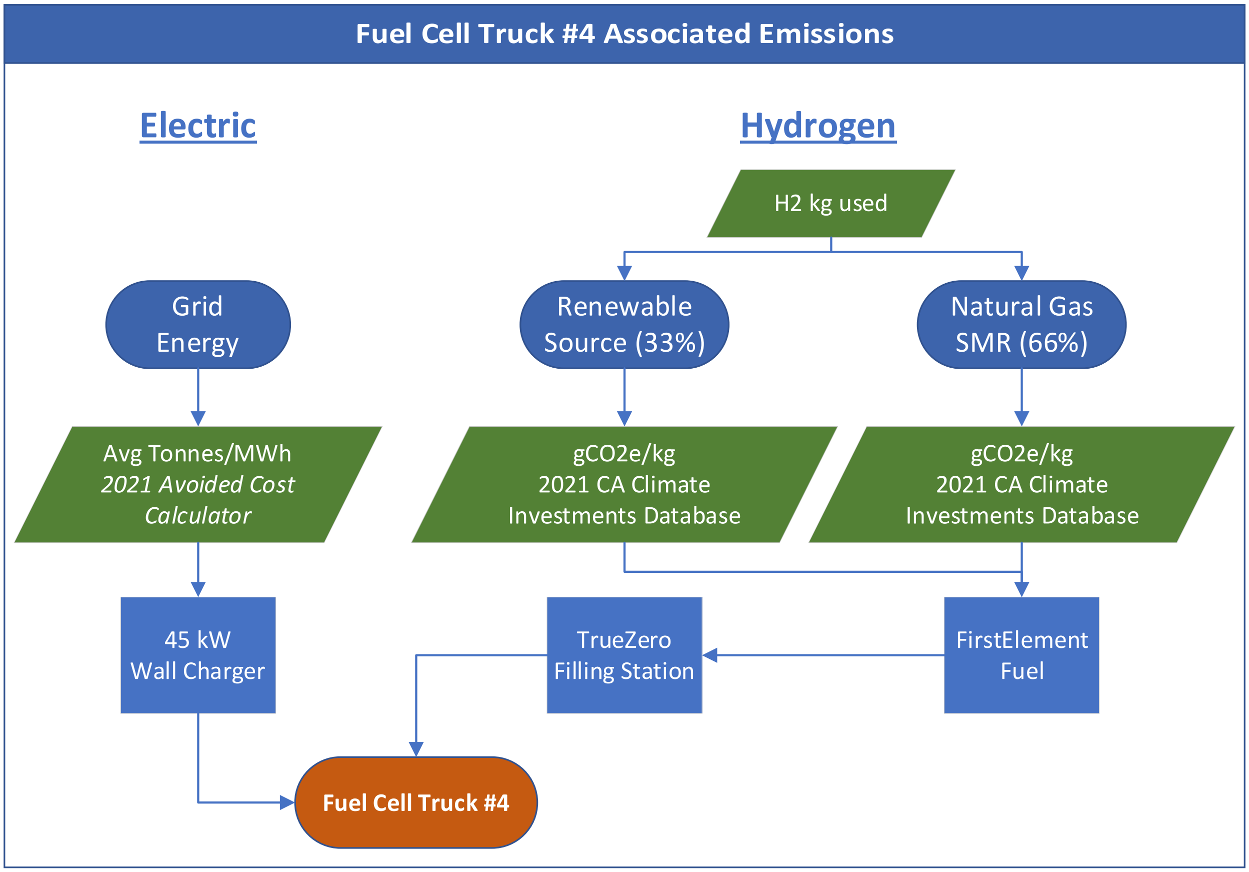
data points such as miles driven, electric energy consumed by the vehicle's battery system, power provided by the fuel cell, hydrogen consumed by the fuel cell and several other points of telemetry. This data was compiled by Frontier Energy into daily averages within an excel spreadsheet and provided to CSE for this analysis. Additional data was made available to CSE, however this analysis focused on estimating emissions with a methodology that is replicable and scalable.

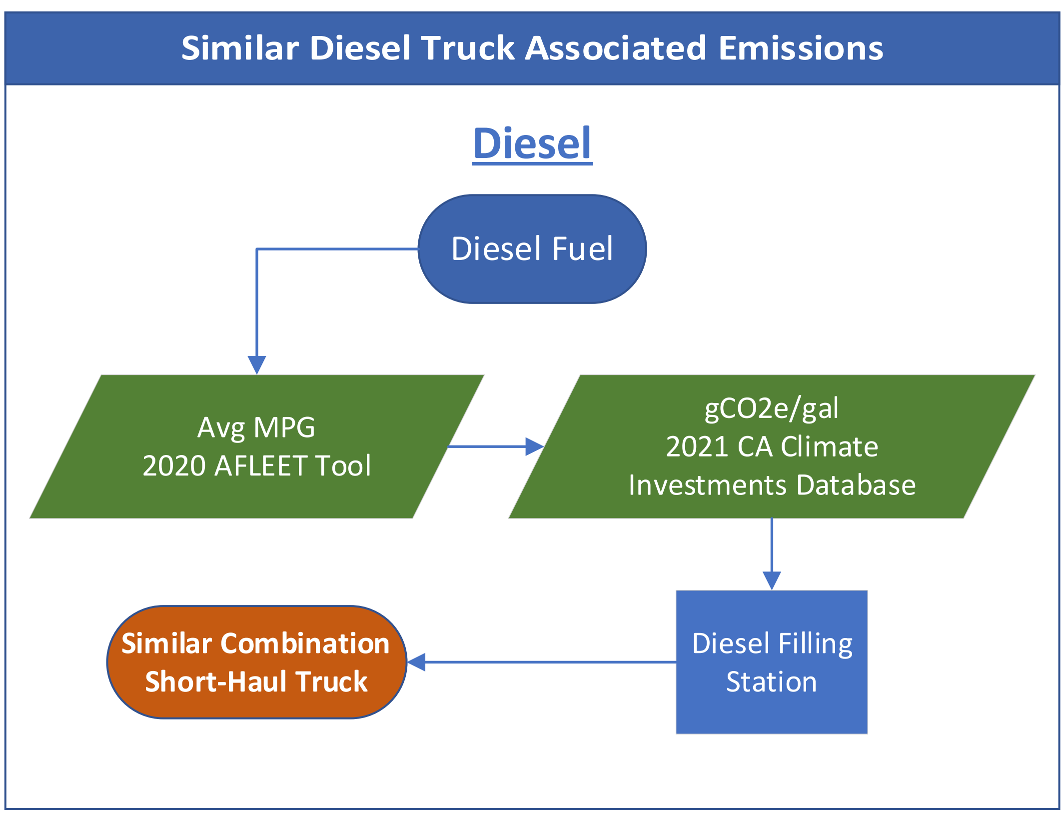
Fuel Cell Truck #4 traveled over 1,800 miles during this time frame, consumed 1,251 kWh of grid electricity and 58.4 kg of hydrogen fuel. This truck operated within San Diego County and utilized the San Diego Gas & Electric (SDG&E) grid for electric charging at it's homebase in Escondido, CA. It was noted that electric vehicle charging from the grid was started each day in the 3pm to 6pm hour, after their daily route. Hydrogen was filled at the True Zero[11] station in Del Mar, which claims 33% renewable hydrogen and supplied by FirstElement Fuel Inc[12].
Methodology

The methodology used for calculating related emissions for the operation of FC4 was a multi-step process using truck performance data provided by Frontier Energy and several trusted industry sources for utility emissions factors. Please refer to Fuel Cell Vehicle vs Diesel associated Emissions figures below.

[11] https://www.truezero.com/

[12] https://www.firstelementfuel.com/


Fuel Cell Truck #4 Associated Emissions
Electric
Hydrogen
H2 kg used
Grid Energy
Renewable Source (33%)
Natural Gas SMR (66%)
Avg Tonnes/MWh
2021 Avoided Cost Calculator
gCO2e/kg
2021 CA Climate Investments Database
gCO2e/kg
2021 CA Climate Investments Database
45 kW Wall Charger
TrueZero Filling Station
FirstElement Fuel
Fuel Cell Truck #4


Similar Diesel Truck Associated Emissions
Diesel
Diesel Fuel
Avg MPG
2020 AFLEET Tool
gCO2e/gal
2021 CA Climate Investments Database
Similar Combination Short-Haul Truck
Diesel Filling Station

The four main steps for evaluating emissions are as follows:

1. Collect all available data points from the Fuel Cell Truck to inform ‘fuel’ consumption
2. Calculate CO2e emissions associated with the electric utility grid charging the vehicle battery
3. Calculate CO2e emissions associated with the hydrogen consumed by the onboard fuel cell
4. Calculate comparable CO2e emissions for a similar diesel truck to identify benefits

The first step was to collect the data points outlined in the Fuel Cell Truck Performance Data section of this report in order to establish two main metrics; grid electric kWh consumed, and kilograms of hydrogen consumed. Grid electric consumed to charge the onboard battery energy system was calculated by taking the total ‘kWh Used’ by FC4 and subtracting the onboard generation sources, ‘kWh Regen’ and ‘H2 kWh’. These two items represent the regenerative braking energy utilized by FC4 and the total electric output from the onboard fuel cell, referred to as the Auxiliary Power Unit (APU). The formula below represents how grid electric kWh consumed was calculated.

Total kWh Used – Regenerative Braking kWh – Fuel Cell kWh = Grid Electric kWh Consumed by FC4

Kilograms of hydrogen consumed by the fuel cell was provided to CSE as a straightforward data point from Frontier Energy for this analysis. These values were calculated using a tank level percent and some applicable gas laws to derive a ‘kilogram of H2 used’ metric.
The second step was to calculate the associated emissions related to the grid energy consumed to charge the vehicle’s battery system, which is used as the main power source for FC4. The Grid Electric kWh Consumed by FC4 daily values were divided by the capacity of the existing charger at 45 kW in order to establish a charging duration. The charging duration will dictate the specific hours of a given day in which FC4 was charging from the grid.

$$\frac{\text{Grid Electric kWh Consumed by FC4}}{\text{Existing Charging Capacity of 45 kW}} = \text{Charging Duration Hours}$$

Hourly emission rates for California were established using the 2021 Avoided Cost Calculator Electric Model[13] prepared by Energy + Environmental Economics (E3). This resource states a Tonnes/MWh emission rate in SDG&E Climate Zone 10[14] (CZ10) for each hour of the year from 2019 through 2050 for use in evaluating distributed energy resource programs in California. The

[13] https://www.ethree.com/public_proceedings/energy-efficiency-calculator/

[14] https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/climate-zone-tool-maps-and

average Tonnes CO2e/MWh rate was calculated for each day based on the Charging Duration Hours and an estimated start time of 3pm, as previously established by Frontier Energy. This average rate was then multiplied by the previously calculated grid electric consumed to obtain Tonnes of CO2e, then converted into pounds of CO2e.

$$\text{Average Tonnes per MWh} \times \frac{\text{Grid Electric kWh Consumed by FC4}}{1{,}000} = \text{Tonnes CO2e}$$

$$\text{Tonnes CO2e} \times 2{,}000\ \text{lbs} = \text{Grid Electric lbs CO2e}$$

An important factor for this method was the consideration of the charging start time. As previously mentioned, a start time of 3pm was used to establish the average emissions rate in the formula above. This value changes as this time period shifts throughout the day. Considering the duck curve[15] phenomenon in California and established utility peak periods of 4pm to 9pm, a 3pm start time would have the vehicle charging during the most costly and highest GHG emitting hours of the day. Shifting this start time to 9pm has a significant effect on emissions related to charging FC4 from the grid. A secondary analysis was completed using the same method as above but shifting the hourly average Tonnes CO2e/MWh to start at 9pm. The result was a reduction of 42.4% in lbs CO2e emissions.

The third step in this approach utilized the provided kilograms of hydrogen used by FC4 for each day and an applied emissions factor to calculate pounds of CO2e. The California Statewide Well-to-Wheel GHG Emission Factor was established by the California Air Resources Board (CARB) as part of the California Climate Investments Quantification Methodology Emission Factor Database[16]. This emission factor of 13,393 gCO2e/kg (29.527 lbsCO2e/kg) accounts for the statewide requirement[17] that not less than 33.3% of hydrogen produced for transportation be derived from renewable sources, such as dairy farms or landfills. This is in line with fuel provided by the True Zero hydrogen filling station in Del Mar, CA used by FC4 which claims 33% renewable hydrogen. Emissions related to the creation of hydrogen fuel is further explained in the Hydrogen Emissions Considerations section of this report. The formula below establishes the daily emissions related to hydrogen consumed by the fuel cell in the vehicle.

$$\text{FC4 Consumed kg of Hydrogen} \times 29.527\ \text{lbs CO2e per kg} = \text{FC4 Hydrogen lbs CO2e}$$

Daily total pounds of CO2e are calculated by adding the two values above, Grid Electric lbs CO2e and FC4 hydrogen lbs CO2e. From here, a metric of Total CO2e per Mile is derived from

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[15] The duck curve is the difference in electricity demand and the amount of available solar energy throughout the day https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

[16] https://ww2.arb.ca.gov/resources/documents/cci-quantification-benefits-and-reporting-materials

[17] SB-662 Energy: Transportation Sector: Hydrogen https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200SB662v

dividing the total pounds of CO2e from both sources by the miles driven in that day. This efficiency value will then be compared to a similar diesel truck in the next step.

$$\frac{\text{Grid Electric lbs CO2e} + \text{FC4 Hydrogen lbs CO2e}}{\text{Total Miles Driven}} = \text{Total CO2e per Mile Driven}$$

The fourth and final step was to calculate emissions of a comparable vehicle vocation, a Regional Haul Freight Truck – Combination Short-Haul Truck, as per the AFLEET Tool[18]. The Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool built by Argonne National Laboratory (ANL) estimates petroleum use, greenhouse gas emissions, and cost of ownership of light-duty and heavy-duty vehicles. This tool provided the average fuel economy metric of 5.415 miles per gasoline gallon equivalent (GGE) that was used to calculate total gallons of diesel consumed for similar trips made by FC4.

$$\frac{\text{Daily Miles Driven by FC4}}{\text{Average Fuel Economy of a Combination Short Haul Truck}} = \text{Daily Gallons of Diesel Consumed}$$

The daily gallons of diesel consumed was then multiplied by the California Statewide Well-to-Wheel GHG Emission Factor, as referenced above, for diesel fuel at a rate of 13,507.51 gCO2e/gal (29.779 lbs CO2e/gal). The estimated diesel emissions for each day were then compared to the total emissions (electric + hydrogen) for FC4 by reduced pounds CO2e and percent reduction. The estimated reduction can be found in the Analysis Results section of this report.

Analysis Results

The analysis results were favorable for FC4 showing a 70.8% reduction in CO2e emissions when compared to a similar diesel truck. There was a total of twenty-one daily trips recorded where FC4 travelled 1,839 miles throughout San Diego County and of these twenty-one trips, only six utilized the hydrogen fuel cell. Considering there was a significant difference between emissions related to electric and hydrogen consumption, it was appropriate to breakout the electric-only trip, and electric + hydrogen trip results. It should be noted that there were no utility or fuel costs evaluated in this analysis, as per the task's scope of work.

During June 2021, there were 943 miles driven using both onboard power systems of FC4 which consumed 303 kWh from the grid and 58.4 kg of hydrogen, resulting in 1,881 lbs of CO2e emissions. One of these trips utilized no grid energy as it was estimated from the data, regenerative braking and the hydrogen fuel cell provided all the electric for the onboard battery drive system. Of the total CO2e emissions, 91.6% (1,724.7 lbs CO2e) can be attributed to the hydrogen fuel consumption and 8.4% (157.4 lbs CO2e) from electric grid consumption. In

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[18] https://afleet.es.anl.gov/home/

comparison, a similar combination short-haul truck utilizing diesel fuel would have consumed 174.2 Gallons of fuel, emitting 5,185.9 lbs of CO2e which translates to an increase of 63.7% in emissions. The table below represents FC4's performance and efficiency over a diesel alternative.

Miles Driven	**943 Miles (6 Trips)**
Grid Energy Consumed	303 kWh
Hydrogen Consumed	58.4 kg
Grid Energy Emissions	157.4 lbs CO2e (8.4%)
Hydrogen Emissions	1,724.7 lbs CO2e (91.6%)
Total Elec + H2 Emissions	1,882.1 lbs CO2e
Grid Energy Fuel Economy	0.17 lbs CO2e per Mile
Hydrogen Fuel Economy	1.83 lbs CO2e per Mile
Total Elec + H2 Fuel Economy	2.00 lbs CO2e per Mile
Diesel Fuel Consumed	174.2 Gallons
Diesel Fuel Emissions	5,185.9 lbs CO2e
Diesel Fuel Economy	5.5 CO2e per Mile
Total CO2e Reduction	3,303.8 lbs CO2e (63.7%)
Total Fuel Economy Reduction	3.5 lbs CO2e per Mile

Table 6: Comparative Analysis Results for Electric + Hydrogen Trip Performance

Through July and August of 2021, there were 896 miles driven using just the onboard battery system which consumed 948 kWh from the grid and zero kilograms of hydrogen, resulting in 1,072.6 lbs of CO2e emissions. In comparison, a similar combination short-haul truck utilizing diesel fuel would have consumed 165.5 Gallons of fuel, emitting 4,927.4 lbs of CO2e which translates to an increase of 78.2% in emissions. It can be assumed from these metrics that FC4 operating only on battery power charged from the grid is overall more efficient than utilizing both the electric and hydrogen fuel cell power systems. The table below represents FC4's electric-only performance and efficiency over a diesel alternative.

Miles Driven	**896 Miles (15 Trips)**
Grid Energy Consumed	948 kWh
Grid Energy Emissions	1,072.6 lbs CO2e
Grid Energy Fuel Economy	1.2 lbs CO2e per Mile
Diesel Fuel Consumed	165.5 Gallons
Diesel Fuel Emissions	4,927.4 lbs of CO2e
Diesel Fuel Economy	5.5 CO2e per Mile
Total CO2e Reduction	3,854.8 lbs CO2e (78.2%)
Total Fuel Economy Reduction	4.3 lbs CO2e per Mile

Table 7: Comparative Analysis Results for Electric Only Trip Performance

Factoring in all twenty-one trips from June through August 2021, there were 1,839 miles driven using both onboard power system of FC4 which consumed 1,251 kWh from the grid and 58.4 kg of hydrogen, resulting in 2,954.7 lbs of CO2e emissions. In comparison, a similar combination short-haul truck utilizing diesel fuel would have consumed 339.6 Gallons of fuel, emitting 10,113.3 lbs of CO2e which translates to an increase of 70.8% in emissions. The table below represents FC4's performance and efficiency over a diesel alternative for the entire testing period.

Miles Driven	**1,839 Miles (21 Trips)**
Grid Energy Consumed	1,251 kWh
Hydrogen Consumed	58.4 kg
Grid Energy Emissions	1,230.0 lbs CO2e (41.6%)
Hydrogen Emissions	1,724.7 lbs CO2e (58.4%)
Total Elec + H2 Emissions	2,954.7 lbs CO2e
Grid Energy Fuel Economy	0.67 lbs CO2e per Mile
Hydrogen Fuel Economy	0.94 lbs CO2e per Mile[19]
Total Elec + H2 Fuel Economy	1.61 lbs CO2e per Mile
Diesel Fuel Consumed	339.6 Gallons
Diesel Fuel Emissions	10,113.3 lbs CO2e
Diesel Fuel Economy	5.5 CO2e per Mile
Total CO2e Reduction	7,158.6 lbs CO2e (70.8%)
Total Fuel Economy Reduction	3.89 lbs CO2e per Mile

Table 8: Comparative Analysis Results for All Testing Trip Performance

The analysis concludes that there is a substantial reduction in CO2e emissions related to the operations of the electric + hydrogen hybrid truck over a comparable diesel truck. It is acknowledged that there are several other factors to consider in a 'like for like' comparison as detailed in the Additional Considerations section of this report such as total weight of the vehicle and elevation gain of each trip. It's apparent that the hydrogen fuel consumed by FC4 resulted in a lower lbs CO2e per mile fuel economy than the grid electric powered battery, however there can be benefits to having both power systems on the same vehicle for longer hauls.

If we were to extrapolate these values to a full year of transit, we can estimate a total reduction of 76,702 lbs CO2e per year for FC4 compared to a similar diesel truck. This would be based on the average distance travelled during the testing period and the performance metrics based on the first six, electric + hydrogen fueled trips. The table below represents the estimated grid

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[19] Based on total hydrogen consumed (first six trips only) divided by total miles (all twenty-one trips)

electric and hydrogen consumption of FC4, gallons of diesel consumed by the alternate, and associated emissions.

Avg Daily Miles Driven	**87.6 Miles**
Operating Days	250 Days
Operating Miles	21,892.9 Miles
Grid Electric Emissions	3,654.5 lbs CO2e
Hydrogen Emissions	40,040.3 lbs CO2e
Total Elec + H2 Emissions	43,694.7 lbs CO2e
Diesel Fuel Consumed	118,548.9 Gallons
Diesel Fuel Emissions	120,396.6 lbs CO2e
Total CO2e Reduction	76,701.9 lbs CO2e (63.7%)

Table 9: Extrapolated Annual Comparative Analysis Results

Hydrogen Emissions Considerations

There are several factors to consider when accounting for CO2e emissions related to the consumption of hydrogen. The appeal of zero tail-pipe emissions can be overshadowed by the 'well-to-wheel' carbon intensity of the supplied fuel due to a standard production process. California mandates that all hydrogen fuels targeted for the transportation industry, at a minimum, must include 1/3rd fuel from renewable sources, which leaves 2/3rd of the fuel from fossil-based fuels. It should be noted that fuel supplied form renewable sources commonly have a positive carbon intensity based on fuel medium and process.

The California Statewide Well-to-Wheel GHG Emission Factor used for this analysis, 13,393 gCO2e/kg, is based on a blend of 2/3rd compressed hydrogen produced in California from Steam Methane Reforming (SMR) of North American fossil-based natural gas (117.767 gCO2e/MJ) and 1/3rd compressed hydrogen from on-site reforming with renewable feedstocks (99.48 gCO2e/MJ). The SMR method utilizes high temperature steam to extract hydrogen from natural gas which is an energy intensive process. The renewable portion can vary from a negative carbon to positive carbon intensity based on reformation process and the feedstock such as dairy manure and landfill gas.

The specific pathway for all alternative fuels in California is identified and certified through the Low Carbon Fuel Standards (LCFS) Program[20], created by CARB. Each fuel's carbon intensity (CI) value can be traced back to its source, such as the hydrogen offered at True Zero filling stations used by FC4. FirstElement Fuel is the parent company of True Zero and as certified by LCFS and has several sources of non-renewable and renewable hydrogen. The current certified CI of their

[20] https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

main non-renewable fuel is 151.01 gCO2e/MJ, which is 28.2% higher than the average statewide CI of 117.767 gCO2e/MJ. Their renewable fuels have a CI that ranges from 109.68 gCO2e/MJ to -287.07 gCO2e/MJ, depending on feedstock.

The importance of these varying metrics will have an effect on the true emissions impact of FC4 as we can see from the analysis results that the hydrogen fuel economy (lbs CO2e/mile) is seven times greater than that of the grid electric fuel economy. By digging into the pathway for local available fuels, there could be a more sustainable option from what True Zero offers. There are known stations in Southern California that do offer 100% renewable hydrogen as discussed in the Renewable Energy Optimization section of this report.

Renewable Energy Optimization

Access to renewable energy resources is becoming more prevalent in California through technology advancements, financially feasible solutions and aggressive policies pushing renewable energy mandates. There are several opportunities to optimize the consumption of renewable fuels, both electrically and hydrogen-based, for FC4 and similar vehicles. As mentioned in the Hydrogen Emissions Considerations section of this report, the only renewable portion of fuel consumed by FC4 during testing is the 33.3% renewable portion of hydrogen from True Zero.

Electric consumption can be optimized through strategies such as switching to a 'Green Tariff', shifting charging times to utility off-peak hours, or implementing onsite solar and battery storage. Senate Bill (SB) 43[21] enacted the Green Tariff Shared Renewables (GTSR) Program which provides an electric rate for residential and small commercial customers to source their energy from 50% or 100% renewable sources, such as solar PV. This tariff incurs a slightly higher cost for commodity and demand but allows for the procurement of renewable energy to charge the vehicle as well as power any loads behind the same meter. All three major utilities, SDG&E, SCE and PG&E, offer a GTSR rate which can be found in the SB 43 reference above.

Shifting the start time for vehicle charging has a significant impact on the associated emissions for electric consumption. As previously stated, FC4 typically begins charging between 3pm and 6pm after the day's activities which extends through the known utility on-peak hours of 4pm to 9pm, when utility emission rates are highest. This is a result of the duck curve in California, referenced in the Methodology section of this report. For reference, the average charging duration is 1.39 hours which was calculated earlier to determine the average hourly emission rate. The table below highlights the difference in estimated lbs CO2e for a 3pm charging start time versus a 9pm start time. There is a reduction of 42.4% in CO2e emissions related to electric energy if charging strategies for FC4 can be implemented.

[21] https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/electric-rates/green-tariff-shared-renewables-program

FC4 Miles Driven	1,839 Miles (21 Trips)
Grid Energy Required	1,251 kWh
3pm Charging Start Time	1,230.0 lbs CO2e
9pm Charging Start Time	708.0 lbs CO2e
Emissions Reduction	522.1 lbs CO2e (42.4% ↓)

Table 10: Reduced Electric Emissions by Shifting Charge Start Time

Investing in onsite solar and storage is a more costly, but direct option for optimizing renewable energy consumption. The installation of solar panels and paired battery energy storage could capture energy from the sun during the day and store it for charging the vehicle at the end of each day, as well as potentially provide renewable energy to other loads behind the same meter. An energy profile of vehicle charging and other loads behind the meter would dictate the capacity of a properly sized system. There is currently an available Federal Investment Tax Credit (ITC) of 26% for solar PV[22] system costs as well as a portion the incentive that can be attributed towards battery storage[23] costs if it's charged from at least 75% solar. The Self Generating Incentive Program[24] (SGIP) also offers incentives for battery storage based on a $/kWh basis for both residential and commercial customers in California.

As for optimizing renewable energy associated with hydrogen consumption, choosing a filling station that claims greater than 33% is the most effective strategy. The particular True Zero station used during this analysis claims that their fuel is from 33% renewable sources, such as dairy farm biomethane and landfill gas. The California Fuel Cell Partnership station map[25] lists all available filling stations and their percent renewable mix such as the 100% renewable hydrogen True Zero station in Playa Del Rey, CA and the Shell Hydrogen station in Torrance, CA.

Additional Considerations

There are few additional considerations worth highlighting for this analysis. One being that fuel economy of a short-haul freight truck can vary based on several factors such as total weight of the vehicle, idle time, driving habits and the type of route. Trucks pulling more weight will inherently have a higher fuel consumption per mile than those pulling no trailer or less weight

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22 https://www.energy.gov/sites/default/files/2021/02/f82/Guide%20to%20the%20Federal%20Investment%20Tax%20Credit%20for%20Commercial%20Solar%20PV%20-%202021.pdf

23 https://www.nrel.gov/docs/fy18osti/70384.pdf
24 https://www.selfgenca.com/
25 https://cafcp.org/stationmap

overall. Emissions related to idle time of a hybrid, battery electric and hydrogen fuel cell powered vehicle could be significantly less than that of a comparable diesel truck. It's assumed that minimal energy from both energy sources on FC4 will be required to idle, while a diesel engine will continue running while sitting at a light or loading dock. Driving habits will also factor into the fuel economy of a vehicle as well as the specific route it must drive. Universally known, a route that requires constant stop-and-go or steep climbs will yield a lower fuel economy as opposed to a flat highway-speed route. It was mentioned that FC4 had several north-south strips up California I-15 and I-5 in San Diego which have significant inclines and elevation gains and losses, both effecting fuel economy.
Another consideration was realized during the analysis where emissions were less for an electric-only powered trip versus an electric and hydrogen powered trip. The initial suggestion would be to evaluate the benefits of the hydrogen fuel cell and prioritize FC4 vehicle power sources accordingly. It's unclear at this moment as to what the total range of the onboard battery energy system is and it's possible the fuel cell is prime for extending that range. Further data collection and analysis should inform the most optimal fuel mix for FC4 to minimize emissions without sacrificing performance and range.

As previously discussed between all teams involved with this project, there is a consensus that improving on the data collection process will help future analysis and evaluation of other electric-hydrogen hybrid trucks. Electric meters can monitor the grid consumption of the vehicle to charge the onboard battery system so that hourly emissions rates can be calculated using the Avoided Cost Calculator Tool mentioned in the Methodology section of this report. Hydrogen consumption should also be closely metered to account for fuel cell performance as well as knowing where the hydrogen fuel comes from considering the variability of carbon intensity based on the fuel pathway as discussed in the Hydrogen Emissions Considerations section of this report.

Conclusion

It is concluded through this analysis, with the data provided, Fuel Cell Truck #4 has a better fuel economy and lower emissions rate as compared to a similar diesel-powered truck. The analysis results were favorable for FC4 showing a 70.7% reduction in CO2e emissions when compared to a similar diesel truck. From June through August 2021, there were 1,839 miles driven using both onboard power system of FC4 which consumed 1,251 kWh from the grid and 58.4 kg of hydrogen, resulting in 2,965 lbs of CO2e emissions. In comparison, a similar combination short-haul truck utilizing diesel fuel would have consumed 339.6 Gallons of fuel, emitting 10,113.3 lbs of CO2e which translates to an increase of 70.7% in emissions. The methodology and resources highlighted in this report can be used with future data to best estimate the environmental benefits of a hybrid electric fuel cell truck.

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Appendix C

Task 3.1 Community Outreach

Appendix C - Task 3.1 Community Outreach

Executive Summary

The Center for Sustainable Energy (CSE) was tasked to conduct community outreach and education to the most impacted by heavy duty diesel pollution for the Fast Track Fuel Cell Truck (FTFCT) project as part of a California Air Resource Board (CARB) grant. These communities are impacted heavily by pollution from the ports / warehouses traffic. Due to the COVID-19 pandemic, CSE was limited by the rules set forth by California Department of Public Health and was unable to conduct any in-person outreach to the community for the duration of the project. After consulting with our project partners GTI Energy and Frontier Energy, we decided to take a more targeted approach and gather community feedback from the communities. By working with two different community-based organizations (CBOs), CSE was able to conduct two listening sessions with community members from Wilmington and San Bernardino. The main conclusions are summaries in the following:

- Most community members mentioned the **poor air quality in their community**, and they know someone whose **health was impacted by the poor air quality**.
- Community members citing **big rig traffic**, **warehouse buildings**, **ports**, and **refinery** as the four main cause of bad local air quality
- While the community members might be not fully aware with zero emission technology (electric or hydrogen vehicles), all of them identified **zero emission vehicles** as a **key component** to improve the air quality in their community.
- Another key takeaway is not only do most participants want **more education on zero emission technology** in their communities, more importantly they want to see more **programs** and **policies** being **implemented in their communities** to reduce air pollution right now.

Community Listening Sessions

A community listening session a type of facilitated discussion with a group of people, aimed at collecting information and feedback from their perspective. Participants in a listening session are often asked to talk about their thoughts and answer specific questions about a topic. The goal is to understand the opportunities and challenges surround a topic as community perceive them. In an environment where disadvantaged community members are often left behind and forgotten, listening session is a great tool to collect valuable information and feedback.
CSE and its partners hosted two listening sessions with the community members from Wilmington and San Bernardino Muscoy area. Both neighborhoods are part of CARB's AB 617 Community Air Protection Program Communities, which focus to reduce exposure in communities most impacted by air pollution. Both events were held virtually and attend by minimum of 12 members of the community. Each session was about an hour and half long.

Listening Session Results

The Wilmington listening session was organized and hosted by CSE's CBO partner Los Angeles Walks. Wilmington is a neighborhood near port of Long Beach and POLA, about 22 miles south of Downtown Los Angeles. Because all 12 attending community members' native language is Spanish, we decided to have this listening session in Spanish. The participants were all Spanish speaking immigrants and they have lived in the Wilmington neighborhood anywhere between 10 to 28 years.

The San Bernardino Muscoy listening session was organized and hosted by CSE's CBO partner Inland Empire Concerned African American Churches. San Bernardino Muscoy is a community bisected by serval major freight arteries including Highways 215 and 210 and Interstate 10. There are also 6 rail yards and clusters of massive warehouse and distribution centers through the community. It is about 55 miles East of Downtown Los Angeles. The participants were all residents of San Bernardino and they have lived in the same community anywhere between 5 to 25 years.

The following quotes are from community members regarding air quality in their community. All community members voiced concern over the air quality in their neighborhood and its direct impact on health of themselves, friends and family members. Some of the health issues are - asthma, allergies, cancer, respiratory issues, premature birth, and emphysema.

- Wilmington Community Members
    - "When my family go outside, we can smell the contaminated air. It smells really bad like rotten or burn smells, sometimes it even smells gas (diesel).."
    - "Even when it is hot, I can't open my window because of the smell. It is really frustrating…"
    - "You see more and more garbage trucks, delivery trucks, big rigs in the neighborhood and the traffic is just nonstop. Even at night where you want to rest and you can still hear them…"
    -
- San Bernardino Muscoy Community Members
    - "It was gotten a lot worse in the recent years. With all these warehouses being built from here all the way to Riverside, there are just trucks everywhere…"
    - "On some days, you can see the idling diesel trucks. That has to change."
    - "There weren't that many people around while I was growing up and a lot less traffic. I mean the air wasn't the best back then but now it is just so bad. All the trucks just fill up the whole freeway."

The following quotes are from community members regarding their knowledge of zero emission technology (electric or hydrogen vehicles) and its potential impact on the community. While 7 out of 12 participants rated themselves as "somewhat familiar" and 3 out of 12 as "Not at all familiar" with zero emission technology, all community members voiced optimism on its impact and how zero emission vehicles can improve their lives.

- Wilmington Community Members
  - "I think at a community level, electric and hydrogen trucks will bring a better quality life to the area. The air will be clear, we will have better community healthy, better environment, better economy and better streets…"
  - "It will bring better health to the community. No more stuffy noses and having a hard time breathing because of the bad air. What we breath does really impact ours and our kids health.."
  -
- San Bernardino Muscoy Community Members
  - "I have gone through one of these before and I know a little bit. But I think we will need more education for the rest of the community so they can speak up when it comes to it"

The following quotes are from community members regarding what else can be done to improve the air quality and the life in the community. All participants were extremely engaged and passionate during this topic and everybody wanted to be heard. It is a clear sign that the community members do not wish to wait any longer and want more action to be done to help with the air quality.

- Wilmington Community Members
  - "I want there to be more action and responsibility by agencies monitor air quality here and for the perpetrators to support the surrounding communities' quality of life…"
  - "There should be more trees and green spaces and parks."
  - "I also think a behavioral change is needed here. We can change our own way of using our cars. We can get electric / hybrid cars, coordinate and use carpool or just not drive too much all together…"
  - "We want cleaner streets. Want more street cleanups, organizing more trash picks-ups and the community needs to know about 311"
  - "Would it be possible to enforce alternative truck routes or creating policies for everyone to follow such as day without car, no drive day. We also need more education for our kids. We need more workshops on zero emission campaigns so more community members will understand the issues and speak up."
  -
- San Bernardino Muscoy Community Members
  - "It is all about the money. What we need is more dollars spend into these neighborhoods. All the talk has been done. I have gone to many meetings

including AB 617. But now I want to see action. I want to see some dollars being spend and bring these projects to the community"

- "I can't wait to see these newer and cleaner trucks on the road. I will look for them now."
- "I have a friend who is owner and operator of his own trucking company. In order of him to switch, the price has to be right. If the incentive is not there, no one will switch."

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Appendix D

Vehicle Operational Data Collected

Appendix D - Vehicle Operational Data Collected

FC3 - 232_01 Red

Color

Red

Vehicle ID

232_01_INTL_PRSTR_FTFC_792176

Year

2018

Model

ProStar

Manufacturer

Navistar

Description of daily use of vehicles; duty cycle

Daily cargo delivery.

Fuel Capacity

32kg @ 5000 psi (350 bar)

Full propulsion system specification

- Propulsion: 400V, 320kW peak
- Batteries: 220kWh NMC.
- Battery only range: 35+ miles
- Fuel Cell: Hydrogenics HD30 fuel cells are rated a nominal 30kW each (two fuel cells).
- Combined range: 200 miles

Gross Vehicle Weight

21,000 lbs

Daily Operations Summary

Days Operating	Miles Traveled	kWh Charged	kWh H2	H2 used
85	424.376	-565.647 kWh	56.67 kWh	68.6 kg

Date	Miles Traveled	Route	kWh Charged	kWh H2	H2 Used	H2 Filled
01/15/2020	14.27			0KWh	0.0 kg	0.0 kg

11/13/2020	21.13		0kwh	0KWh	0.0 kg	0.0 kg
12/16/2020	52.57		-69kwh	2KWh	8.9 kg	0.0 kg
01/13/2021	10.32		-39kwh	0KWh	11.2 kg	0.0 kg
01/14/2021	71.33		-56kwh	0KWh	11.9 kg	0.0 kg
02/01/2021	41.51			15KWh	18.5 kg	0.0 kg
02/02/2021	39.77			16KWh	18.2 kg	0.0 kg
02/25/2021	22.49			6KWh	0.0 kg	0.0 kg
03/22/2021	32.06			3KWh	0.0 kg	0.0 kg
03/23/2021	33.68			0KWh	0.0 kg	0.0 kg
03/25/2021	74.19			0KWh	0.0 kg	0.0 kg

FC4 - 232_02 Blue

Color
Blue

Vehicle ID
232_02_INTL_PRSTR_FTFC_519216

Year
2018

Model
ProStar

Manufacturer
Navistar

Description of daily use of vehicles; duty cycle
Daily cargo delivery.

Fuel Capacity
32kg @ 5000 psi (350 bar)

Full propulsion system specification
- Propulsion: 400V, 320kW peak
- Batteries: 220kWh NMC.
- Battery only range: 35+ miles
- Fuel Cell: Hydrogenics HD30 fuel cells are rated a nominal 30kW each (two fuel cells).
- Combined range: 200 miles

Gross Vehicle Weight
21,000 lbs

Daily Operations Summary

Days Operating	Miles Traveled	kWh Charged	kWh H2	H2 used
120	7, 090.462	-6,262.206 kWh	1, 722.07 kWh	378.5 kg

Date	Miles Traveled	kWh Charged	kWh H2	H2 Used	H2 Filled
02/10/2021	14.54		0KWh	0.0 kg	0.0 kg
02/17/2021	36.54	-87kwh	0KWh	0.0 kg	0.0 kg
02/22/2021	14.54	-97kwh	10KWh	0.0 kg	0.0 kg
02/23/2021	111.10	-28kwh	49KWh	11.9 kg	0.0 kg
02/24/2021	44.74	-7kwh	11KWh	2.0 kg	15.2 kg
02/25/2021	96.93	-234kwh	13KWh	3.3 kg	0.0 kg
02/26/2021	65.37	-1kwh	26KWh	5.3 kg	0.0 kg
03/01/2021	128.50	-99kwh	73KWh	12.5 kg	15.8 kg
03/02/2021	111.47	-98kwh	22KWh	5.0 kg	0.0 kg
03/04/2021	130.49	-112kwh	35KWh	6.6 kg	18.8 kg
03/05/2021	57.29	-2kwh	21KWh	3.3 kg	0.0 kg
03/08/2021	65.00	-109kwh	27KWh	5.6 kg	2.3 kg
03/09/2021	64.87	-83kwh	42KWh	6.3 kg	0.0 kg
03/10/2021	142.05	-79kwh	48KWh	9.6 kg	19.1 kg
03/11/2021	62.26	-80kwh	31KWh	6.3 kg	0.0 kg
03/12/2021	64.50	-78kwh	32KWh	6.3 kg	0.0 kg
03/15/2021	14.42	-33kwh	0KWh	0.0 kg	0.0 kg
03/16/2021	72.95	-2kwh	0KWh	0.0 kg	0.0 kg
03/18/2021	76.18	-257kwh	0KWh	0.0 kg	0.0 kg
03/19/2021	136.33	-2kwh	39KWh	6.6 kg	18.2 kg
03/22/2021	98.18	-59kwh	32KWh	5.6 kg	0.0 kg
03/23/2021	109.24	-63kwh	52KWh	7.6 kg	0.0 kg
03/24/2021	43.87		8KWh	27.1 kg	0.0 kg
03/29/2021	151.99	-111kwh	59KWh	16.8 kg	24.8 kg
04/01/2021	52.07	-80kwh	0KWh	0.0 kg	0.0 kg
04/02/2021	91.71	-134kwh	0KWh	0.0 kg	0.0 kg
04/05/2021	127.75	-61kwh	43KWh	9.2 kg	9.9 kg
04/06/2021	152.86	-23kwh	33KWh	5.3 kg	0.0 kg
04/07/2021	20.88	-64kwh	11KWh	8.3 kg	2.3 kg
04/13/2021	104.89	-16kwh	49KWh	10.2 kg	0.0 kg
04/14/2021	21.62	-16kwh	7KWh	1.7 kg	0.0 kg
04/15/2021	94.82	-138kwh	6KWh	2.6 kg	0.0 kg
04/16/2021	96.06	-147kwh	0KWh	0.0 kg	0.0 kg

04/19/2021	89.23	-143kwh	0KWh	0.0 kg	0.0 kg
04/20/2021	43.12	-8kwh	0KWh	0.0 kg	0.0 kg
04/22/2021	91.96	-1kwh	0KWh	0.0 kg	0.0 kg
04/28/2021	95.32	-148kwh	0KWh	0.0 kg	0.0 kg
04/29/2021	99.05	-2kwh	0KWh	0.0 kg	0.0 kg
05/03/2021	67.23	-194kwh	4KWh	0.0 kg	0.0 kg
05/04/2021	74.57	-1kwh	29KWh	4.0 kg	12.5 kg
05/05/2021	53.19	-27kwh	16KWh	4.3 kg	0.0 kg
05/06/2021	35.79	-32kwh	12KWh	1.3 kg	0.0 kg
05/07/2021	152.11	-91kwh	62KWh	9.9 kg	9.9 kg
05/10/2021	144.66	-153kwh	33KWh	4.3 kg	0.0 kg
05/11/2021	86.12	0kwh	4KWh	5.9 kg	20.8 kg
05/12/2021	99.42	-206kwh	28KWh	4.6 kg	0.0 kg
05/13/2021	150.37	-124kwh	43KWh	6.3 kg	7.3 kg
05/14/2021	86.62	-50kwh	31KWh	5.6 kg	0.0 kg
05/15/2021	123.53	-51kwh	46KWh	9.9 kg	6.3 kg
05/17/2021	275.27	-128kwh	114KWh	18.5 kg	6.6 kg
05/18/2021	208.66	-115kwh	68KWh	13.9 kg	11.9 kg
05/19/2021	112.34	-86kwh	0KWh	0.0 kg	0.0 kg
05/24/2021	220.46	-163kwh	84KWh	15.5 kg	0.0 kg
05/25/2021	149.88	-149kwh	19KWh	4.6 kg	0.0 kg
06/09/2021	150.00	-93kwh	49KWh	9.9 kg	13.9 kg
06/10/2021	152.24	-80kwh	45KWh	9.9 kg	25.7 kg
06/11/2021	190.26	-49kwh	73KWh	15.2 kg	5.9 kg
06/14/2021	185.17	-129kwh	38KWh	8.6 kg	0.0 kg
06/15/2021	135.21	-137kwh	18KWh	4.6 kg	4.3 kg
06/16/2021	131.48	-1kwh	46KWh	16.8 kg	11.2 kg
07/01/2021	92.21	-86kwh	17KWh	8.9 kg	0.0 kg
07/08/2021	38.03		10KWh	2.0 kg	0.0 kg
07/13/2021	67.85	-40kwh	14KWh	3.3 kg	0.0 kg
07/14/2021	102.53	-90kwh	20KWh	4.3 kg	0.0 kg
07/19/2021	97.56	-146kwh	0KWh	0.0 kg	0.0 kg
07/20/2021	76.06	-116kwh	0KWh	0.0 kg	0.0 kg
07/21/2021	60.65		0KWh	0.0 kg	0.0 kg
07/30/2021	57.91	-154kwh	6KWh	1.7 kg	0.0 kg
08/10/2021	51.95		0KWh	0.0 kg	0.0 kg
08/11/2021	10.44		0KWh	0.0 kg	0.0 kg
08/12/2021	46.11	-51kwh	0KWh	0.0 kg	0.0 kg
08/13/2021	51.33	-185kwh	0KWh	0.0 kg	0.0 kg
08/18/2021	52.44		0KWh	0.0 kg	0.0 kg
08/24/2021	27.71	-143kwh	0KWh	0.0 kg	0.0 kg
08/25/2021	55.05		0KWh	0.0 kg	0.0 kg

08/26/2021	52.69	-169kwh	0KWh	0.0 kg	0.0 kg
08/27/2021	53.69	-79kwh	0KWh	0.0 kg	0.0 kg

FC5 - 232_3 Barney

Color

Purple

Vehicle ID

FTFC5 : 232_03

Year

2015

Model

579

Manufacturer

Peterbuilt

Description of daily use of vehicles; duty cycle

Daily cargo delivery.

Fuel Capacity

32kg H2

Full propulsion system specification

300kW electric drive with nominal 220kWh battery energy storage. Loop fuel cells are rated a nominal 50kW each (two fuel cells).

Gross Vehicle Weight

21,000 lbs

Daily Operations Summary

Days Operating	Miles Traveled	kWh Charged	kWh H2	H2 used
45	1, 949.739	-1,912.380 kWh	530.07 kWh	146.5 kg

Date	Miles Traveled	Route	kWh Charged	kWh H2	H2 Used	H2 Filled
01/18/2021	47.60		-98kwh	0KWh	0.0 kg	0.0 kg
01/19/2021	44.37		-10kwh	0KWh	0.0 kg	0.0 kg
01/21/2021	87.49		-88kwh	43KWh	12.2 kg	3.0 kg
01/26/2021	40.39		-144kwh	0KWh	0.0 kg	0.0 kg

01/27/2021	88.48		-1kwh	0KWh	0.0 kg	0.0 kg
02/22/2021	55.80			34KWh	14.9 kg	0.0 kg
02/23/2021	107.12			29KWh	11.9 kg	0.0 kg
02/24/2021	67.11			28KWh	3.6 kg	5.3 kg
02/25/2021	75.43			33KWh	4.6 kg	0.0 kg
02/26/2021	54.18		-26kwh	0KWh	0.0 kg	0.0 kg
03/01/2021	108.49		-107kwh	14KWh	9.2 kg	20.8 kg
03/02/2021	75.93		-71kwh	29KWh	0.0 kg	0.0 kg
03/04/2021	45.73		-82kwh	0KWh	0.0 kg	0.0 kg
03/05/2021	64.75		-97kwh	31KWh	10.9 kg	8.6 kg
03/08/2021	43.37		-121kwh	0KWh	0.0 kg	0.0 kg
03/09/2021	143.04		-160kwh	50KWh	17.5 kg	0.0 kg
03/17/2021	154.35			43KWh	12.2 kg	0.0 kg
03/18/2021	76.06		-141kwh	0KWh	0.0 kg	0.0 kg
03/22/2021	107.00		-55kwh	45KWh	7.9 kg	0.0 kg
03/23/2021	63.50		-50kwh	24KWh	0.0 kg	0.0 kg
03/24/2021	207.54		-2kwh	100KWh	29.0 kg	4.0 kg
03/25/2021	134.96		-195kwh	27KWh	12.2 kg	0.0 kg
03/26/2021	42.88		-2kwh	0KWh	0.0 kg	0.0 kg

FC6 - 232_4 Eleanor

Color

White

Vehicle ID

FTFC6 : 232_04

Year

2020

Model

579

Manufacturer

Peterbuilt

Description of daily use of vehicles; duty cycle

Daily cargo delivery.

Fuel Capacity

32kg @ 5000 psi (350 bar)

Full propulsion system specification

- Propulsion: 400V, 320kW peak
- Batteries: 220kWh NMC.
- Battery only range: 35+ miles
- Fuel Cell: Loop Energy fuel cells rated a nominal 50kW each (two fuel cells).
- Combined range: 200 miles

Gross Vehicle Weight

21,000 lbs

Daily Operations Summary

Days Operating	Miles Traveled	kWh Charged	kWh H2	H2 used
91	1, 324.641	-1,394.862 kWh	566.54 kWh	80.2 kg

Date	Miles Traveled	kWh Charged	kWh H2	H2 Used	H2 Filled
01/14/2021	65.24	-94kwh	0KWh	5.6 kg	10.9 kg
01/19/2021	50.21	-139kwh	0KWh	4.0 kg	3.3 kg
01/20/2021	132.73	-237kwh	0KWh	7.3 kg	15.8 kg
01/25/2021	63.75		35KWh	4.6 kg	0.0 kg
01/28/2021	49.83		9KWh	0.7 kg	0.0 kg
02/02/2021	124.90	-67kwh	98KWh	7.9 kg	13.9 kg
02/03/2021	43.37	-1kwh	0KWh	0.0 kg	0.0 kg
02/17/2021	35.79	-81kwh	19KWh	2.0 kg	0.0 kg
02/25/2021	50.58		11KWh	1.7 kg	0.0 kg
03/11/2021	13.92		0KWh	0.0 kg	0.0 kg
03/16/2021	13.92	-122kwh	0KWh	0.0 kg	0.0 kg
04/13/2021	43.25		20KWh	4.0 kg	22.4 kg
04/14/2021	100.66		59KWh	7.6 kg	0.0 kg
04/20/2021	92.71	-145kwh	0KWh	0.0 kg	0.0 kg
04/21/2021	32.93		33KWh	3.0 kg	0.0 kg
04/27/2021	146.89		80KWh	6.6 kg	6.6 kg
04/28/2021	43.50		0KWh	0.0 kg	0.0 kg
05/04/2021	58.16		41KWh	3.3 kg	0.0 kg
05/05/2021	12.43		0KWh	4.3 kg	15.2 kg
06/07/2021	32.06		33KWh	7.6 kg	0.0 kg

06/17/2021	47.22		0KWh	0.7 kg	22.8 kg

FC7 - 232_05

Color

White

Vehicle ID

232_05_PB_579_ET_712730

Year

2020

Model

579

Manufacturer

Peterbuilt

Fuel Capacity

32kg @ 5000 psi (350 bar)

Full propulsion system specification

- Propulsion: 400V, 320kW peak
- Batteries: 220kWh NMC.
- Battery only range: 35+ miles
- Fuel Cell: Loop Energy fuel cells rated a nominal 50kW each (two fuel cells).
- Combined range: 200 miles

Gross Vehicle Weight

32kg @ 5000 psi (350 bar)

Daily Operations Summary

Days Operating	Miles Traveled	kWh Charged	kWh H2	H2 used
25	556.127	-573.357 kWh	311.18 kWh	11.2 kg

Date	Miles Traveled	kWh Charged	kWh H2	H2 Used	H2 Filled
07/07/2021	53.56		0KWh	0.0 kg	0.0 kg
07/16/2021	13.42		0KWh	0.0 kg	0.0 kg
02/25/2022	81.28	-123kwh	0KWh	0.0 kg	0.0 kg
02/28/2022	90.97	-135kwh	0KWh	0.0 kg	0.0 kg
03/01/2022	60.02	-1kwh	1KWh	0.0 kg	0.0 kg
03/08/2022	45.86		0KWh	0.0 kg	19.5 kg
03/11/2022	38.03		28KWh	4.3 kg	0.0 kg
03/16/2022	30.32		44KWh	3.6 kg	0.0 kg
03/17/2022	19.14	-65kwh	64KWh	2.6 kg	0.0 kg
03/18/2022	101.66	-1kwh	157KWh	0.0 kg	0.0 kg