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Electric Top Loader Project

Final Report

A California Air Resources Board Demonstration of Zero-Emission Technologies for Freight Operations at Ports

Submitted by:
Center for Transportation and the Environment

Acknowledgements

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Acronyms and Abbreviations

A&E	Architecture and Engineering
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation
AIC	Ampere Interrupting Capacity
AMTEK	Company Name
AP	Air Products
ARFTVP	Alternative and Renewable Fuels and Vehicle Technology Program
BAFO	Best and Final Offer
BOM	Bill Of Materials
CA	California
CAN	Control Area Network
CARB	California Air Resources Board
CEO	Chief Executive Officer
CEQA	California Environmental Quality Act
CH4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPUC	California Public Utilities Commission
CTE	Center for Transportation and the Environment
DAC	Disadvantaged Communities
DC/DC	Direct Current to Direct Current
DI	Deionization
DOE	Department of Energy
DOT	Department of Transportation
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMS	Eagle Marine Services
ERP	Emergency Response Plan
ESD	Emergency Shut Down
ESS	Energy Storage System
ETL	Electric Top Loader
EU	European Union
EV	Electric Vehicle
EVPCS	Electric Vehicle Propulsion Control System
FC(E)	Fuel Cell (Engine)
FCS	Fuel Cell System
FENIX	Company Name
FMS	Fenix Marine Services
GHG	Greenhouse Gas
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GTL	Leasing Company Name
GVW	Gross Vehicle Weight
HF	High Frequency
HSM	Hardware Security Module
HSS	Hydrogen Storage System
HV	High Voltage
HYMH	Hyster-Yale Material Handling

IGX	Company Name
ILWU	International Longshore and Warehouse Union
IMD	Isolation Monitoring Device
kg	Kilogram
kW	Kilowatt
LA	Los Angeles
LAFD	Los Angeles Fire Department
LCT	Low Carbon Transportation
LV	Low Voltage
MSA	Master Service Agreement
MSP	Maintenance and Support Plan
NFPA	National Fire Protection Association
NMHC	Non-Methane Hydrocarbons
NO_X	Nitrogen Oxide
OEM	Original Equipment Manufacturer
O&M	Operations and Maintenance
PEMS	Portable Emissions Measurement System
PM	Preventative Maintenance
PMA	Pacific Maritime Association
PMP	Project Management Plan
POLA	Port Of Los Angeles
RD&D	Research, Development and Demonstration
RFB	Request for a Bid
RFP	Request for Proposal
RFQ	Request for Quote
RTLS	Real-Time Locating System
SCAQMD	South Coast Air Quality Management District
SMR	Steam Methane Reformation
SOC	State of Charge
SoCalGas	Southern California Gas Company
SOH	State of Health
SOP	Standard Operating Procedure
SO_X	Sulfur Oxides
TEUP	Temporary Experimental Use Permit
THC	Total Hydrocarbons
TL	Top Loader
UK	United Kingdom
UL	Company Name
US	United States
VOC	Volatile Organic Compounds
WAVE	Wireless Advanced Vehicle Electrification
WCS	Wireless Charging System
WTW	Well To Wheels
ZEV	Zero-Emission Vehicle

Project Introduction

Background

The California Air Resources Board (CARB) is charged with protecting the public from the harmful effects of air pollution and developing programs and actions to fight climate change. From requirements for clean cars and fuels to adopting innovative solutions to reduce greenhouse gas (GHG) emissions, California has pioneered a range of effective approaches that have set the standard for effective air and climate programs for the nation, and the world.

Assembly Bill 118 (Nùñez, Chapter 750, Statutes of 2007), created the Alternative and Renewable Fuel and Vehicle Technology (ARFVT) Program. The statute authorizes CARB to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. On June 9, 2017, CARB issued an Off-Road Advanced Technology Demonstration Projects solicitation to provide funding for projects, which leverage ARFTVP funds to bring federal cost-sharing projects to California that would provide GHG, criteria pollutant, and toxic air contaminant emission reduction benefits to disadvantaged communities.

In response to this solicitation, the Center for Transportation and the Environment (CTE) partnered with Hyster-Yale Group Inc. (now known as Hyster-Yale Materials Handling, Inc., HYMH), Nuvera Fuel Cells LLC, Fenix Marine Services (FMS), Wireless Advanced Vehicle Electrification (WAVE), and originally StratosFuel**,** collectively referred to as the "Project Team", to propose the demonstration of Zero-Emission Technologies for Freight Operations at Ports (Electric Top Loader) Project. The project aimed to extend fuel-cell hybrid electric drive transportation technology with wireless-charging to an ETL. This is a market sector where electric drive transportation systems were beginning to be introduced commercially.

To support their portfolio of fuel-cell technologies and applications, CARB awarded CTE's Demonstration of Zero-Emission Technologies for Freight Operations at Ports Project on November 22, 2017. CTE executed the contract with CARB on May 3, 2018.

The purpose of this project was to accelerate the development and deployment of on-board fuel-cell hybrid powered Class-8 heavy-duty freight vehicles to substantially increase the zero-emission driving range, thereby reducing petroleum consumption and related emissions, and increasing the viability of these electric drive vehicles. The project also aimed to determine the feasibility of 16-hour freight operation at port facilities by utilizing fuel-cell and wireless-charging technology.

Project Partners and Roles

The following figure illustrates the project partners and roles of each at the conclusion of the demonstration. However, over the course of the project there were changes in project partners. Please see the *Changes in Project Team* section for further detail.

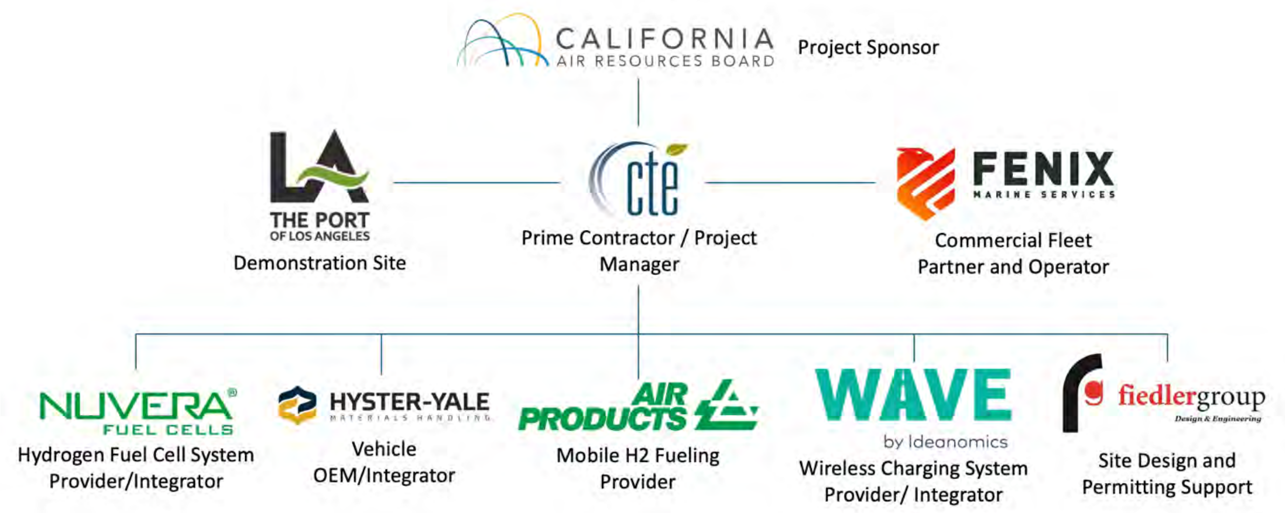

Figure 1: Project Organization Chart

Center for Transportation and the Environment – CTE is an Atlanta-based 501(c)(3) nonprofit organization whose mission is to improve the health of our climate and communities by bringing people together to develop and commercialize clean, efficient, and sustainable transportation technologies. The CTE Team provided project management, engineering design/support, system integration support, operator and maintenance training, field deployment and maintenance support for a fuel-cell hybrid electric top loader (ETL). CTE served as the prime contractor providing overall program management and administration. CTE also provided a single point of contact to provide program management throughout the project.

Fenix Marine Services (FMS) – Fenix Marine Services operated the ETL at their Global Gateway South Terminal in the Port of Los Angeles during the demonstration phase. However, FMS was not always the name of the fleet operator. After the project was awarded, Eagle Marine Services changed ownership and rebranded as FMS. The fleet operator is referred to as FMS throughout this report.

Port of Los Angeles (POLA) – The Project Team's demonstration site was located at the Port of Los Angeles. POLA personnel provided consultation services to the Project Team and ensured compliance with the California Environmental Quality Act (CEQA). POLA is a national leader in freight cargo reception, representing approximately 20% of all cargo coming into the United States.

Hyster-Yale Materials Handling (HYMH) – Hyster-Yale Materials Handling, Inc. (formerly Hyster-Yale Group) is a public entity that designs, engineers, manufactures, sells, and services a comprehensive line of lift trucks and aftermarket parts marketed globally. In this role, HYMH built and validated a hybrid battery/fuel cell ETL with wireless charging from the product line of one of their primary brands, HYMH. HYMH also led integration efforts of the fuel cell system into the base vehicle as well as provided engineering support throughout the project demonstration period. A Hyster® 1150HD-CH model electric-drive ETL developed by HYMH was modified to allow fuel cell compatibility. This base electric vehicle was manufactured in the Netherlands where HYMH led the integration of two Nuvera® OS1L2-45 fuel cell engines and auxiliaries such as the hydrogen storage system and necessary software controls with support from Nuvera. HYMH led the integration of the wireless charging technology into the fuel cell hybrid vehicle with support from WAVE.

Nuvera – Founded in 2000, Nuvera Fuel Cells, LLC is a subsidiary of Hyster-Yale Materials Handling and is a leading global developer fuel cell power systems. Nuvera led final analysis and design for integration of the fuel cell powertrain into the base electric utility vehicle. Nuvera supported integration of the fuel cell engines with the base electric vehicle.

Air Products – Air Products offers end to end solutions including hydrogen production and distribution, carbon capture and sequestration, and hydrogen refueling technology. Air Products provided hydrogen fuel for a portion of the demonstration. The hydrogen fuel provider was previously IGX, who was acquired by BayoTech in 2022.

Wireless Advanced Vehicle Electrification (WAVE) – Wireless Advanced Vehicle Electrification provides standards-based, interoperable, warrantied wireless-charging infrastructure for transit, port, industrial and off-road electric vehicles and is the premier developer of wireless-charging solutions for medium- and heavy-duty vehicles in the U.S. WAVE's experience with complete vehicle integration and system interoperability position the company to support further commercialization of wireless-charging in these markets. WAVE developed the wireless-charging system and supported integration of the wireless-charging technology into the fuel-cell hybrid vehicle.

Fiedler Group – The Fiedler Group is a design and engineering firm that provided site planning, design, and permit application support. Fiedler Group supported the project during various stages of development including site design and hydrogen-fueler permitting.

Changes to Project Team

The Project Team evolved throughout the course of the program. In the project proposal, StratosFuel was named as a member of the Project Team. StratosFuel would provide a modular hydrogen-fueling station during the demonstration period using Luxfer-GTM mobile fueling technology. StratosFuel would also be responsible for data collection and reporting on their equipment. After the project award, StratosFuel notified CTE that they would not be able to complete its scope of work for the same cost that was awarded by CARB and withdrew from the project. StratosFuel was replaced with the IGX Group (IGX), and IGX was named as the new hydrogen fuel supplier for the project. In 2021, BayoTech acquired the IGX Group. Throughout 2023, the Project Team worked to procure a new hydrogen fuel supplier. The final fuel provider for this program was Air Products.

In the project proposal, Moffat & Nichol (M&N) was named as the Project Team's Architecture and Engineering (A&E) partner. M&N was to complete engineering and design work for each charging station, including coordinated design reviews. After the project award, M&N withdrew from acting as the contracted A&E firm for the project. Instead of releasing a request for proposals (RFP) for only site design, CTE requested proposals for a combined design and build solution. P2S, Inc. was selected as the project's new A&E partner responsible for site design and permitting for two wireless chargers. AMTEK was added as the construction and installation service provider.

Project Objectives

The objective of this project was to increase the range and thus viability of fuel-cell top loaders in port operation. This objective was achieved by developing and demonstrating a hybrid battery/fuel cell ETL with fuel-cell range extension and wireless-charging capability. Demonstration of the ETL occurred in regular terminal operation services at POLA and utilized both on-site hydrogen refueling and wireless-charging deployed by the

Project Team. All related support activities necessary for a successful deployment were provided by the Project Team. These activities included operations, project management, manuals, training, maintenance support, and data collection.

The ETL Project included of four major tasks. The primary objectives for each phase were as follows:

- Task 1: The Project Team satisfied all administrative project requirements such as contracting, project kickoff and other meetings, project management plan, and reporting documents.
- Task 2: The Project Team developed, manufactured, and validated a fuel-cell assisted ETL.
- Task 3: The Project Team completed all activities necessary for preparation for a safe and successful demonstration of the ETL. These activities included establishing on-site hydrogen fueling, installation and commissioning of a wireless-charging station, completing safety/operations manuals, coordinating training, and vehicle delivery.
- Task 4: The Project Team conducted a vehicle demonstration.

Project Approach

General Approach

The Technical Approach section below discusses the methodology implemented for the successful development and demonstration of the ETL. The project was accomplished through four main tasks. Task 1 was led by CTE, focused on project administration and management. Through Task 1, CTE ensured all subtasks required to meet project objectives were successfully completed. Task 2 was managed by CTE and led by Hyster. It was focused on the development, build, and validation of the ETL. During Task 3, the Project Team completed supporting activities necessary to prepare for the successful demonstration of the equipment along with charging and fueling infrastructure. Task 4, led by CTE and FMS, focused on demonstration, data collection, and reporting.

Technical Approach

Note, not all tasks had associated deliverables.

Task 1: Project Management

Task Summary: CTE developed a detailed project work plan, coordinated execution with members of the Project Team, identified and managed risks associated with the project, and worked with CARB to manage project schedule and budget changes.

Task Details:

- CTE provided overall program administration, budget, and schedule oversight
- CTE coordinated and conducted project kickoff
- CTE coordinated press releases and press events
- CTE ensured completion of required CEQA documents
- CTE provided project partner oversight
- CTE submitted project reports and disbursement requests to CARB
- CTE submitted data as requested by CARB
- CTE coordinated and led periodic project status update meetings

CTE also provided technical support and project management services to the Project Team above and beyond the administrative activities highlighted above. These additional services included, but were not limited to:

- Technical oversight
- Risk analysis and mitigation strategies

- Permitting
- Equipment and station deployment
- Training
- Commissioning assistance

Task 2: ETL Development, Build and Validation

Task Summary: The purpose of this task was to successfully develop, manufacture, and validate a fuel-cell assisted electric-drive top loader. The vehicle utilized a hydrogen fuel-cell for extended range operations. HYMH built upon their wireless charged electric container handler (top loader) design by modifying the electric drive system to include a Nuvera fuel-cell and a hydrogen storage system (HSS). The energy storage system (ESS) and supervisory control system was reconfigured and optimized to meet the operational requirements in the hybrid configuration. The Nuvera fuel-cell system was based on an existing architecture but modified for the top loader application. All associated electrical and mechanical integration work was accomplished during the course of the design and manufacturing phases of this project.

Task 2.1: Requirements Definition

Task Summary: HYMH, with support from CTE, Nuvera, WAVE, and FMS, completed a final requirements definition and documented the vehicle specification. This task included modeling and simulation analysis of the vehicle duty cycle data and establishment of operational requirements.

Task 2.2: Vehicle System Design & Build Upgrade Electrification

Task Summary: HYMH, with support from Nuvera and WAVE, designed the integration necessary to incorporate the fuel-cell and hydrogen storage system and optimize the electric drivetrain to meet the requirements previously established. As part of this task, HYMH completed the electrical and mechanical design of the traction motor drive, ESS, fuel-cell integration, power electronics, HSS, and supervisory controls. Also, as part of this task, WAVE completed the procurement process of the wireless-charging system.

Deliverables:

- Documentation and photos of complete base truck and wireless-charging
- Bill of Materials
- 3D modeling of vehicle systems
- Compiled invoices and confirmations

Task 2.3: Final Fuel-Cell System (FCS) Design

Task Summary: Nuvera adapted, tested, and adjusted the fuel-cell stacks and balance of the plant to complete the updated fuel-cell system design. Prototype fuel-cell systems were built and bench tested with results used to incorporate iterative design updates. Nuvera conducted durability testing and investigated potential system improvements. Nuvera finalized the design of the fuel-cell system used in the ETL.

Deliverables:

- FCS design

Task 2.4: Vehicle FCS Build and Delivery

Task Summary: Nuvera procured hardware, built the fuel-cell system, tuned, completed factory acceptance testing, and shipped the fuel-cell system for integration into the prototype top loader.

Deliverables:

- FCS performance testing summary
- Delivered fully functional fuel-cell system

Task 2.5: Top Loader Integration (FCS and WCS)

Task Summary: HYMH procured the base top loader and electric propulsion system components. WAVE built and delivered the onboard charging hardware including the wireless-charging receiving pad (secondary coil) for the wireless-charging system (WCS). HYMH, with support from Nuvera, integrated the fuel-cell into the propulsion system. HYMH, with support from WAVE, integrated the WCS into the vehicle. This task included hybrid system development tasks (including power electronics, and system controls), component packaging, system component sourcing, and mechanical and electrical integration of the fuel-cell engine and wireless receiving pad.

Deliverables:

- Functional fuel-cell top loader
- Complete wireless-charging integration
- Complete fuel-cell integration

Task 2.6 and 2.7 System Test and Validation

Tasks Summary: A fully executable validation plan was developed by HYMH to accurately track and manage testing. HYMH, with assistance from Nuvera and WAVE, tested and validated all performance and safety elements of the fuel-cell ETL in operation. This served to ensure that all systems and components operated properly and within the developed specifications. Subsystem tuning and calibration were completed during this task. This was completed and reviewed prior to delivery. This task resulted in the completion of a vehicle commissioning report, which was submitted to CARB.

Deliverables:

- Fuel-cell system test
- Validation report
- ETL and WAVE test and validation report
- Commissioning Report

Task 3: Demonstration Readiness

Task Summary: The purpose of this task was to complete all of the supporting activities necessary to prepare for safe and successful demonstration of the ETL. These activities included establishing on-site hydrogen fueling, installation, commissioning the WCS, completing manuals development, preparing for and coordinating training, vehicle shipping, preparing for maintenance support, and on-site vehicle, fueling, and charging system validation and shakedown.

Task 3.1: Install and Commission Hydrogen Fueling

Task Summary: CTE, with support from BayoTech, FMS, and POLA, conducted a kickoff to establish goals, roles, tasks, communications, and expectations for hydrogen fueling. CTE and the BayoTech coordinated with the FMS to finalize the staging location of the mobile hydrogen-fueling unit and for the provision of any necessary utilities. The Project Team coordinated and executed a fueling agreement and obtained the necessary permits. BayoTech delivered and staged the hydrogen fueling supply equipment.

Deliverables:

- All necessary approved permits
- Refueling procedure including responsibilities and site plan
- Executed fueling agreement
- Confirmation of fueling supply equipment delivered to site
- Hydrogen purity report
- Confirmation of station commissioning

Task 3.2: Install and Commission Wireless Charger

Task Summary: CTE provided overall coordination with FMS, POLA, P2S, AMTEK, and WAVE to complete charging station design and construction. CTE conducted a kickoff to establish goals, roles, tasks, communications, and expectations for installation of the wireless-charging station. WAVE provided site requirements for installation of a wireless-charging station at the ETL parking location. P2S, with support from FMS, WAVE, and POLA, completed engineering and design work for the charging station, including coordinated design reviews. Mechanical, civil, and electrical layouts were established along with all necessary environmental reviews and construction scheduling. Project leads applied for and obtained the required permits to begin station installation. CTE procured a general contractor for the required construction work. WAVE ordered, built, and delivered all necessary wireless-charging equipment. WAVE coordinated with AMTEK, CTE, FMS, and P2S to ensure installation and commissioning of the charging equipment at the site occurred in an efficient and effective manner in parallel with construction. AMTEK completed construction and final inspections occurred. WAVE commissioned the charging station.

Deliverables:

- All necessary approved permits
- Site plan and project schedule
- Progress reports and copies of updated project schedules
- Final design drawings
- Construction contract
- Invoices for major equipment
- Confirmation of major equipment delivery
- Confirmation of final site inspections
- Commissioning report
- Commissioning of wireless-charging station

Task 3.3: Manuals Development

Task Summary: HYMH, with the support of CTE, and Nuvera, developed and delivered maintenance and operation manuals for the ETL. FMS reviewed the draft manuals and provided feedback for incorporation by HYMH. HYMH delivered the final manuals to FMS. WAVE also developed and delivered a maintenance and operation manual for the WCS.

Deliverables:

- Operators and Maintenance manuals

Task 3.4: Develop Maintenance Support Plan

Task Summary: The Project Team developed a Maintenance and Support Plan (MSP) to provide dedicated maintenance and support of the ETL throughout demonstration operations. Given the various roles and locations among the Project Team, this task was necessary to ensure maximum availability for the ETL during the demonstration period. Based on the content of the MSP, the Project Team provided technical support to address any issues the ETL might encounter, focusing on maintaining optimal reliability, efficiency, and performance. The MSP was distributed and reviewed as part of the training materials.

Task 3.5: ETL Shipping and Acceptance

Task Summary: HYMH prepared, shipped, and delivered the ETL to POLA.

Deliverables:

- Shipping and delivery documents

Task 3.6: On-Site Validation & System Shakedown

Task Summary: CTE provided overall coordination with all project members to conduct on-route validation and system shakedown for the ETL, WCS, and mobile hydrogen fueling system. This included multiple days of monitored test service, charging, and fueling to make sure any issues were discovered and addressed prior to placing the ETL into regular service. This also ensured the vehicle was received in the same condition that it was in when it left the integration facility. Any issues identified in the system shakedown were addressed and additional tuning was made.

Task 3.7: Training

Task Summary: CTE, with the support of HYMH, Nuvera, WAVE, BayoTech, and FMS, developed and administered a training plan for the ETL, the WCS, and the hydrogen fueling equipment. HYMH, with support from Nuvera, provided ETL operation and maintenance training. HYMH, with support from WAVE, also provided WCS operations training, and BayoTech provided training for the mobile hydrogen refueling. When Air Products became the Project's new hydrogen fuel provider, Air Products conducted an additional hydrogen refueler unit operation training. With the help of Project Team, CTE coordinated and executed a training plan for local first responders. Once the ETL was commissioned and accepted by FMS, the Project Team completed training requirements.

Deliverables:

- Training plan
- Completed training roster

Task 4: Vehicle Demonstration and Data Collection

Task Summary: The purpose of this task was to safely and successfully complete in-service ETL demonstration and all necessary data collection. HYMH was engaged throughout the demonstration period, working with FMS staff to provide technical support. The Project Team focused on maintaining optimal reliability, efficiency, and performance. HYMH followed the data collection plan and established procedures to report on vehicle specifications, performance, fuel and energy consumption, along with associated costs. WAVE provided ongoing maintenance and technician support throughout the demonstration period for the successful operation of the wireless charger. The Project Team provided data points related to energy consumption and charging of the ETL battery system. The hydrogen fuel providers both provided ongoing fuel delivery service and technician support throughout the demonstration period for the successful operation of the hydrogen mobile refueling solution. They were positioned to maintain constant communication with CTE and fleet operator staff to provide fueling training, to report fuel consumption data, and to schedule fuel deliveries as needed.

Task 4.1: ETL Operations and Support

Task Summary: The purpose of this task was to demonstrate and support the ETL in real-time port operations, charging, and associated fueling. FMS operated the ETL in routine service, and the Project Team provided technical support.

Deliverables:

- Monthly and Quarterly Reports summarizing vehicle operation

Task 4.1.1: Data Collection Plan

Task Summary: CTE, with support from HYMH, WAVE, and FMS, established a data collection plan that was completed prior to the start of the demonstration. The data collection plan included descriptions of how the data is collected (on-board or logged), where the data is collected (vehicle, charging station, or mobile hydrogen refueler), how it is transmitted (telemetry, data card, etc.), how it is processed, and who is responsible for each activity. HYMH provided parameters to include in the data collection plan. WAVE's system engineers reviewed and approved their internal data collection process to ensure compliance with the overall data collection plan. Nuvera acknowledged its responsibilities for the data collection plan and provided system information for the fuel-cell engines. CTE also requested sample data output files for internal review and verification. The data collection plan was submitted to CARB for review.

Deliverables:

- Data collection plan

Task 4.2: Hydrogen Fueling Station Support

Task Summary: BayoTech, with support from FMS and CTE, ensured that hydrogen fuel was supplied throughout the demonstration period.

Deliverables:

- Monthly reports with summary of support
- Invoices for hydrogen and equipment

Task 4.2.1: Hydrogen Fueling Station Operations and Maintenance

Task Summary: BayoTech provided hydrogen fuel using the mobile fueling unit. As part of this task, BayoTech completed regular preventative maintenance on the unit.

Deliverables:

- Monthly reports with summary of support

Task 4.2.1.1: Monitor and Confirm Hydrogen Supply

Task Summary: CTE provided technical expertise to coordinate permitting, operation and fuel supply for the hydrogen station. This task resulted in an operational fueling system with a reliable supply of hydrogen.

Deliverables:

- Station operating permit
- Invoice for first hydrogen delivery

Task 4.3: Wireless-Charging Station Support

Tasks Summary: WAVE provided maintenance support for the WCS throughout the demonstration to ensure optimal reliability, efficiency, and performance.

Deliverables:

- Monthly Reports with summary of support

Project Results

The following section outlines the work accomplished over the duration of the project. This section is presented in three parts to reflect the phased approach of this demonstration.

1. Task 1: Project Management
2. Task 3: Infrastructure Planning and Deployment
3. Tasks 2 and 4: Vehicle Planning and Deployment

Task 1: Project Management

Over the course of the project, CTE conducted weekly team meetings and compiled monthly and quarterly reports with input from team members. The Project Team administered action items for the project and managed the project schedule, budget, and cost share projection.

Upon the project award in 2018, CTE and CARB executed the prime agreement. The Project Team encountered delays in finalizing the subcontractor agreements due to negotiations over terms and budgets. In response, CTE developed a resolution plan to mitigate these delays and ensure that the project demonstration period remained unaffected. Concurrently, project partners HYMH and WAVE raised concerns about potential additional delays stemming from equipment and subcomponent lead times.

CTE managed budget and fuel availability risks associated with the hydrogen fuel supply. In January 2019, CTE received an updated quote from the original hydrogen supplier, StratosFuel, which significantly exceeded the initial quote and the project budget. To mitigate budgetary risks associated with the high cost of hydrogen from StratosFuel, CTE issued a Request For Quote (RFQ) to find a replacement supplier. Through this RFQ process, the Project Team identified three potential suppliers. While this process affected CTE's project administration budget, the Project Team successfully avoided major schedule impacts. To address budget overruns, CTE worked with CARB to extend the project schedule, reduce the project scope, and reallocate funds. Further details can be found in the *Infrastructure Planning and Deployment* section.

Throughout 2019, additional project delays were encountered due to the structure of WAVE's scope of work and budget in the project contract. Many tasks in the CARB agreement were set up as milestone payments, meaning funds could not be disbursed until each task was completed. Specifically, the WAVE "Confirmation for Final Site Inspection" task suggested that WAVE needed to complete final site inspection to receive payment. However, before the site inspection can take place, several prerequisite tasks needed to be completed, including designing the WCS, procuring parts, preparing the site, and building and validating both the primary and secondary systems. The initial project proposal did not adequately account for the tasks, schedule, and budget necessary for much of WAVE's scope of work. Consequently, the Project Team had to determine how to secure funds so WAVE could begin procuring parts for the WCS.

Due to the structure of the work breakdown and milestone schedule, HYMH could not commission the vehicle until WAVE's secondary charging system was installed and validated on the vehicle at HYMH's facility in Nijmegen, Netherlands. In response to these challenges, HYMH agreed to supply working capital to WAVE to procure parts for the WCS ahead of the CARB procurement milestone. WAVE was able to provide a dummy secondary system to allow HYMH to validate their system in parallel with WAVE's validation of the actual secondary system.

To address the challenges with the milestone payment schedule, CTE developed and submitted a proposal to extend the demonstration period at no additional cost to CARB. Grant Amendment One reduced the project scope from two wireless chargers to one and reallocated the savings to cover infrastructure cost overruns. The amendment also adjusted the milestones into smaller tasks, allowing partners to receive payments more frequently. Executed on February 5, 2020, this amendment extended the project completion date from March 30, 2020, to February 28, 2021. Additionally, the Project Team shifted administrative funding to Tasks 3.2.1 and 3.2.6 to offset the increased cost of infrastructure construction and installation. This amendment added IGX, P2S, and AMTEK as project partners.

CTE executed four additional amendments to the original CARB agreement. The changes and reasons for each of these amendments are summarized below:

Figure 1: Top Loader Lifting Container

Grant Amendment Two, executed on February 25, 2021, extended the timeline for most incomplete tasks and set the new project completion date to May 19, 2022. The amendment introduced a Commissioning Report task and reallocated funds to the project administration task to address budget shortages caused by delays. Additional budget adjustments were made to better align with actual costs incurred and updated budget projections.

Grant Amendment Three was executed on June 2, 2022. This amendment extended the timeline for most tasks and set the new project completion date to March 31, 2023. It also updated key personnel and CARB Project Liaison information.

The fourth Grant Amendment was executed on May 1, 2023. CARB Amendment Four updated the standard CARB terms and conditions, extended the timeline for incomplete tasks, and set a new project completion date of April 30, 2024. This amendment also replaced the previously executed Temporary Entry and Use Permit (TEUP) with a new Revocable License from POLA. The original TEUP, valid for one year, was no longer sufficient due to the project extension, necessitating a review of permitting requirements. POLA informed the Project Team that TEUPs had been replaced with Revocable Licenses. Securing the new Revocable License ensured that both FMS and CTE had the appropriate real-estate entitlements, with insurance and indemnity protections in place for the duration of the project. Additionally, CARB Amendment Four updated key personnel and CARB Project Liaison information, and reflected a change in the hydrogen fuel provider from BayoTech to Air Products.

The last Grant Amendment, Amendment Five, was executed on April 10, 2024. This amendment updated the Guarantee Liaison Information, reduced the demonstration duration to three months, and extended the project completion date to August 31, 2024. It also introduced a new task for monitoring and confirming the hydrogen supply. Additionally, Amendment Five updated Work Task Names, Descriptions, and Deliverables to ensure consistency with the Project Schedule and to clarify deliverable locations. This amendment also made budget adjustments to better align with actual costs incurred and updated projections. Lastly, it updated key project personnel.

CTE also pursued additional funding to support the project. In 2023, CTE sought funding from Southern California Gas Company (SoCalGas) to ensure financial support for the demonstration period. In January, CTE submitted a proposal to SoCalGas for additional funds to support the ETL demonstration, specifically for hydrogen fueling station support and to cover hydrogen fuel costs throughout the demonstration. Throughout the year, CTE actively monitored this funding opportunity from SoCalGas to extend the demonstration period. In April 2023, CTE and SoCalGas worked together to develop a contract. However, final contract execution was contingent upon budget approval from the California Public Utilities Commission (CPUC).

On October 24, 2023, CPUC issued Draft Resolution G-3601 in response to SoCalGas's proposed 2023 Research, Development and Demonstration (RD&D) Research Plan. The Draft Resolution stated that CPUC denied any funding for projects under the SoCalGas Clean Transportation program portfolio, which included the ETL project. While CPUC agreed that the SoCalGas Clean Transportation Program projects align with the State's decarbonization goals, they argued that the Clean Transportation program does not demonstrate reasonable probability of providing benefits to SoCalGas ratepayers. In November, to reverse CPUC's decision, CTE submitted comments to more than 1,500 individuals on the CPUC service list explaining how the Clean Transportation Program does in fact provide ample benefits to SoCalGas ratepayers. On November 30, 2023 CPUC released the final resolution which denied the funding request to SoCalGas Clean Transportation Program projects. As a result, CTE focused on aligning the project budget and schedule to determine available funding for the ETL's operation and demonstration, as well as for any necessary administrative and technical tasks. CTE, in collaboration with all project partners, conducted a financial audit and analysis to assess the availability of project and cost-share funding. These adjustments to the project budget and schedule were incorporated into Amendment Five of the CARB Agreement.

Task 3: Infrastructure Planning and Deployment

Members of the Project Team met in early August 2017 at the FMS location to review the equipment and station requirements, both for hydrogen supply and the charging stations, and the Project Team evaluated power supply locations. Originally, the two wireless-charging stations were to be deployed at different ETL parking locations, one near the Gatehouse and one near the Power Shop. These were chosen for close proximity to the locations where equipment typical sits during breaks and shift changes, as shown in Figure 2: Original Locations for Wireless Chargers and H2 Refueling Equipment. However, with the change in WAVE's scope, described in the *Wireless-Charging Equipment* section below, the Project Team choose the Power Shop location for the wireless-charging station.

Figure 2: Original Locations for Wireless Chargers and H2 Refueling Equipment

The wireless-charging equipment requires one step-down transformer to supply 480V, 3-phase power with 600A service. Required WAVE infrastructure equipment included a WAVE power supply, a WAVE cooling unit, a WAVE primary cabinet, a WAVE primary charging pad, and associated conduit and wiring. The first three pieces of equipment are installed above ground on a concrete pad and connected to the primary charging pad located on a second concrete pad via conduit and wiring. The substation at the Power Shop already had 480V supply and a 600 A circuit that was no longer being used.

In the original work scope, StratosFuel was to provide a mobile refueler that could be supplied on demand without any compression or electrical connection. The equipment was to cascade fill directly into the ETL with an anticipated refueling time of 10-15 minutes depending on the amount of fuel dispensed. The mobile fueling system was entirely self-contained and only required 110-volt electrical service to operate a small booster pump. All equipment was to comply with relevant codes and standards for mobile fueling units, and permits were to be addressed and presented to CTE by StratosFuel. StratosFuel would also be responsible for data collection and reporting on their equipment.

Figure 3: Original Site Plan for Operations and H2 Fueling

After the project was awarded, Eagle Marine Services changed ownership and rebranded as Fenix Marine Services (FMS). FMS's new management reassessed the original equipment locations detailed in Figure 3: Original Site Plan for Operations and H2 Fueling and mandated for the Project Team to consolidate the equipment into a common space. The surface of the new location was undeveloped which had downstream impacts detailed below under *Wireless-Charging Final Site Design.*

Wireless-Charging Final Site Design

Originally, CTE was to provide overall coordination with FMS, POLA, M&N, and WAVE to complete charging station design and construction. As the Project Team's A&E partner, M&N was to complete engineering and design work for each charging station, including coordinated design reviews. WAVE provided site requirements for installation of wireless-charging stations at two ETL parking locations. M&N would properly establish mechanical, civil, and electrical layouts along with all necessary environmental reviews and construction scheduling. Additionally, M&N project leads would apply for and obtain the required permits to begin station installation.

It was originally planned for CTE to procure a general contractor for the required construction work. In this way, WAVE would coordinate with the General Contractor, CTE, FMS, M&N to ensure installation and commissioning of the charging equipment at both sites occurs in an efficient and effective manner in parallel with construction. Ultimately, the General Contractor would be responsible for completing construction and final inspections, and WAVE would be responsible for final commissioning of the two charging stations.

After the project award, M&N withdrew from acting as the contracted A&E firm for the project. Instead of releasing a request for proposals (RFP) for only site design, CTE requested proposals for a combined design and build solution. CTE received proposals that significantly exceeded the budgeted amount for design and construction. The original budget was created by CTE and WAVE's combined experience with installing WAVE equipment. The Project Team learned that POLA did not have topographic maps of the new location for infrastructure equipment which led to an increase in cost for design and permitting in order to complete a topographic survey. As a result, CTE split the scope of work back into the original two phases, design/permitting and construction/installation. Separating the design phase of the project would provide final and complete drawings that set requirements and define the scope of work in order to remove unnecessary construction costs.

After re-releasing the RFP for design only, CTE selected P2S, Inc. as the project's new A&E partner responsible for site design and permitting for two wireless chargers. P2S has considerable experience with projects at the POLA and was cost competitive with the original budget.

P2S conducted the topographic survey and found that the new wireless-charging location was in an area with poor water drainage. Pooled water could cause loss of performance or damage to equipment, and due to a larger asphalt plan for the area, the vehicle would have to drive up on an elevated concrete pad to charge. Although it would reduce the risk of water pooling on the charging equipment, the concrete pad added complexity to operation and added cost to construction. The elevated concrete pad would also require wheel stops to prevent the vehicle from overrunning the pad. However, adding wheel stops doubles in benefit to provide appropriate charging alignment.

P2S's civil engineering group revised the civil plans and calculations to reduce project scope from two wireless chargers to one. P2S, in coordination with CTE, WAVE, and FMS, completed and passed three gates to final design: 60% complete, 90% complete, and 100% complete. The POLA Harbor Department and Los Angeles Department of Build and Safety (LA City) plan checkers were required to sign off on the drawings before construction could begin.

During the LA City plan check, WAVE reached out to the LA City Plan Check Engineer to establish communication regarding the UL field certification required before the wireless-charging system could be used in demonstration. At this time, the LA City Plan Check Engineer raised concern over the potential physiological effects that the wireless-charging process could have on the ETL's operator or other bystanders. They were reassured that there are no human health impacts of wireless-charging, even at 250kW power level, with reference to compliance of IEEE Standard C95.1-2005 which covers electromechanics fields in the range from 0 Hz to 300 GHz and their potential hazards for human exposure, volatile materials, and explosive devices. Adherence to this standard was not acceptable by the LA City Plan Check Engineer who offered no alternative means of satisfying the concern over human health impacts. This was ultimately resolved, however it held up the permitting process from February 2019 to May 2019.

With permitting complete, CTE wrote and released an RFP for construction and installation services. This RFP included relevant specifications provided by P2S who remained on the Project Team to provide construction support. Funds from CTE's project administration budget were shifted to the charger construction and installation task to cover P2S's additional scope of work (support during the construction phase).

CTE received two proposals in response to the RFP for construction and installation services. Both proposals were considerably over the estimated budget for this task, the main reason being the complicated concrete work that would be required. To better understand the cost overruns, the Project Team held post-bid interviews with both organizations. Common clarifications and questions included changing backfill material to be slurry for ease and cost, removing the truck tire wash station, modifying the as-built drawing requirements from 3D rendering to red-lines, and clarify that electrical testing did not include infrared or arc flash studies. Ultimately, the post-bid interview informed clarifications documents released to both organizations to provide their best-and-final offer (BAFO).

BAFOs were evaluated by an evaluation team consisting of CTE, P2S, WAVE, and FMS. Scoring criteria included strength of response, qualifications, ability to meet schedule, and price. AMTEK was selected due to their previous experience, ability to complete work ahead of schedule, and competitive cost.

Site Work

AMTEK construction began work during the fourth quarter of 2019. The firm completed initial excavation to verify underground locating done with ground penetrating radar (GPR) and began lab testing of subgrade and soil. Trenching was required to run the conduits and electrical connections from the power transformer to the primary cabinet equipment and from the primary cabinet equipment to the wireless-charging pad. AMTEK completed the trenching without issue. See Figure 4: Excavation for Wireless-Charging Pad of the completed excavation.

Figure 4: Excavation for Wireless-Charging Pad

Next, AMTEK installed the electrical conduit to provide power from the transformer to the primary cabinet equipment and from the primary cabinet equipment to the wireless-charging pad. The conduit installation was verified by P2S and passed POLA and LA City inspections.

After verification of electrical conduits, AMTEK graded the site and set the rebar as the structure for the concrete pour of the primary equipment pad and wireless-charging pad. AMTEK encountered issues passing grading inspection due to the junction box being too small and the ampere interrupting capacity (AIC) rating for the circuit breaker being too low. The junction box and the circuit breaker were both replaced by March 10, 2020. After a lengthy inspection, the LA City electrical inspector gave their approval, and the concrete was poured. See Figure 5: Concrete Equipment Rebar Set for Cabinet Pad and Figure 6: Concrete Cabinet Completed Work for Equipment for completed concrete work.

Figure 5: Concrete Equipment Rebar Set for Cabinet Pad

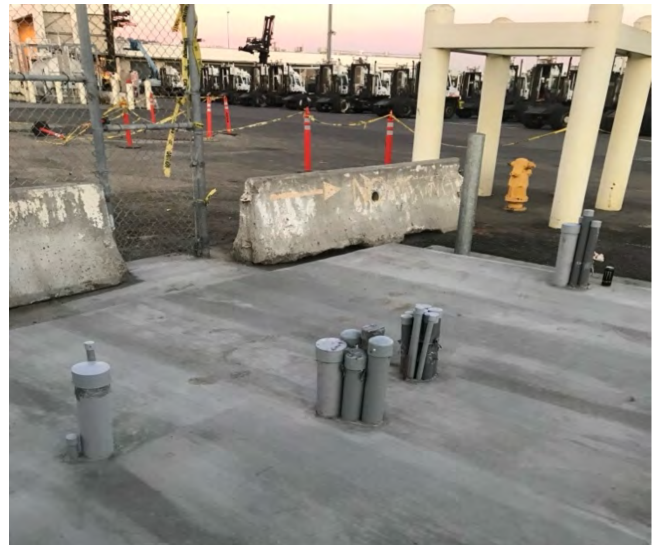

Figure 6: Concrete Cabinet Completed Work for Equipment

Wireless Charger Installation

In early 2019, WAVE faced significant procurement delays for essential components, particularly the primary charging pad and power supply units. These are some of the many components in the WCS. See Table 1: WAVE WCS Components for the list of WCS components. These delays, impacting the schedule by approximately one month, prompted WAVE to reorganize its procurement, build, and validation timeline. WAVE coordinated with HYMH directly to develop mitigation strategies and reached an agreement where HYMH would provide bridge funding for WAVE to finalize their procurement as to not further impact the project schedule.

Table 1: WAVE WCS Components

System	Component
Primary Pad	Primary Cabinet
	Primary Pad
	Lift (full assembly)
	Power Supply
Secondary Pad	LV Control Box
	Rectifier
	Cold Plate
	Secondary Pad

WAVE supplied HYMH with a “dummy system” that was installed onto the vehicle to finalize vehicle interfaces with the wireless-charging secondary equipment. This strategic approach ensured minimal disruption to the project timeline. WAVE shipped the dummy secondary system to HYMH on August 8, 2019. By the end of 2019, HYMH received the power supply unit and was able to begin integration and full system validation. However, unforeseen delays stemming from the COVID-19 pandemic necessitated additional testing and preparations, maximizing the system validation time.

HYMH successfully integrated the secondary system onto the vehicle in Nijmegen the week of January 6, 2020. In May of 2020, WAVE completed a full system validation. This included completion of automatic power transfer, automatic lift actuation, final controls development, and alignment features. WAVE reported that full system power transfer characteristics and efficiencies showed good results at the contracted power transfer level of 250 kW. However, in normal operation the vehicle would be charging at a rate of approximately 90 kW.

The complete system was shipped to POLA on July 8, 2020 and arrived on July 10, 2020. AMTEK was responsible for offloading the charging pad equipment the prior week, placing it at the project site, and completing the installation of the WCS. WAVE, AMTEK, and FMS installed the charger the week of July 13, 2020. On July 16, 2020 the charger passed the UL Field Evaluation and the UL report was distributed to inspectors from the port and city. See Figure 7: WAVE Charging Pad Preparation for the completed charging pad installation.

WAVE tested and validated the primary and secondary equipment. However, without the ETL on-site there was no use for the charger.

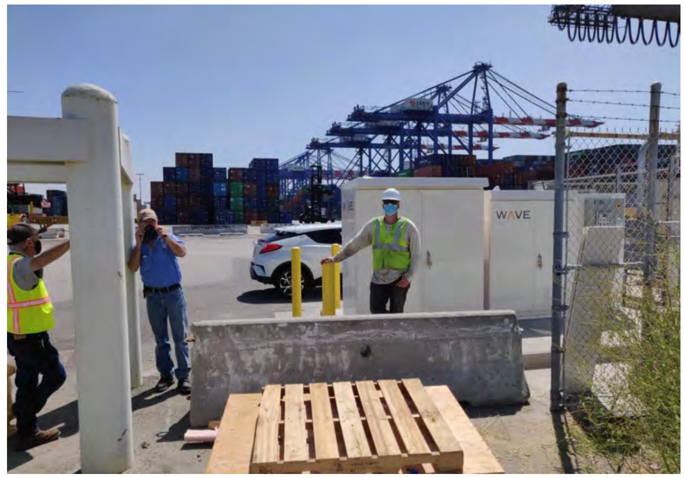

Figure 7: WAVE Charging Pad Preparation

When the vehicle arrived in September 2022, technical challenges emerged, notably regarding misalignment between the wheel guides and the charging pad. The misalignment between the wheel guides and the charging pad was due, in part, to how the wireless-charging pad was installed. There was a misalignment of four inches (measured on the insides of the duals to the outsides of the guides) that prevented the vehicle properly sitting on the primary pad. WAVE had to cut and re-fit part of the wheel guide to allow the vehicle to move for enough forward to properly align.

WAVE developed a detailed plan to rectify alignment issues, involving the fabrication of spacers and meticulous adjustments to the guide assembly. The steps were as follows:

- Step 1. Fabricate two 3” aluminum spacers to widen the guides prior to the work at FMS (the intended spacers were missing and not installed)
- Step 2. Remove the entire assembly from the concrete pad in four pieces
- Step 3. Cut off thirty-eight 22-mm anchors flush to the concrete slab
- Step 4. Replace assembly and center to the charging pad, and confirm with the top handler with 3” of spacing to widen the guide rails, (confirm alignment with top handler and WAVE software)
- Step 5. Drill and anchor the two first-stage assemblies right and left
- Step 6. Add wheel stops to the second section of the guide assembly
- Step 7. Confirm alignment of second stage of wheel guide stops and anchor
- Step 8. Weld the wheel stop section back to the main body, weld 2” angle wheel chalks to stop section
- Step 9. Align and level secondary pad on top handler
- Step 10. Commission WAVE system and confirm charging

The installation of wheel guides was successfully completed in October 2023, facilitating promising charging tests. However, persistent communication issues between the WCS and the vehicle necessitated ongoing software updates, and the discovery of miswiring in the secondary pad required further attention and resolution.

Through collaborative efforts between WAVE, HYMH, and FMS throughout October 2023, significant strides were made in addressing software-related challenges, with HYMH undertaking further developments to enhance communication between the truck and WCS. By September 2023, substantial progress was evident, with the WCS deemed functional, albeit requiring additional fine-tuning.

Hydrogen Fuel Supply - Demonstration Period 1

As discussed in the *Changes to Project Team* section, upon project award StratosFuel notified CTE that they would not be able to complete its scope of work for the same cost that was awarded by CARB and withdrew from the project. CTE worked to understand the withdrawal and ultimately released a RFQ to procure a new supplier for hydrogen fuel and refueling equipment. CTE received three proposals, which were evaluated based on technical approach and budget. The IGX Group was selected and partnered with Fiedler Group for site design and permitting.

By the third quarter of 2019, CTE executed its subcontractor agreement with IGX to provide hydrogen refueling equipment and fuel during vehicle demonstration. IGX planned to use a GTM-1500 mobile refueler, shown in Figure 8: Fueling the Top Loader with GTM-1500, which required a permit from the LA Fire Department and site access agreement. See the *Data Report* section for details on the GTM-1500.

Figure 8: Fueling the Top Loader with GTM-1500

After CTE and IGX executed the subcontractor agreement, FMS and IGX executed a site access agreement. FMS acquired a copy of the Harbor Engineer's permit, while Fiedler Group continued to work to obtain the permit from the LA Fire Department. Permitting was completed by the end of 2019, and IGX delivered the hydrogen refueling trailer to FMS in April 2020.

Although the refueling unit was on-site, it was not utilized until the vehicle arrived at POLA in August 2022. The delay was due, in part, to the COVID-19 pandemic. During this 30-month period, the vehicle was at the HYMH facility in Nijmegen, Netherlands.

The Project paid IGX monthly equipment lease fees. However, IGX gave the Project a significant discount to help mitigate the budgetary impact of the COVID-19 related delays. Please see the *Vehicle Planning and Deployment* section of the report for details about the vehicle design, build, and commissioning delays.

In April 2022, the CTE and IGX agreement expired and IGX was acquired by BayoTech. As part of the acquisition, BayoTech asked CTE to sign a Master Service Agreement (MSA) directly with the trailer leasing company. Rather than signing a new agreement, in September 2022, CTE sent BayoTech a revised agreement that incorporated MSA provisions from the trailer leasing company. When reviewing the revised agreement, BayoTech increased in the price of hydrogen from $18 to $25 per kg.

For the next four months, between September and December 2022, CTE and BayoTech were in negotiation regarding the terms of the revised agreement.

In early December 2022, BayoTech informed the Project Team of a significant increase in fuel and delivery costs due to sourced hydrogen from Northern California. This made it infeasible for CTE to manage the project budget effectively. As a result, CTE began exploring alternative fueling options, and the last BayoTech fill was on December 5, 2022.

Hydrogen Fuel Supply - Demonstration Period 2

In early 2023, CTE began contacting hydrogen fuel suppliers. Due to fuel unavailability, the ETL was not regularly operational in 2023, causing severe delays to the demonstration. CTE was able to secure fuel from OneH2 to operate the ETL for a few days in April 2023; however, the Project Team was unable to come to a long-term fueling agreement with OneH2.

In February 2023, CTE met with Air Products to discuss the availability of an HF-150 mobile refueler. In March 2023, CTE received a quote from Air Products and determined that the HF-150 Portable Hydrogen Fueler would be the best fueling solution for the remainder of the demonstration. CTE and Air Products entered into a fueling agreement in April 2023.

Unlike the BayoTech GTM-1500, the Air Products HF-150 required the vehicle to be driven to a stationary hydrogen trailer. This added step contributed to cost overruns from the Project Team. FMS stated that union restrictions prevented their operators from fueling the vehicle, so the Project Team had to find someone to connect the nozzle from the HF-150 to the ETL. With a 26.7 kg tank on the ETL and a daily consumption of up to 25 kg, the refueler had to be present every morning to fill the ETL with hydrogen. In September 2023, CTE identified a third-party refueler and began negotiations.

Figure 9: Top Loader Image from Launch Event

Operating the HF-150 required a Special Operating Permit from the Los Angeles Fire Department (LAFD). Having developed the permit package for the GTM-1500, CTE worked with the Fiedler Group to make updates. In May 2023, CTE met with LAFD to review the drawings. CTE, the Fiedler Group, and LAFD completed three rounds of revisions before receiving final approval for site drawings and a notice to proceed with site inspections. The preliminary site inspection took place in August 2023. LAFD provided several corrections, and CTE installed alternate grounding, mounted a fire extinguisher enclosure onto K-rails, and added additional NFPA placards around the site. The greatest challenge was obtaining timely responses from LAFD for clarification and guidance on next steps.

The Project Team held another LAFD inspection on November 6, 2023. During this inspection, LAFD triggered the alarm on the Air Products unit, but the alarm notification was not received. As a result, the inspection could not be completed. After further investigation the Project Team learned that the delay in the transmission of the alarms was due to the limited local cell service around the refueler. CTE explained this to LAFD, and another inspection was scheduled for November 14, 2023.

During this inspection, the Project Team received a notice to proceed. The final step was to work with the City Department to receive the operating permit. Over the next month, CTE coordinated wet signatures for the operating permit. In January 2024, the operating permit was fully executed, and the Project Team was clear to mobilize the mobile refueler.

Tasks 2 and 4: Vehicle Planning and Deployment

The following section outlines the project lifecycle from initial concept and build through to the vehicle demonstration. This structured approach helped ensure that the vehicle met quality standards and performed reliably. This section is presented in the following topics:

1. Design, Build, and Integration
2. Commissioning
3. Shipping and Delivery
4. On-Site Validation
5. Training
6. Manuals Development
7. Vehicle Deployment

Design, Build, and Integration

Once contracting was completed in early 2019, the Project Team began necessary tasks associated with the procurement components for the vehicle. It was essential to order vehicle components with long lead items early to adhere to the project timeline and meet task milestones. HYMH ordered storage system components and worked to develop controls for the battery pack and fuel-cell system.

The base vehicle was design finalized in July 2019, and components began arriving at the HYMH facility Nijmegen, Netherlands. Nuvera supported HYMH with fuel-cell system integration remotely and conducted durability testing. Fuel-cell integration was delayed because the fuel-cell engines needed to be returned to Nuvera for upgrades. Modifications were made to increase the isolation resistance in the engine design, and Nuvera conducted another full factory acceptance test before returning the fuel-cells to HYMH.

By the fourth quarter of 2019, HYMH’s fuel-cell installation was verified, and controls were tested to ensure proper communication between systems. The full build, including fuel-cell integration, was completed as scheduled.

Figure 10: Project Team with ETL at HYMH Facility

Commissioning

Once the fuel-cells were integrated, HYMH and Nuvera began vehicle commissioning. Due to COVID-19, international and organizational travel restrictions to HYMH's facility delayed the initial startup and commissioning required to complete vehicle testing and validation.

During commissioning in 2020 and 2021, HYMH and Nuvera experienced several challenges including electromagnetic compatibility (EMC) issues, motor malfunctions, battery concerns, and fuel-cell sensor issues. For further detail, please see the Hyster Maintenance Logs in Appendix D.

EMC Issues Causing Fuel-Cells to Shut Down: Nuvera was able to successfully complete a cycle of starting up and shutting down a fuel-cell engine and controls all worked as expected. However, when running the fuel-cells at higher power, the team ran into electromagnetic compatibility (EMC) issues with the buck DC/DC converters' high-frequency switching. The buck of the ETL is the attachment that is used to lift the containers. This caused issues with the fuel-cell CAN buses and would force the fuel-cells to shut down. Nuvera and HYMH consulted with the DC/DC supplier, but were unable to remedy the situation with any of the standard troubleshooting procedures. It was decided that the layout of the DC/DC converters would have to be redesigned to minimize both HV and LV wire crossing. This redesign also required new wire harnesses and brackets.

HYMH purchased equipment to allow for higher resolution measurements to aid the testing and the troubleshooting process. Adjustments were made that allowed the vehicle controller area network (CAN) to operate without interruption, and HYMH, with support from Nuvera, continued to work on a layout redesign to reduce electromagnetic interference (EMI) to an acceptable level. The four-to-six-week delay to address the EMC issues allowed HYMH and Nuvera to upgrade the "alpha" fuel-cell engines. The upgraded "beta" engines had more robust production hardware and wiring harnesses which were designed to reduce EMC sensitivity. The new engines arrived at HYMH's facility and were integrated into the vehicle. However, the same EMC issues reappeared during truck testing. HYMH conducted additional tests and determined that EMC radiation from the DC/DC converter interfered with the isolation monitoring device (IMD) resulting in a faulty signal. This was corrected with additional filters on the IMD thereby closing out this issue.

Motor Issues: There were several issues reported with the vehicle motor controls, specifically with the traction motor and hydraulic pump motor. During the initial startup of the traction motor, the isolation value of the inverter continued dropping below the target value of 500 kiloohm. To address the traction motor issue, HYMH worked remotely with the supplier to tune the motor. Additionally, fixing the hydraulic pump motor required the supplier to come on-site for tuning. However, travel restrictions prevented the supplier from going to the HYMH facility. HYMH was able to finish approximately one-third of the hydraulic pump tuning before the battery drained. In June 2020, HYMH ordered a vehicle battery charger from a different supplier to continue motor tuning and solve some of the previous control issues.

Battery Issues: The truck continued to experience intermittent issues with the battery modules during commissioning. This was attributed to difficulties integrating the new (replacement) modules with the older modules that sat in storage due to project delays. HYMH worked closely with the battery supplier to continue balancing the overall pack and develop a robust support plan for modules that may need to be replaced during the demonstration. An additional battery module had to be replaced due to issues when charging. HYMH worked to troubleshoot an issue with accurately calculating the state of charge (SOC) of the battery pack. This issue was due to discrepancy in firmware with the newer modules resulting in a different calculation for SOC. This was resolved via firmware update that did not require additional disassembly/reassembly of battery packs.

However, due to the battery balancing issues, HYMH determined that the vehicle would need to ship with a plug-in charger to be used for approximately two hours every two weeks to rebalance the batteries. Originally, the Project Team considered using a charger from a different electric vehicle project at FMS; but, the location and timing of the project would not be optimal for the ETL demonstration.

WAVE's wireless charger was a high-risk alternative, as it was unlikely to be able to deliver the controlled, low-power charging needed to allow the battery management system to balance the battery. The POLA substation had enough capacity for a plug-in charger, and it could potentially use the same switchgear as the wireless charger. However, the pad for the WAVE equipment was too small for a plug-in charger; therefore, the plug-in charger would need to be anchored to a skid and complete the POLA permitting process again. The associated time and costs for this effort was a risk to both the project budget and timeline. Therefore, HYMH investigated a low-power, mobile charging solution.

During a final validation test, HYMH set the vehicle in operation for over 6 hours. They found that high battery C rating caused the battery pack to overheat during continuous operation. The root cause was that the battery pack did not have a cooling system. HYMH and Nuvera added a cooling system to the battery pack and monitored the battery deterioration closely.

Fuel-Cell Sensor Issue: In early 2022, ETL validation continued and was matching performance expectations. HYMH planned to disassemble the truck in preparation for shipping. However, during one of the final validation tests required before disassembling, HYMH encountered an issue where one of the fuel-cell engines was cycling off quicker than expected. After performing diagnostics, the root cause was a faulty wire harness which was connected to the fuel-cell current sensors, causing it to report inaccurate values. The fuel-cell engines were replaced, and the issue was resolved.

Shipping and Delivery

The ETL was sent from the HYMH facility in Nijmegen, Netherlands, to the Port of Zeebrugge in Belgium. On June 20, 2022, it was loaded onto the Tannhauser, bound for the Port of Hueneme in California, before being shipped to POLA. Initially scheduled to arrive at POLA on July 21, 2022, the ETL was delayed by the shipping company and arrived the week of August 8, 2022.

On-Site Validation

After arriving at POLA in August 2022, HYMH began reassembling the ETL. HYMH found that the modules appeared to have low voltage. However, battery modules are known to have a long shelf life with low reduction in battery capacity over time. As a result, the team began evaluating potential root causes of the weak battery modules.

One possibility was that that main switch was left on during shipping. As a result, parasitic current could have drained the battery during the month-long voyage. Another possibility was that the truck was operational during transport. This was the most likely cause, and could have occurred at any of the following stages of transport:

- In transit from HYMH facility in Nijmegen to the Port of Zeebrugge. This was unlikely because HYMH left vehicle with the main switch off and there was no external interference with vehicle during shipment
- At the Port of Zeebrugge after delivery. This was unlikely because the duration until embarking was too long.
- Aboard the Tannhauser. This was the likely reason because the ETL would have shut down based on low voltage warning, then the battery would recover, giving the ETL just enough energy to drive off.
- Arrival at POLA was also unlikely because the driver indicated that they had to use the main switch, and the battery reported critically low voltage.

Due to weak battery modules, HYMH needed to rebalance the battery during reassembly. During this process, HYMH discovered three dead modules that required replacement. They ordered and installed the replacements, then rebalanced the battery pack. The issue was resolved in September 2022.

During reassembly, Nuvera conducted shakedown test and pre-deployment tests. As part of the pre-deployment tests, the fuel-cell engines powered the ETL vehicle during operational tests on power profiles that included transitions from high to low power, on/off cycles, and multi-hour sustained power production. Nuvera reviewed available engine data and cleared the vehicle for deployment.

Training

The Project Team developed a training plan to educate FMS and First Responders on the safe operation and maintenance procedures for the ETL, and general hydrogen safety. However, due to the replacement of the faulty battery modules, training was postponed until October 6, 2022.

On October 6, 2022, training began with an overview of the program and was followed by a session on hydrogen safety, emergency response, and truck safety. See Table 2: Training Overview for an overview of the training.

Table 2: Training Overview

Topic	Description
Introductions and Program Overview	• Project Description • Deployment Schedule
Hydrogen Characteristics and Hydrogen Safety	• Properties of Hydrogen • Hydrogen Safety
Emergency Response and Documentation	• Types of Incidents • Responding to and Documenting Emergencies
Overview of Truck Safety Features	• Truck Design and Safety Features

There were thirteen attendees at the training session. Each attendee received first responder and general safety training as well as operations and maintenance training on the vehicle, and the mobile refueler. Attendees included members from CTE, HYMH, CARB, POLA, Port of Los Angeles Police, BayoTech, FMS, and SoCalGas.

CTE led the First Responder Training. HYMH walked participants through a general vehicle overview, a vehicle operations training session, and a vehicle maintenance training session. Lastly, BayoTech led attendees through a hydrogen station and hydrogen station maintenance training. CTE coordinated training day logistics such as confirming attendance, location, schedule and collected training material from HYMH.

Figure 11: Project Team at Training

WCS training was scheduled once the wireless charger issues were resolved. On October 4, 2023 WAVE completed both operator and maintenance training with FMS staff. The training covered topics related to instructions for using the charging pad along with safety and alignment details. There were seven FMS personnel in attendance for operator training and fifteen personnel in attendance for maintenance training.

Manuals Development

During commissioning, the Project Team developed an Operations and Maintenance (O&M) manual for the various project components. The Project Team elected to consolidate each individual team member's manual and support plan information into HYMH's overall vehicle manual and support plan. The Project Team believed a consolidated approach was the best approach for the interests of the operator and would produce the quickest possible response time to issues encountered during the demonstration. In this way, the operator only had to depend on one resource and one communication pathway through HYMH, who would be responsible for distribution of support-related activities, including diagnosis and resolution.

Vehicle Deployment

For the purposes of this report, the Project Team refers to the 2022 demonstration as Demonstration Period 1. This period covers the initial deployment when the ETL was placed in service in October 2022 and operated regularly through December 2022. In December 2022, the project lost its hydrogen fuel supply (see *Hydrogen Fueling Solution* section). As a result, the project was put on hold until a new hydrogen fuel supplier was procured. The demonstration resumed in February 2024 and is referred to as Demonstration Period 2.

Demonstration Period 1 (October - December 2022)

After the Project Team completed training, the vehicle was ready to be demonstrated. The ETL was successfully deployed on October 17, 2022, and was intermittently operational up until December 8, 2022. However, shortly after beginning the demonstration, the ETL experienced a fuel-cell issue. The isolation warning caused the fuel-cells to shut down during operation. Unfortunately, this depleted the battery, but the team was able to recharge and balance the battery pack. Charging with a 3-phase 240V took longer than expected. Nuvera and HYMH began analyzing the data and working through the isolation reaction for a better strategy. HYMH found that the deionization (DI) filter in the fuel-cell was tripping the battery pack. In early November 2022, HYMH replaced the DI filter, and the issue was resolved.

Due to a lack of hydrogen fuel supply, the last day of Demonstration Period 1 was December 8, 2022. Over the next year the ETL sat stationary as the Project Team worked to procure hydrogen fuel supply.

Demonstration Period 2 (February - April 2024)

In September 2023, the Project Team approached the conclusion of the mobile refueler permitting process. The permitting process had significantly strained the project budget. CTE conducted a financial audit to assess how to achieve project objectives within the remaining budget and determined that a three-month demonstration phase was feasible.

CTE developed a revised demonstration schedule, as shown below in Figure 12: Demonstration Period 2 Timeline. With a clear start date for Demonstration Period 2, the team worked to prepare the ETL operate in-service on February 1, 2024. This preparation included conducting a shakedown test to ensure that the ETL was functioning as expected.

<table>
<tr><th colspan="40">Demonstration Timeline</th></tr>
<tr><td colspan="4">November</td><td colspan="4">December</td><td colspan="4">January</td><td colspan="4">February</td><td colspan="4">March</td><td colspan="4">April</td><td colspan="4">May</td><td colspan="4">June</td><td colspan="4">July</td><td colspan="4">August</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td colspan="6">Permitting</td><td colspan="4">Battery Lead Time</td><td colspan="2">Replacement</td><td colspan="12">Demonstration</td><td colspan="8">Draft Final Report</td><td colspan="4">Final Report, Final DR</td><td colspan="4">End Term of Agmt.</td></tr>
</table>

Figure 12: Demonstration Period 2 Timeline

During this test, HYMH noticed an issue where the vehicle battery system. HYMH charged the ETL; however, the battery was completely depleted and did not charge. There was a total of 54 modules in the pack and some needed to be replaced due to quick discharge. HYMH then completed a charge and balancing exercise for the battery.

In early November 2023, four battery modules were ordered, received, installed, and balanced by HYMH. However, once the pack was assembled into the equipment, additional battery modules were detected as faulty. This was an indication that the state of health of the battery pack was not good. The battery's poor health was attributed to its age (approximately six years old) and extensive use during testing phases, including vehicle integration and testing. Consequently, the battery pack suffered from significant discharge.

On November 28th, 2023, HYMH concluded that the entire battery pack required replacement. Although there was a lead time from the supplier, the battery modules arrived in Los Angeles in early January 2024 and were installed two weeks later. HYMH conducted tests and the vehicle was prepared to operate on February 1, 2024.

In February and March 2024, the ETL was operational for several days. However, there were frequent operations and maintenance issues that impacted the availability of the vehicle. For example, in early March, the team identified that the low-voltage (24 V) batteries appeared to be frequently discharging and that the high-voltage battery charge dropped by 40% overnight. To resolve, HYMH replaced the low-voltage batteries and charged the high-voltage batteries to allow the truck to move and to allow the fuel-cell to turn on.

The Project Team discussed the root cause of these battery charge issues and found that they were oftentimes due to a lack of communication among the Project Team. Preparing the vehicle for service required multiple points of contact: FMS Operations Team, FMS Maintenance Team, CTE's third-party fueler, and Air Products logistics staff in order to determine consistent fueling and fuel delivery schedules. Often times, the main switch would be left on or the vehicle was parked in the wrong place. Instances like these prevented the vehicle from charging on the WCS or getting hydrogen fuel.

For example, on February 14, 2024, the ETL was parked too far away from the fueler. Parking the ETL incorrectly resulted in one less day of vehicle operation. Additionally, in February 2024, FMS left the ETL main switch on overnight. This resulted in drained low-voltage batteries and required additional charging time before the equipment systems could function properly. This issue required HYMH to perform unscheduled corrective maintenance and resulted in a week where the ETL was not available for service.

Furthermore, in March 2024, HYMH reported issues with the hydrogen tank pressure sensors and SOC communication, which took the ETL out of service. HYMH replaced the hydrogen tank pressure sensors and worked with FMS to resolve the SOC commutation issues by cycling the vehicle startup. Both issues were resolved by early April and the ETL was ready for regular operational service the rest of the month.

Data Report

The following section provides details as they relate to the design and performance of the ETL. The Vehicle description parameters are the signals required to effectively analyze the operation and performance of the ETL. HYMH, FMS, Nuvera, and WAVE provided data for the analysis.

Vehicle & Equipment Specification

Table 3: ETL Specifications

Component	Parameter	Units	Measurement
Vehicle	Year	yyyy	2020
	Make		Hyster
	Model	--	A258
	Usable Hydrogen Storage	kg	25.3
Fuel Cell System	Manufacturer	--	Nuvera Fuel Cells
	Model	--	E-45-HD (OS1L2-45)
	System Net Power Rating	kW	45
	Fuel Cell Stack Max Power	kW	55
	Open Circuit Voltage	V	290
	Idle Current Load	Amp	62.5
	Max Operating Current	Amp	312.5
	Fuel Cell System Mass	kg	217
	Fuel Cell System Volume	L	300
	Calculated Specific Power	W/kg	207.3732719
	Calculated Power Density	W/L	150
FCS Efficiency	Gross System Power at Idle	kW	13.5
	Net System Power at Idle	kW	12
	Fuel Cell Efficiency at 100% net power	% (Ratio of Energy Out to Energy In)	50
Hydrogen Storage	Number of Tanks	--	4
	Tank Type	--	ALT-1034F Filament Wound Aluminium Cylinder
	Cycle Life	cycles	5000
	Tank Pressure	bar	350
	Total H2 Mass	kg	26.7
	Total H2 Volume	L	275*4
Electric Motor for traction	Number of Traction Motors	--	1
	Type	--	ACX-3508
	Peak Power Rating	kW	220
	Torque @ 0 rpm (locked rotor)	Nm	2500
Battery (ESS)	Type	--	54x U27-12XP
	Manufacturer	--	LithiumWerks
	Total Capacity	kWh	95
	Voltage	V	700

Vehicle & Equipment Operation

Vehicle Usage: FMS operated the ETL one shift per day. One shift is approximately 10 hours long. During a shift, the ETL was only expected to operate between six to eight hours. During this demonstration, the maximum time that the ETL operated was for 6.3 hours in one day (occurred on April 22, 2024). The ETL was powered up on 57 different days, across Demonstration Period 1 and 2. The ETL was only utilized during weekdays, Monday through Friday. The odometer readings can be found in the Appendix. Figure 13: ETL Operating Hours Per Day summarizes the vehicle operating hours per day during both demonstration periods.

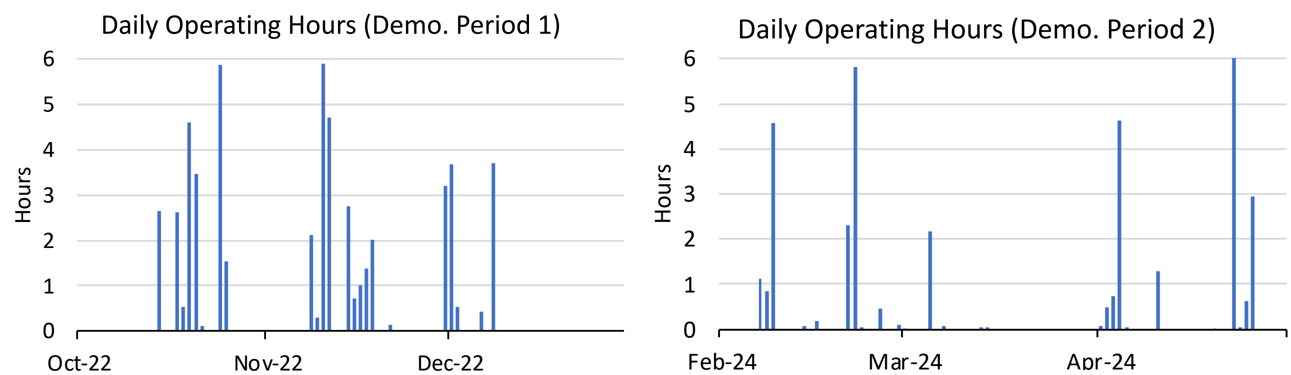

Figure 13: ETL Operating Hours Per Day

GPS Data: HYMH sampled the vehicle coordinates and operation state at a 1 Hz sampling rate. The operation state of the vehicle is described as: 0=off, 1=standby/idling, 2=operating, 3=charging/fueling, 4=shutdown. This data can be found in Appendix C.

Daily Use of Vehicle and Equipment: The ETL is part of a fleet of 50 top loaders, and FMS operates between 25 to 42 top loaders each day. Each morning, at 7:00 am PT, the FMS Maintenance Team sends out an operational checklist that states which vehicles are ready for operation. The FMS Operations Team then selects the units and assigns them a type of operation for the day; rail, yard, or vessel operation. The FMS Operations Team prioritizes the reliable vehicles for operation. During the ETL demonstration, HYMH communicated the status of the ETL to the FMS Maintenance & Repair team. The FMS Maintenance & Repair team communicated the status of the ETL to FMS Operations on a daily basis.

Duty-Cycle Logging: The speed, elevation, longitudinal and latitudinal coordinates of the vehicle during operation were reported by HYMH at a rate of 1 Hz. HYMH captured the idle time of the vehicle as a percent of the time the truck was idle. In Demonstration Period 2, the vehicle was idled 71% of the time. HYMH captured this data in the following parameters: *PercentageLaden(%), TimeLaden(s), avgLadenTime(mins/h).* These parameters describe the duty cycle and can be found in Appendix C.

Average Speed and Idling Time: HYMH sampled with distance traveled and the operation state of the vehicle at a 1 Hz sampling rate. These signals were used to calculate the average speed and idling time of the vehicle. See the following parameters in Appendix C for detail: *Truck_Idle(%), Truck_Idle(s), average_speed (km/hr),* and *max_speed(km/hr).*

Odometer Reading: HYMH logged the odometer of the vehicle at the beginning and end of each session. This signal was used to determine the *Distance_Driver(km*). See the Appendix C for odometer readings in kilometers.

Estimated Loads: HYMH captured the *TotalLiftedWeight.* Please see the Appendix C for further detail.

Vehicle Performance

Performance During Normal Work Week vs. Peak: The vehicle only operated on weekdays between Monday and Friday. The peak season for port operations is August through September, driven by retailers stocking up for the holiday season. Due to the fueling issues described in the *Hydrogen Fuel Supply* sections above, the vehicle was utilized for a limited period of time during this peak window.

Comparison of Appropriate Productivity Metric with Advanced Technology vs. Baseline Vehicle: A baseline diesel top loader typically works for six to eight hours per day and picks 33.7 containers per hour[1]. In Demonstration Period 2, the ETL lifted an average of 12.8 containers per hour when operating.

Battery Degradation: On the first day of data collection in October 2022, the battery SOH was estimated at 98%. On the last day of data collection, the battery SOH was estimated at 96%. However, the battery system was replaced twice. Therefore, the HYMH data does not provide a conclusive battery degradation metric.

Fuel & Energy Consumption

Fuel and Energy Consumption, Including Price Per Unit and Date: According to the invoices from BayoTech and Air Products, the Project purchased a total of approximately 422 kg of hydrogen in Demonstration Periods 1 and 2. However, based on the vehicle data from HYMH, approximately 160 kg of hydrogen was consumed throughout the demonstration. Although there is a 52% difference between the hydrogen purchased and hydrogen consumed by the ETL, there are expected losses that account for some of this difference. These losses may include:

- **Evaporative and Boil-off Losses:** For gaseous storage, evaporative losses can be minimal but might still account for up to 1-2% under certain conditions.
- **Leakage:** Leakage may account for up to 0.5% loss.
- **Temperature and Pressure Management:** These can result in small, intermittent releases, typically less than 1% overall.

Combining these factors, the Project would expect minimal total losses of the hydrogen purchased, primarily minor contributions from leakage, evaporative losses, and other factors. However, losses can vary based on the quality of equipment, operational practices, and environmental conditions. Though these expected losses only explain a small percentage of the 52% difference between the hydrogen purchased and hydrogen consumed, the quality of the data limits the Project Team's analysis of these losses. Table 4: Hydrogen Dispensed and Price illustrates the dates of fueling, amount of fuel dispensed and unit cost per kilogram.

Table 4: Hydrogen Dispensed and Price

Date of Delivery	Invoice Amount for Product ($)	Unit Price ($/kg)	Amount Purchased (kg)	Supplier
9/29/22	$163.80	$18.00	9.1	BayoTech
10/6/22	$154.80	$18.00	8.6	BayoTech
10/11/22	$72.00	$18.00	4.0	BayoTech

[1]*According to HYMH monitoring data for a diesel TL*

10/14/22	$180.00	$18.00	10.0	BayoTech
10/18/22	$198.00	$18.00	11.0	BayoTech
10/24/22	$655.20	$18.00	36.4	BayoTech
11/3/22	$180.00	$18.00	10.0	BayoTech
11/18/22	$237.24	$18.00	13.2	BayoTech
11/29/22	$163.62	$18.00	9.1	BayoTech
12/5/22	$261.90	$18.00	14.6	BayoTech
9/8/23	$3,032.94	$20.23	149.9	Air Products
2/29/24	$1,231.72	$20.23	60.9	Air Products
4/12/24	$1,728.27	$20.23	85.4	Air Products

The WAVE charger was not used during the Demonstration Period 1 due to the technical challenges encountered in late 2022 (see the *Wireless-Charging Installation* section for further detail). However, in Demonstration Period 2, a total of 255 kWh was delivered to the ETL over 45 hours, with a maximum of 52 kWh delivered during a single session. There were 11 charging sessions that took place. Figure 14: WCS Energy Delivered to ETL, Demonstration Period 2 depicts the frequency of the charge sessions and the energy delivered by the WAVE charger during Demonstration Period 2.

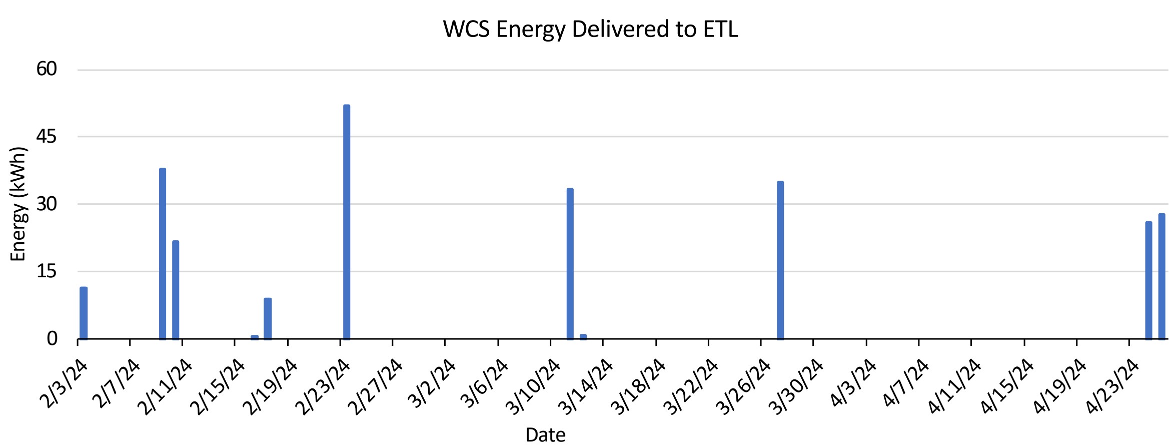

Figure 14: WCS Energy Delivered to ETL, Demonstration Period 2

Refueling and Charging Time and Frequency: The GTM-1500 and HF-150 are two distinct hydrogen fueling solutions, each with unique operational characteristics and implications for refueling schedules. With the GTM-1500, refueling occurred when hydrogen was delivered. With the HF-150, hydrogen was delivered to a stationary trailer, and the vehicle would be refueled at a later time, depending on when the vehicle needed fuel.

The table below shows the days that the vehicle received hydrogen fuel. In Demonstration Period 2, the days that Air Products delivered fuel were different than the days that the vehicle received fuel.

During Demonstration Period 1, the ETL was fueled with a GTM-1500. The fueling unit and the ETL were fueled in 10 different instances. In Demonstration Period 2, the ETL was fueled with a HF-150. The HF-150 was refueled twice, however the ETL was refueled 36 times by a CTE subcontractor. Table 5: Dates of ETL Hydrogen Fills below shows the dates that the ETL was refueled throughout the demonstration.

Table 5: Dates of ETL Hydrogen Fills

Date of ETL Hydrogen Fill				
Demonstration Period 1		**Demonstration Period 2**		
9/29/22		10/12/23	3/5/24	3/28/24
10/6/22		2/1/24	3/6/24	3/29/34
10/11/22		2/5/24	3/7/24	4/1/24
10/14/22		2/13/24	3/8/24	4/2/24
10/18/22		2/14/24	3/11/24	4/4/24
10/24/22		2/16/24	3/12/24	4/5/24
11/3/22		2/22/24	3/13/24	4/8/24
11/18/22		2/23/24	3/14/24	4/9/24
11/29/22		2/26/24	3/15/24	4/23/24
12/5/22		2/27/24	3/18/24	4/24/24
		2/29/24	3/19/24	4/25/24
		3/1/24	3/21/24	4/26/24
		3/4/24	3/22/24	

As described above, the WAVE charger was not utilized during the Demonstration Period 1. However, during Demonstration Period 2, there were a total of eleven charging session that totaled 45 hours and averaged five hours per session. See Figure 15 below.

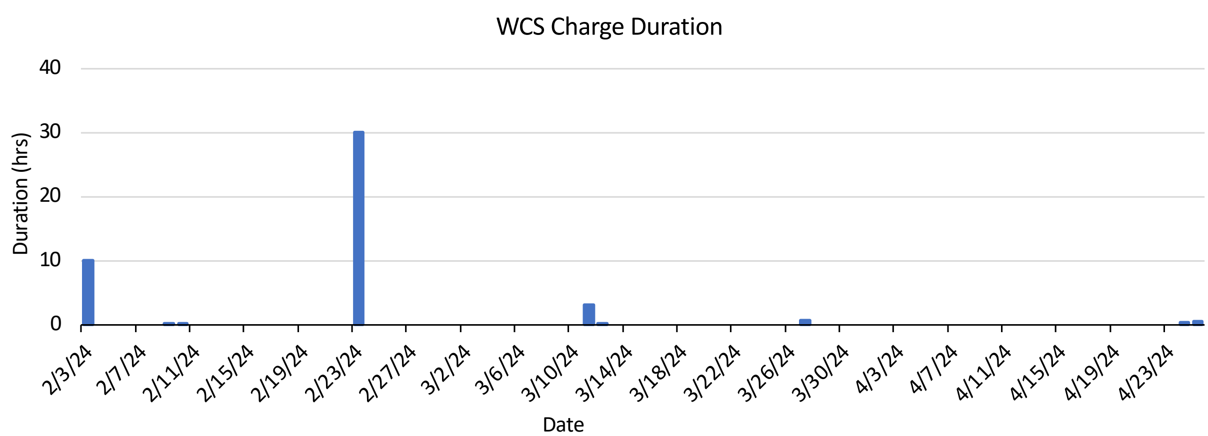

Figure 15: WCS Charge Duration, Demonstration Period 2

Refueling/Charging Source: The WAVE charger used electricity from the standard grid at POLA. The hydrogen delivered was from the Air Products Long Beach production facility. California's SB 1505 (Lowenthal, Chapter 877, Statutes of 2006) requires that at least 33% of hydrogen sold at publicly co-funded stations in California comes from renewable resources. This requirement applies to hydrogen that receives state funding, as well as applications that request funding for hydrogen refueling stations. Eligible renewable resources include feedstocks or electricity. The hydrogen fuel utilized for the ETL was at least 33% renewable. Additionally, the fuel provided by both Air Products and BayoTech met the J2719 standards.

Fuel Consumption Rate: The fuel consumption of the ETL was 2.0 kilograms per hour across both demonstration periods. The ETL was only inductively charged in Demonstration Period 2. Combining the energy consumption from hydrogen fuel and the total energy charged to the battery, the average energy consumption rate was 68.4 kWh/hr during operation.[2] The energy used from the inductive charger was 11% of the total energy consumed during operation. Figure 16: ETL Daily Fuel Consumption below shows the fuel consumption in both demonstration periods.

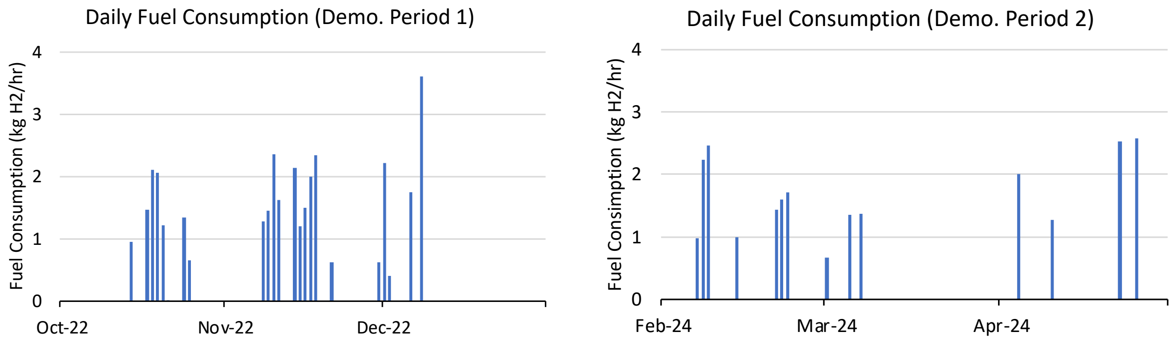

Figure 16: ETL Daily Fuel Consumption

Maintenance

Preventative Maintenance for Advanced Technology and Baseline Vehicles: Table 6: Preventative Maintenance of Diesel vs. Electric Top Loader below provides an overview of the preventative maintenance schedule for both a diesel top loader (the H1150XD-CH) and the ETL. Generally, much of the preventative maintenance is similar for common truck systems such as the mast, lifting hydraulics, wheels, drive axles, and cabin systems. The ETL has fewer maintenance needs since the fuel-cell engines do not require oil changes, diesel exhaust fluid (DEF) maintenance, belt changes, or alternator maintenance. While the fuel-cell engine design does not require routine maintenance, interfacing systems that are external to the engine must be properly maintained. This includes maintaining the specified quality of air and coolant, which is important to maximize the engine performance and lifetime. The air and coolant quality are achieved using filters external to the engine. Therefore, coolant level and coolant conductivity should be checked on a regular basis, and air filters should be replaced regularly. Filter lifetimes can vary based on the ambient air quality, radiator construction, and other factors. It is recommended that the effectiveness of the air and deionization filters be checked frequently until the filter change interval is established.

Table 6: Preventative Maintenance of Diesel vs. Electric Top Loader

System	Diesel	ETL	Frequency
Lift Chains Lubricate	Yes	Yes	Every 250 Hours
Check Engine Air Intake and Engine Oil	Yes	No	
Mast Load Rollers, Pivot, and Surfaces Lubricate	Yes	Yes	
Coolant Level	Yes	Yes	

[2] *Hydrogen converted to energy at rate of 33.3 kWh/kg based on hydrogen consumed, not delivered [(Alternate Fuels Database, Department of Energy)]*

Change Fuel Filter	Yes	No	
Wheels, Tires, and Tire Pressure	Yes	Yes	
Hydraulic System oil	Yes	Yes	
Parking and Service Brake	Yes	Yes	
Header Hose Assembly	Yes	Yes	
Change Engine Air Intake Filter	Yes	Yes	Every 500 Hours
Change Transmission Oil	Yes	No	
Drive Axle Differential and Hub Assembly Oil	Yes	Yes	
Lubricate Steering Axle	Yes	Yes	
Change Engine Oil and Filter	Yes	No	
DEF Tank Suction Filter	Yes	No	Every 1,000 Hours
Change Transmission Oil and Filters	Yes	No	
Drive Belts	Yes	No	Every 1,500 Hours
Alternator and Charging System	Yes	No	
Crankshaft Pulley	Yes	No	
Air Intake	Yes	Yes	
Air Compressor Discharge Lines	Yes	No	
Lubricate Drive Shaft	Yes	No	Every 2,000 Hours
Change Drive Axle Differential Oil	Yes	Yes	Every 2,500 Hours
Change Fuel Tank Breather	Yes	No	
Change Hydraulic System Oil, Suction Filter, and Return Filter	Yes	Yes	Every 3,000 Hours
Change DEF Pump Filter	Yes	No	Every 4,500 Hours
Replace Air Conditioning Dryer, Lubricant, and Refrigerant	Yes	Yes	Every 5,000 Hours
Replace Automatic Greasing System Filter	Yes	Yes	

For the WCS, both the charger (Ground Side Equipment (GSE)) and the vehicle side electronics (Vehicle Side Equipment (VSE)) have regular maintenance inspection requirements (Table 7: WAVE Charger Maintenance for GSE and VSE) that mainly relate to the coolants. To maintain proper alignment with the charger, the ETL tires need to be re-aired or replaced if the vehicle pad is below 9.5 inches from the ground. Attempting to charge under these levels will cause damage to the equipment.

Table 7: WAVE Charger Maintenance for GSE and VSE

	Action	Responsibility	Frequency					
			Weekly	Monthly	Quarterly	Bi-Annually	Yearly	Other
GSE	Pad Visual Inspection	Port Operator	Inspect					
	Pad Lift Inspection	WAVE				Inspect		
	Pneumatic System					Inspect		
	Pad Electrical Hardware	WAVE					Inspect	
	High Voltage Power Supplies	WAVE					Inspect	
	Inverter Electrical Hardware	WAVE					Inspect	
	Enclosure Seal	Port Operator			Inspect			
	Cooler Filter	Port Operator			Inspect			
	Cooler Inspection	Port Operator			Inspect			
	Filter Inspection	Port Operator			Inspect			
	Coolant and Hoses	Port Operator					Inspect	Replace 5 years
	System Functionality	WAVE					Inspect	
	Alignment Boundary	WAVE					Inspect	
	Magnetic Coupling	WAVE					Inspect	
VSE	Pad Visual Inspection	Port Operator	Inspect					
	Pad Electrical Hardware	WAVE					Inspect	
	LV Box Electrical Hardware	WAVE					Inspect	
	Coolant and Hoses	Port Operator					Inspect	Replace 5 years
	Vehicle Ride Height	Port Operator		Inspect				

Maintenance and Repairs: The maintenance performed on the ETL throughout the demonstration is described in the *Vehicle Planning and Deployment* section of the report. Please see the Hyster Maintenance Reports in appendix D for further details.

Time Out of Service: As described in the *Vehicle Planning and Deployment* section of this report, delays were due to vehicle maintenance issues and hydrogen fuel supply issues. Please refer to that section for further details.

Service Calls

Date, Description, Repair Performed, Parts Replaced, Odometer Reading: The limited demonstration did not result in any service calls.

Time Out of Service: Delays were due to the procurement of hydrogen fuel and vehicle maintenance problems. The time out of service including the time between Demonstration Periods 1 and 2 are addressed in the *Operations and Maintenance* section of the report in detail.

Service Response Time to New Trouble Call: There were no trouble calls during the limited demonstration period.

Safety

Description of Accidents or Incidents: There were no safety incidents throughout the demonstration.

Emissions Testing

The ETL was operated for 89 hours over the demonstration (both Demonstration Period 1 and Demonstration Period 2), and used 255 kWh from the WAVE charger, and 422 kg of hydrogen purchased from BayoTech and Air Products. CTE compared the emissions of the ETL to an equivalent HYMH diesel top loader over 89 hours based on the 2023 AFLEET Off Road Footprint[3] tool and a PEMS test[4] of the diesel top loader (see Appendix B for methodology).

Overall, the ETL emitted 24.7 tonnes of GHGs from well to wheels (WTW). While there are no tailpipe emissions from a fuel-cell ETL, there are emissions created during the hydrogen and electricity production. In comparison, the diesel TL emits 2.54 tonnes WTW. The emissions from the ETL are higher due to the significant loss of hydrogen between delivery and consumption in the ETL.

A diesel top loader releases local harmful air pollutants. Deploying the ETL, which has no tailpipe air pollutants, saved 0.2 kg of carbon monoxide (CO), 5.5 kg of Nitrogen Oxides (NOx), 3.1 kg of particulate matter under 10 micrometers (PM10), 1.5 kg of particulate matter under 2.5 micrometers (PM2.5), and 0.03 kg of Volatile Organic Compounds (VOCs). These pollutants have a considerable health impact on the community.

Table 8: Tailpipe Air Pollutants and WTW Petroleum and GHGs

		Tailpipe Air Pollutants (kg)						
	WTW GHGs (tonnes)	CO	NOx	PM10	PM2.5	VOC	VOC (Evap)	SOx
ETL	4.7	0	0	0	0	0	0	0
Diesel TL	2.54	0.20	5.5	3.1	1.5	.03	0	0

The pollutants associated with the ETL come from the upstream production of electricity and hydrogen. The upstream pollutants for the ETL are relatively higher than the upstream pollutants for the diesel ETL.

Table 9: Upstream Air Pollutants

	Upstream Air Pollutants (kg)						
	CO	NOx	PM10	PM2.5	VOC	VOC (Evap)	SOx
ETL	2.3	2.7	0.2	0.1	0.8	0.0	1.0
Diesel TL	0.2	0.3	0.0	0.0	0.1	0.0	0.1

Fueling/Charging Infrastructure and Maintenance Infrastructure

The project utilized the BayoTech GTM-1500 during Demonstration Period 1 and the Air Products HF-150 during Demonstration Period 2 for hydrogen refueling.

BayoTech GTM-1500 hydrogen refueler is a lightweight, hydrogen transport that is towable behind most ¾-ton and greater pick-up trucks and provide a high capacity and high-pressure hydrogen source for refueling fuel-cell

[3] *AFLEET 2023, Argonne National Laboratory*

[4] *Portable Emissions Measurement System (PEMS) Testing of Container Handler at the Port of Los Angeles. Johnson et. al, 2022*

equipment. The GTM-1500 used 450 bar (6,525 psig) type-3 composite cylinders and WEH's SAE fill receptacles and nozzles for safe filling and discharging. The GTM-1500 has a main pneumatic control valve which integrates to a front, rear, and remote stanchion ESD (emergency shutdown system) for NFPA compliance when the GTM is on-site to provide great safety to operators and nearby personnel. Cylinders are equipped with a glass bulb, thermal relief device system that can vent the entire contents of the GTM within 90 seconds in the event of a fire regardless of the internal cylinder pressure.

GTM1500-450 Key Specifications:

- Hydrogen storage capacity: 146.6 kg
- Working pressure: 450 bar (6,525 psig)
- Maximum ambient operating temperature: 65 C (149 F)
- Minimum ambient operating temperature: -40 C (-40 F)

Figure 17: GTM-1500 with the ETL at 2022 Training Day

The Air Products HF-150 units combine hydrogen storage and dispensing equipment into one trailer. The mobile fueler can dispense H35 hydrogen with close to 80 kg of dispensable product on a single load. The trailer is 26 ft long, 8.5 ft wide, and 7 ft tall. Every mobile fueler is equipped with combustible gas detectors in the rear valve panel and on the dispensing cabinet. Fuelers are further protected with a flame detector that is installed with a view of the fueling area. Activation of any of these detectors results in the fueler isolating hydrogen storage and displaying the relevant alarm.

HF-150 Key Specifications:

- Hydrogen storage capacity: ~ 80 kg
- Working pressure: Steel DOT Cylinders: 450 bar (6600 psig)
- Maximum ambient operating temperature: 50 C (120 F)
- Minimum ambient operating temperature: -20 C (-4 F)

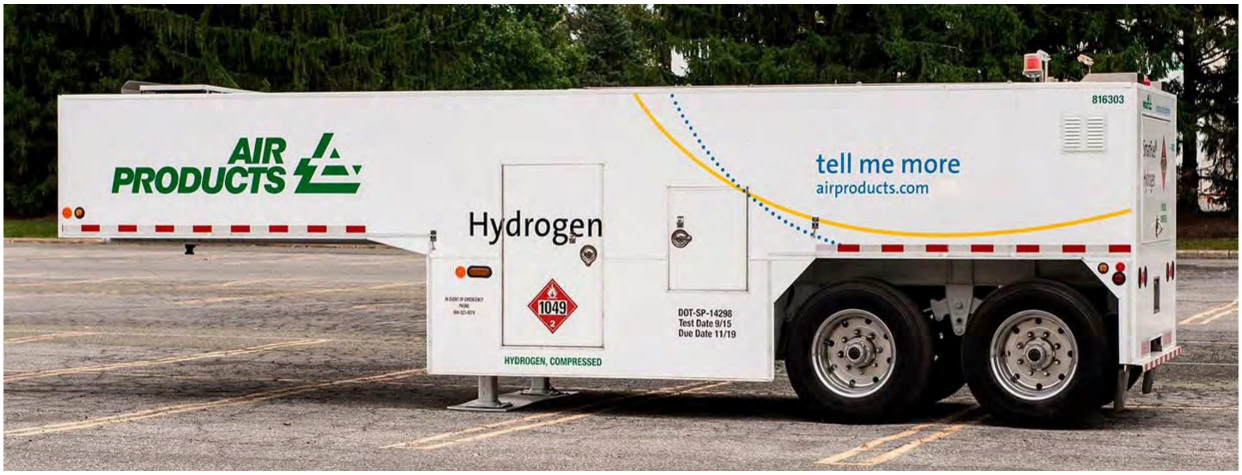

Figure 18: Air Products HF-150

The WAVE WPT 250-L v1.0 system is a wireless-charging system that can provide up to a constant 250 kW inductive charge to the vehicle; for the demonstration, the charger was configured to a 90 kW rate. The GSE was installed on the port, and the VSE was designed into the ETL. The ground side charging station feed is 480 V AC, three phase. The guaranteed alignment tolerance is +/- 4" laterally with a pad distance to ground between 12.6" and 9.5".

Figure 19: WAVE Charger Installed on Terminal

Infrastructure reliability: Due to the limited demonstration periods, the reliability data is inconclusive.

Operating and Maintenance Costs

Detailed Operating Costs for Baseline and Advanced Technology Vehicle/Equipment: The FMS hourly and daily operation rates are shown in the Table 10: FMS Operating Rates. The rates are the same for both types of technology. The daily rates assume a full day of operation.

Table 10: FMS Operating Rates

Role	Rate per Day	Rate per Hour
Top Handler Day Costs	$1,086.82	
Top Handler Day Weekend Costs	$1,308.34	
Top Handler Night Costs	$1,234.50	
Top Handler Night Weekend Costs	$1,308.34	
Clerk Day Costs	$1,070.07	
Clerk Day Weekend Costs	$1,286.23	
Clerk Night Costs	$1,214.15	
Clerk Night Weekend Costs	$1,286.23	
EMS Project Management - Director of M&R		$100.00
EMS Data Collection	$80.00	
Gearman Day Costs		$89.91
Gearman Day Weekend Costs		$116.93
Gearman Night Costs		$107.92
Gearman Night Weekend Costs		$116.93
Mechanic Day Costs		$94.48
Mechanic Day Weekend Costs		$123.59
Mechanic Night Costs		$113.88
Mechanic Night Weekend Costs		$123.59
EMS Tracking and Reporting		$115.00

Detailed Maintenance Costs for Baseline and Advanced Technology Vehicles/Equipment: HYMH provided an estimate for yearly maintenance (both preventative and repair) costs of the baseline diesel TL (H1150XD-CH) over ten years of operation at 1,000 hours per year. These numbers represent a typical duty cycle in a normal operating environment; however, it may not be representative in all situations. Assumptions applicable to FMS operations include an hourly labor rate of $168.73 for technicians. Because some repairs and maintenance are expected only every few years, the operational cost of parts and labor cumulates to $16.06 per hour of operations over ten years, for a total cost of $160,550 in maintenance. In comparison, the ETL accumulated significantly more in maintenance costs over 89 hours of operations. A high cost is expected because the ETL is a first of its kind vehicle with a lower technology readiness level than a diesel top loader, and it is expected to decrease with further iterations of the machine. Because there is less maintenance needed on a fuel-cell engine and fewer consumables, the total O&M costs should be decreased with more mature ETLs.

Table 11: Breakdown of Diesel Top Loader Maintenance Costs in Year One and Year Ten of Operation

Year	Year	1	10
Expected Annual Running Hrs.	Hrs.	**1000**	**10000**
Preventative Maintenance			
PM Parts including lubricants	$	2,928	6,123
Labor Cost for preventative maintenance	$	4,319	7,694
Travel Cost for preventative maintenance	$	0	0
TOTAL PM	$	7,247	13,817
Cumulative PM Cost	$	7,247	73,517
Cumulative Cost per hour	$	7.25	7.35
Repair Parts & Consumables (no damage)			
Repair Parts & Consumables (no damage)	$	0	16,798
Labor Cost for repairs	$	0	16,384
Travel Cost for repairs	$	0	0
TOTAL Repairs Cost	$	0	33,182
Cumulative Repairs Cost	$	0	87,034
Cumulative Cost per hour	$	0.00	8.70
TOTAL PM + Repairs Cost			
TOTAL PM + Repairs Cost	$	7,247	46,999
(TOTAL PM + Repairs Cost)/Hour	$	7.25	47.00
Cumulative PM + Repairs Cost	$	7,247	160,550
Cumulative Cost per hour	$	7.25	16.06

Challenges, Risks, and Applied Solutions

Table 12: Project Challenges and Applied Solutions describes the issues and challenges that the project faced along with the applied solutions.

Table 12: Project Challenges and Applied Solutions

<table>
<tr><th>Issue/Challenge/Risk</th><th>Description and/or Applied Solution</th></tr>
<tr><td>WCS Construction and Installation Cost Overruns

Date: Throughout 2019</td><td>Description: Throughout 2019, additional project delays were encountered due to how the WAVE tasks were structured in the project contract. The tasks, schedule, and budget associated with much of WAVE's scope of work were not adequately captured in the initial project proposal and contract. As a result, the Project Team had to address how to get funds for WAVE so that WAVE could begin to procure parts for the WCS.

Applied Solutions:
1. CTE reallocated administrative funding to project funds to cover cost overruns for WCS site design.
2. HYMH supplied working capital to WAVE in advance of the CARB procurement milestone to help with cost overruns. HYMH agreed to receive a design-intent "dummy" secondary system from WAVE to allow HYMH to validate their systems in parallel with WAVE's validation period. This parallel validation period reduced the risk of issues during demonstration associated with unvalidated or partially validated components and systems.</td></tr>
<tr><td>Impacts and Delays in Schedule due to COVID-19

Date: Q1 2020</td><td>Description: When the pandemic began, members of the Project Team implemented restrictions on all visitors to their facilities, thereby placing the vehicle commissioning timeline in jeopardy. By mid-March 2020, full travel restrictions were in effect preventing Nuvera and HYMH's hydraulics supplier (located in UK) from assisting in vehicle commissioning at HYMH's facilities. FMS remained operational throughout the reporting period with new equipment cleaning protocols and mask requirements. On average, their container volume throughput was 25% lower than normal. These impacts, among others, put the proposed project plan, schedule, and budget at risk.

Applied Solutions:
1. HYMH began allowing visits to their facilities from outside organizations on a case-by-case basis.
2. Nuvera had their Italian colleagues complete the fuel-cell commissioning at HYMH's facilities.
3. HYMH used the additional time to make vehicle improvements such as update the wire harnesses, continue development on service and maintenance manuals, and prepare for a rapid commissioning as soon as travel bans were lifted.</td></tr>
<tr><td>Vehicle Integration Issues (Hydrogen Storage System and Pressure Sensors)</td><td>Description: After building the base vehicle, HYMH ran into integration issues. One of the hydrogen storage system valves was rated for 500 psi instead of 5000 psi, and the pressure sensors were not appropriately calibrated. Additionally, the prototype wiring harness had faulty splices and welding and</td></tr>
</table>

Date: Throughout 2020	were missing epoxy. It was expected that replacement of these harnesses would result in a three-to-four-week delay. However, due to COVID-19 commissioning delays, the wire harnesses were no longer the critical path and arrived during the reporting period. **Applied Solutions:** HYMH reported several issues with the motor controls. During the initial startup of the traction motor, the isolation value of the inverter continued dropping below the target value of 500 kiloohm. 1. HYMH had been working remotely with the motor supplier on motor tuning to address the issue. This approach was effective but limited due to lacking a battery charger. On the other hand, the hydraulic pump motor troubleshooting and lift/lower commissioning required the supplier, Danfoss, to come on-site. 2. HYMH worked with the hydrogen storage system provider to procure a replacement valve and new pressure sensors.
Vehicle Commissioning and Battery Balancing Challenges Date: Q1 2021	**Description:** Nuvera's Italian colleagues traveled to HYMH's facility for fuel-cell commissioning. Nuvera was able to successfully complete a cycle of starting up and shutting down a fuel-cell engine and controls all worked as expected. However, when running the fuel-cells at higher powers, the team ran into EMC issues with the buck DC/DC converters' high frequency switching. This caused issues with the fuel-cell CAN buses and forced the fuel-cells to shut down. Nuvera and HYMH consulted with the DC/DC supplier and an external expert, but were unable to remedy the situation with any of the standard troubleshooting procedures. **Applied Solution:** 1. The Project Team decided that the layout of the DC/DC converters would have to be redesigned with the goal to minimize both HV and LV wire crossing. This redesign required new wire harnesses, brackets and testing equipment to allow for higher resolution measurements to aid testing and the troubleshooting process. Adjustments were made to allow the vehicle CAN to operate without interruption, and HYMH, with support from Nuvera, two additional suppliers, and HYMH's domestic consultant, completed the layout redesign work to reduce EMI to an acceptable level. The updated layout was assembled onto new frames to prepare for final installation onto the truck and integration into the HV system. However, further battery balancing issues resulted in delays due to all HSS components needing to be removed from the truck. **Description:** While running the vehicle in EV mode, two of the battery pack's 54 modules became unbalanced. HYMH worked with the battery pack and charger supplier to better understand the issue, but could not receive on-site support due to COVID-19. HYMH managed to rebalance the battery pack with slower charging than mandated by the battery supplier, but had to replace one of the battery modules that was continuing to have issues. However, the module that was not replaced became unbalanced again during testing. Replacing battery modules required HYMH to remove the entire HSS due to how the frame is mounted. To help mitigate any further delays to the schedule, HYMH's

<table>
<tr><td></td><td>engineering team redesigned the battery pack mount to reduce the current battery swap time from approximately three weeks to a single day.

Applied Solution:
1. HYMH considered shipping a plug-in charger with the truck as a contingency plan. The team did not anticipate this charger to be part of regular operations and worked through discussions with FMS regarding placement and power requirements.</td></tr>
<tr><td>Hydrogen Infrastructure Issues

Date: Q4 2022</td><td>Description: In April 2022, the term of agreement in CTE and IGX Amendment 1 came to an end and BayoTech acquired IGX. As part of the acquisition, BayoTech asked CTE to sign an MSA with the trailer leasing company, but CTE pushed back. Rather than signing a new agreement, in September 2022, CTE sent BayoTech a draft of Amendment 2, adding some MSA language into the draft. Amendment 2 changed the term of agreement end date, changed the company name from IGX to BayoTech, changed the price of hydrogen from $18 to $25 per kg, updated the budget, and included the updated temporary experimental use permit (TEUP) as an attachment. Between September and December 2022, CTE and BayoTech communicated about edits for the draft of Amendment 2. BayoTech edited the indemnification clause language in early November and the teams continued to try and find a middle ground. On December 7, 2022, BayoTech called CTE stating that they would be increasing the delivery cost from a flat rate of $350 to $2,800 per delivery. BayoTech informed CTE that they are sourcing hydrogen from Livermore. The last BayoTech fill was on December 5, 2022. CTE worked with the Project Team to develop possible solutions to resolve the hydrogen fueling issue.

Applied Solution: After conducting an analysis, the Project Team selected Air Products as the new hydrogen fuel provider.</td></tr>
<tr><td>Mobile Refueler Permitting Challenges

Date: Throughout 2023</td><td>Description: Throughout 2023, the Project Team has faced challenges in procuring hydrogen fuel.
● Beginning in August 2023, CTE worked with the Fiedler Group to deliver a permit package to LAFD. LAFD inspection was rescheduled multiple times.
● On September 7, 2023 LAFD conducted a site-inspection and provided the Project Team with a list of corrections.
● The next LAFD inspection was scheduled for October 12, 2023. The inspection was not able to be completed due to the position of the Top Loader and inability to move it.
● The next LAFD inspection was expected to be on November 2, 2023. This inspection was delayed due to schedule unavailability.
● The next LAFD inspection was scheduled for November 6, 2023. This inspection was delayed due to issues with the AP alarm and notification system. The system worked, but there was a delay in receiving an instantaneous notification.
● The final LAFD inspection was scheduled for November 14, 2023. The unit inspection was completed, and the team received notice to proceed.</td></tr>
</table>

Project Conclusions

Overall, this project achieved success deploying the fuel-cell ETL and associated hydrogen and charging infrastructure within a DAC in Southern California. FMS and HYMH have decided to continue the operation of the ETL.

There were many lessons learned through this project that can inform future developments of fuel-cell port equipment and demonstrations. The following recommendations aim to address these issues and support the growth of ETLs in the market.

Lessons Learned

The Project Team identified a number of opportunities for learning that were expressed throughout the report. To ensure the successful adoption and implementation of fuel-cell ETLs, several key areas must be addressed on both the vehicle and infrastructure side. Permitting hydrogen fueling solutions at Ports remains a significant challenge, necessitating comprehensive involvement all partners on a project team. The Project's experience in acquiring a source of hydrogen fuel, highlights the need for more mature and reliable fueling infrastructure. Additionally, demonstrating the scalability of hydrogen technology is crucial for its adoption by large fleet operators.

One key consideration for fuel-cell vehicle deployments is the feedback mechanism between the operator and the OEM. Multiple departments within large companies must coordinate effectively, and having a zero-emission vehicle champion is critical for bringing an organization together to successfully deploy zero-emission vehicles and maximize the benefits of the technology.

There was also learning associated with the vehicle itself. Between vehicle commissioning and deployment, the ETL experienced extended periods of downtime emphasizing the importance of timing infrastructure availability and vehicle deployment. These windows of downtime drained the low-voltage batteries, and required the batteries be replaced before the vehicle could operate. The Project Team recommends that future designs be equipped with an off switch to these low-voltage batteries, which, once utilized, will allow this problem to be avoided in the future. The other unexpected design challenges that arose, from both the vehicle and the WCS, led to delays which impacted the demonstration period. As a result, the Project Team recommends adding more time for component testing during the vehicle build task. These lessons learned inform CTE's recommendations for optimizing the performance of the ETL and planning future deployments.

Commercialization and Future Development

Building and demonstrating heavy-duty fuel-cell electric cargo handling equipment is a critical step to illustrate to terminal operators that transitioning away from diesel-powered mobile equipment is possible. As deployments of zero-emission container handlers continue to grow, the entire logistics chain at container ports has massive potential for decarbonization.

The partnership between HYMH and its subsidiary, Nuvera, ensured a comprehensive and simple design and provided a clear path toward commercialization, representing a commitment to develop advanced technologies that are necessary to meet state and federal climate goals. For operators such as FMS, the commercial availability of zero-emission equipment supports business goals to reduce their environmental footprint and promote sustainability.

Nuvera considers the ETL project to have had a substantial impact on the commercialization prospects for heavy-duty fuel cell vehicles and equipment. Shipping ports are among the most promising locations for the expansion of both hydrogen infrastructure and large-scale hydrogen off-take. This project, featuring the world's first fuel cell ETL, was instrumental in engaging the key stakeholders, including the port authority, the terminal operator, the OEM, a hydrogen provider, community groups, along with Nuvera as the fuel cell provider. This collaboration would not have happened without a development and deployment project such as this to catalyze it. The project provided invaluable feedback from the OEM and the end-user that has improved Nuvera's next-generation fuel cell engines.

It is likely that the very high visibility of the CARB-funded project at POLA has helped spur other port projects around the world involving both the same and other types of Nuvera-powered container handling equipment, such as reach stackers, terminal tractors, and empty container handlers. Nuvera is now involved in fuel cell deployments at the Port of Valencia (Spain) and the HHLA Clean Ports and Logistics Program in Hamburg (Germany). Other fuel cell manufacturers and port equipment OEMs are engaged in similar development efforts and projects. Nuvera expects that fuel cell port applications will be one of the main drivers of their business in both the short- and long-term.

In late 2023, HYMH shipped a hydrogen fuel-cell-powered Reach Stacker to Spain's Port of Valencia, where it is undergoing a pilot program at one of Europe's largest container terminals. HYMH will also supply an empty container handler and a terminal tractor, both powered by hydrogen fuel-cells, to a port terminal in Germany, and is working with Capacity Trucks to develop electric and hydrogen-powered terminal tractors.

WAVE has gained valuable insights into port operations and believes this environment will greatly benefit from wireless-charging to meet clean air requirements. They continue to seek more demonstration opportunities in the port market to promote commercialization of wireless-chargers and help solve charging issues.

Air Products views the ETL project as a great success and will apply the learnings and experiences gained as they move forward to develop port infrastructure. The equipment demonstrated the operational efficiency and clean energy potential of hydrogen as fuel source for heavy-duty port equipment. The comparison to diesel demonstrated similar refueling times, operational working hours and high-power output. This demonstration provided valuable learnings for future enhancements and broader deployment.

Air Products is committed to the clean energy transition as evidenced by their $15 billion investment to provide reliable zero and low carbon hydrogen to heavy industrial and transportation markets worldwide. Air Products has developed a fueling contract with Fenix Marine to continuing supplying hydrogen for the Hyster ETL and a yard tractor slated for delivery in late 2024. The ETL project supports their strategic decision to invest in port infrastructure, and the Air Products engineering team continues to collaborate with Hyster, Nuvera and the other major port equipment manufacturers. They fully support participating in demonstrations that result in the adoption of new technologies and that lead to reduced emissions and sustainable practices ensuring compliance with future regulations.

Promoting the commercial availability of zero-emission container handlers allows for continued investments in clean technology. Deployments of empty container handlers and terminal tractors at customer locations are planned throughout 2024 at POLA. Using similar technologies, lessons learned from ongoing pilots, and working closely with end customers, HYMH anticipates an acceleration of zero-emission container handling products in the market. The recently announced H2Hubs funding from the Department of Energy will work towards a reliable hydrogen fuel supply at a competitive price which facilitates operational needs and impacts the TCO for operators, such a FMS. A reliable and low-cost fuel supply in conjunction with successful demonstration of vehicle and fueling technology can increase operator confidence and lead to commercialization in the market.

Furthermore, due to the efficient fuel-cell design, the overall energy consumption of the fuel-cell ETL is lower than the diesel equivalent. Hydrogen container handling solutions are currently more expensive than both fossil fueled and battery-electric solutions, due to both vehicle cost and fuel cost. The H2Hub are expected to decrease the costs of hydrogen fuel significantly in coming years, striving for cost parity with diesel. Additionally, the design simplifications and economies of scale planned by HYMH for the fuel-cell ETL will decrease the upfront costs of container handling equipment, creating affordable commercialization and reducing the gap in expenditures for a scaled deployment.

Market Impact

Fuel-cell electric technology has the potential for widespread commercialization and significant transformation of the goods-movement industry while achieving reductions in GHG emissions by offsetting fossil fuel use. Current battery-electric container handlers are limited in runtime due to the demanding heavy-duty cycle of port equipment, sometimes in continuous operation for multiple 12-hour shifts. The intense energy consumption of these large vehicles requires a considerable amount of energy to be stored on board the equipment and makes refueling time a critical factor in operations schedules and costs. Battery electric vehicles require fixed charging infrastructure and longer charging time, compared to fueling time for hydrogen or traditional fueled vehicles. This presents challenges for maintaining equipment uptime and complying with labor contracts.

Additionally, the market is experiencing a significant lack of commercially available zero-emission CHE. At the time of this report, HYMH is the only OEM offering a factory-designed, vertically integrated hydrogen solution and production line. These technical and financial limitations have obstructed the electrification of equipment such as container handlers and large forklifts, even with the use of advanced battery technology.

Disclosures

- The Project Team participated in CARB's Low Carbon Transport Heavy-Duty Showcase presentation on March 19 - 20, 2019.
- CTE planned on attending the CARB Low Carbon Transportation Symposium on March 24, 2020; however, this event was canceled due to COVID-19.
- On November 17, 2022, HYMH hosted a Deployment event at POLA. The Project Team was in attendance. CTE spoke about the importance and impact of this project. The official deployment video can be viewed with this link: https://youtu.be/uUCOYT4j7kE
- The ETL was featured in the 2024 State of the Port: Hydrogen Hub video in February 2024: https://youtu.be/KYDBHdewpyk?si=GkhNod1TFKeeMwN8

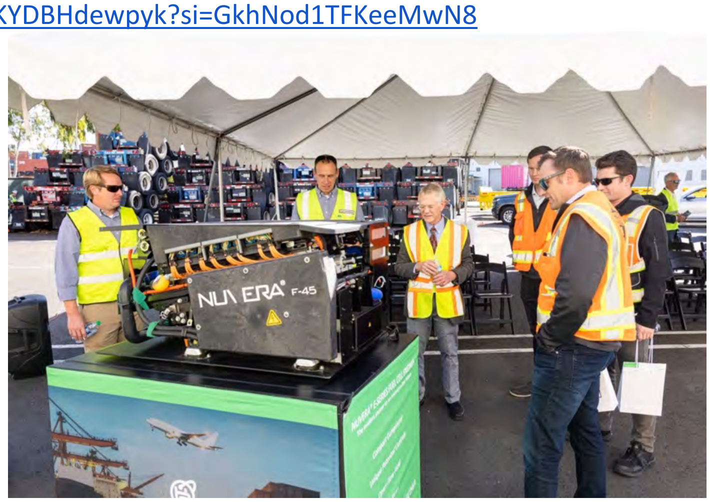

Figure 20: Nuvera Fuel-Cell on Display at Launch Event

Appendix

Appendix A: Data Collection Plan (attached to PDF)
Appendix B: Emissions Estimate Methodology (attached to PDF)
Appendix C: Demonstration Operational Data (attached to PDF)
Appendix D: Hyster Maintenance Logs (attached to PDF)