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FINAL PROJECT REPORT

The Hydrogen Zero-Emission Tugboat Project

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public and private research institutions. This program promotes greater gas reliability, lower costs, and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

This document is the final report for the Hydrogen Zero-Emission Tugboat Project PIR-20-002 conducted by CALSTART, Inc. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Commercial harbor craft and marine vessels are a transportation segment that has historically been difficult to decarbonize. To advance the commercialization of zero-emission harbor craft, the California Energy Commission funded the Hydrogen Zero-Emission Tugboat Project. The project team developed a design for a hydrogen fuel cell tugboat that is rated to provide up to 90 tons of bollard pull (the pulling or towing power of a vessel, usually defined in tonnes). The vessel is designed to provide assist service and to use fuel cells, batteries, and liquid hydrogen storage tanks. The project team investigated the economic viability of the vessel, as well as the technical, safety, and regulatory requirements that this vessel must meet. The project team also investigated pathways for supplying hydrogen to the vessel and liquid hydrogen bunkering technologies. The project team found that the tugboat is technologically feasible.

Keywords: tugboat, commercial harbor craft, hydrogen, fuel cell, liquid hydrogen

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Background

The San Pedro Port Complex, which includes the Port of Long Beach and the Port of Los Angeles, is a major source of air pollution in the Southern California region. As a result, many of the areas surrounding the port complex have elevated levels of air pollution, which negatively impacts public health. Ocean-going vessels and commercial harbor craft are responsible for approximately 75 percent of particulate matter and nitrogen oxide emissions at the Port of Los Angeles. As a result, the California Air Resources Board adopted the Commercial Harbor Craft regulation in 2008 and amended it in 2010 and 2022 to enforce the replacement of older engines with newer and cleaner technology to reduce emissions. However, to date, relatively few zero-emission commercial harbor craft have been deployed.

Commercial harbor craft face barriers to adopting zero-emission technology due to their high energy requirements, rigorous duty cycles, unpredictable operating schedules, and vessel design constraints. Zero-emission technologies such as hydrogen fuel cells have the potential to overcome these barriers for tugboats, which are equipped with relatively powerful engines and work in combination with other harbor craft such as barges or ocean-going vessels. Federal, state, and utility efforts may expand the scale and availability of clean renewable hydrogen in the future. However, there is a need to study the feasibility of hydrogen fuel cells for this end-use, including supporting fueling infrastructure.

Project Purpose and Approach

The main objectives of this project were to:

- Develop a baseline harbor craft design, including detailed specifications and costs, which will be used to inform the fuel cell-powered harbor craft design and future deployment.
- Evaluate the costs of constructing, operating, and maintaining the fuel cell-powered harbor craft when compared to the baseline vessel.
- Develop a cost-benefit analysis to estimate and compare the emissions reduction potential with other solutions.
- Identify technology and regulatory barriers to using hydrogen fuel cell systems in the maritime industry.
- Develop supporting plans for refueling infrastructure, including analysis of hydrogen production and delivery pathways.

This project was carried out by a consortium that included:

- ABB Inc. Marine & Ports
- Ballard Power Systems, Inc.
- CALSTART, Inc.

- Chart Industries, Inc.
- Crowley Engineering Services
- DNV
- The Port of Los Angeles
- Southern California Gas Company

The project team developed baseline specifications for the vessel, which is designed to guide ocean-going vessels in and out of the Port of Los Angeles. The project team collected data on an equivalent conventional tugboat. The data collected from the baseline vessel was used to understand the power demand from the engines and to develop a load profile for the vessel. This analysis indicated that power demand is not constant throughout the day; it is high when the vessel is actively providing service and decreases when the vessel is awaiting its next task.

The project team conducted an economic analysis to understand the costs of building the vessel. To conduct this economic analysis, Crowley Engineering Services (Crowley) requested a price estimate from a local shipyard for building the vessel without the major equipment. Then pricing for the major equipment (fuel cell, batteries, liquid hydrogen tank) was added to this figure. CALSTART estimated the cost of subsequent vessels by using a learning rates analysis to project the impact of economies of scale.

CALSTART also investigated the feasibility of supplying hydrogen to the vessel and the market for liquid hydrogen bunkering equipment. The project team conducted this analysis based on interviews with hydrogen providers and liquid hydrogen bunkering system manufacturers. CALSTART also interviewed stakeholders to understand the regulatory environment to which bunkering systems are subject.

Key Results

The project team carried out modelling to determine how this load could be met entirely with fuel cells and a battery energy storage system, alongside liquid hydrogen storage. The project team designed the vessel to use fuel cells to produce a constant power output throughout the day. The battery energy storage system was designed to be used to respond to increases in power demand during times of high activity and then to recharge when power demand decreased. The project team also determined that the vessel would require approximately 3,500 kilograms of hydrogen per week. This would be met with 4,000 kilograms of liquid hydrogen storage on board the vessel.

This analysis found that a tugboat powered entirely with liquid hydrogen, using fuel cells and a battery energy storage, can meet the duty cycle for tugboat operations in the Port of Los Angeles. This can be achieved with commercially available technology. However, the estimated $41.8 million vessel cost is significantly higher than a conventional tug, which costs approximately $17 million. Much of this premium comes from the zero-emission components on the vessel. However, the cost of the vessel is likely to decrease as multiple vessels are deployed and economies of scale for the zero-emission components are achieved. The project team's projections estimate that the cost of the second vessel would be between $31.47 million and $35.28 million. These projections estimate that the cost of the twentieth vessel would be between $30.01 million and $32.77 million. In addition, there are some technology and regulatory barriers that will need to be addressed to obtain regulatory approval for the vessel. However, these risks can be overcome using existing technologies and changes to the design of the vessel.

The project team found that there are feasible pathways for supplying liquid hydrogen fuel to the vessel and for deploying a liquid hydrogen bunkering system that connects the vessel to a tanker truck. This is the most appropriate solution because there is limited land availability at the ports of Los Angeles and Long Beach. Furthermore, one vessel will not consume enough liquid hydrogen to justify building a permanent bulk storage tank at the bunkering facility. The fuel capacity of a tanker truck matches the amount of liquid hydrogen that the vessel will require. Since liquid hydrogen bunkering is a new technology, there are some novel safety challenges that need to be addressed. However, new technologies such as insulated connectors, were developed recently or are undergoing development to address these concerns. The bunkering system will be regulated under the same regulatory environment as liquified natural gas bunkering. As a result, the bunkering system operator will need to prove that the system is at least as safe as a liquified natural gas equivalent.

Knowledge Transfer and Next Steps

This project will help to advance the zero-emission technologies for commercial harbor craft applications. The zero-emission hydrogen fuel cell tugboat design developed through this project is applicable to 32 other assist tugboats operating in the San Pedro Port Complex. Adoption across these tugboats could result in emissions reductions of 3.4 tons of PM10 (particulate matter 10 micrometers or less in diameter), 3.3 tons of PM2.5 (particulate matter 2.5 micrometers or less in diameter, 165 tons of NOx (nitrogen oxides), and 35.3 tons of CO (carbon monoxide) emissions per year. To deploy the vessel, the operator will need to obtain funding to build the vessel and obtain regulatory approval from the United States Coast Guard. The lessons learned from this project could also be applicable to similar vessel types, such as towboats and articulated towing barges. There are nearly 230 tugboats, towboats, and articulated towing barges in California. This design is unique in that it deploys liquid hydrogen storage below deck, which is a more desirable configuration for smaller vessels with space constraints.

The results of this project were shared at: the World Fuel Cell Conference 2022 in Irvine, California; the 2023 Tugs Towboats and Barges Conference in Mobile, Alabama; and the 36th Electric Vehicle Symposium in Sacramento, California. These conferences are widely attended by members of the fuel cell, maritime, and zero-emission transportation industries. The presentations generated discussion about the vessel design and liquid hydrogen as a transportation fuel. CALSTART also conducted industry outreach to share project results with stakeholders such as liquid hydrogen providers, hydrogen production and liquefaction equipment manufacturers, bunkering equipment manufacturers, and relevant regulatory agencies. This outreach indicated that there is a lot of industry interest in liquid hydrogen as maritime fuel. Furthermore, truck manufacturers are interested in deploying liquid hydrogen on Class 8 trucks. As a result, any advances in maritime liquid hydrogen technology will likely impact the on-road vehicle segment.

CHAPTER 1: Introduction

The San Pedro Port Complex, which includes the Port of Los Angeles (POLA) and the Port of Long Beach (POLB) is one of the busiest port complexes in the United States, handling 40 percent of America’s containerized imports and 30 percent of America’s exports (Legislative Analyst’s Office, 2022). Large numbers of on-road and off-road vehicles, including Class 8 trucks, cargo handling equipment, commercial harbor craft, and ocean-going vessels, operate at this port complex. The San Pedro Port Complex is the single largest source of air pollution in the Southern California region, producing large amounts of particulate matter (PM), nitrogen oxides (NOx), and greenhouse gas (GHG) emissions. This has public health ramifications for communities in the surrounding areas, contributing to increased levels of asthma, respiratory illness, and cancer (SCAQMD, 2015).

Marine vessels are responsible for a large portion of emissions from the ports. As a result, the California Air Resources Board (CARB) responded by enforcing the Commercial Harbor Craft (CHC) regulation. This regulation enforces emissions standards on CHC, which includes crew and supply boats, fishing vessels, ferries, excursion vessels, tugboats, barges, and dredges. This regulation effectively requires CHC to adopt cleaner propulsion technologies. Some CHC operators have responded by deploying technologies such as Tier 4 engines and diesel particulate filters, which significantly reduce emissions. However, other operators have opted to deploy zero-emission technology to comply with the CHC regulation and entirely eliminate point-source emissions from their vessels.

Vehicle segments such as buses adopted battery electric and fuel cell technology. These technologies experienced rapid technological development and became commercial products. However, CHC face more barriers to adopting zero-emission technology, due to high energy requirements, rigorous duty cycles, unpredictable operating schedules, and vessel design constraints. Since, this sector is still in the early stages of commercialization, CARB has focused primarily on vessels with predictable duty cycles and return-to-base operations.

The Hydrogen Zero-Emission Tugboat (HyZET) Project was intended to produce an actionable design for a hydrogen fuel cell tugboat that is designed to operate in POLA. The main objectives of this project were to:

- Develop a baseline harbor craft design, including detailed specifications and costs. These detailed specifications would be used to inform the fuel cell-powered harbor craft design and future deployment.
- Evaluate the costs of constructing, operating, and maintaining the fuel cell-powered harbor craft when compared to the baseline vessel.
- Develop a cost-benefit analysis to estimate and compare the emissions reduction potential with other solutions.

- Identify technology and regulatory barriers to using hydrogen fuel cell systems in the maritime industry.
- Develop supporting plans for refueling infrastructure, including analysis of hydrogen production and delivery pathways.

If the design is deemed to be viable, the consortium can collaborate to seek funding to build the vessel. The technical expertise developed through the HyZET Project can also be applied to other CHC segments and potentially to ocean-going vessels.

The HyZET Project was carried out by a consortium consisting of leading maritime stake-holders with extensive experience in electric propulsion system integration, fuel cell energy solution production, feasibility analysis and technology qualification, independent safety and quality assurance, vessel operation and design, liquid hydrogen system integration, and upstream hydrogen production. The HyZET consortium includes:

- **ABB Inc. Marine & Ports:** ABB analyzed the feasibility of deploying battery and power electronic systems and contributed to the design for the vessel.
- **Ballard Power Systems, Inc.:** Ballard Power analyzed the feasibility of deploying a fuel cell system and contributed to the design for the vessel.
- **CALSTART, Inc.:** CALSTART served as the project manager and developed supporting plans for fueling the HyZET vessel.
- **Chart Industries, Inc.:** Chart Industries analyzed the feasibility of deploying liquid hydrogen and contributed to the design for the vessel.
- **Crowley Engineering Services:** Crowley defined the baseline parameters for the HyZET vessel, contributed to the design of the vessel, and analyzed the economic feasibility of the design.
- **DNV:** DNV contributed to the design of the vessel, conducted a cost-benefit analysis of competing maritime fuels, identified technology and regulatory barriers to the vessel, and contributed to the supporting plans for fueling the HyZET vessel.
- **The Port of Los Angeles:** The Port of Los Angeles contributed to defining the baseline parameters of the vessel and to the supporting plans for fueling the HyZET vessel.
- **Southern California Gas Company:** The Southern California Gas Company partially funded the HyZET Project.

CHAPTER 2: Project Approach

The project team carried out a techno-economic feasibility analysis of the HyZET vessel and its supporting hydrogen infrastructure. This effort involved defining tugboat baseline parameters, integrating the hydrogen fuel cell and battery energy storage systems in the vessel, developing a vessel design, analyzing economic feasibility, conducting a cost-benefit analysis of marine fuels, identifying technological and regulatory barriers, and analyzing hydrogen supply and infrastructure needs. This section outlines the methodology that the project team used to conduct this analysis.

Tugboat Baseline

The fuel cell tugboat was designed to provide escort and docking service in POLA, as well as offshore operations. Crowley's HERCULES diesel-powered tugboat, which has a bollard pull of about 90 tons, was used as the design basis for the vessel. The vessel was designed in several stages. The first stage involved collecting data to understand the duty cycle and energy requirements of the HERCULES tugboat. This data was then used to size the propulsion system, the fuel cell system, the battery systems, and the liquid hydrogen storage system. Based on these system requirements, a general arrangement for the vessel was developed. This general arrangement then served as the basis for estimating the cost of the vessel.

The HyZET team analyzed data from Crowley's HERCULES tugboat to understand its duty cycle and develop a baseline profile. This data was collected using the BareFleet monitoring program developed by Reygar LTD Marine Systems. This monitoring program continuously records potentially dozens of different data points at 10-second intervals, allowing in-depth review of the vessel and its equipment. For this project, data on engine loading, fuel consumption, and speed over ground was reviewed to establish the load profiles. The week of September 1 through September 7, 2021, was chosen as a representative week for this phase, with additional trips analyzed for variations in vessel operations. Crowley examined the loading of the individual main engines, broken down by the port and starboard engines (designated as p and s in Table 1, respectively). Engine loads were then broken into 5 percent increments of total engine power to obtain a distribution of loading over each trip.

This analysis indicates that, for the vast majority of the time the vessel was underway, power use was less than 50 percent of the maximum engine loading. Of the eight trips analyzed, four trips had engine loads of 50 percent or less at least 95 percent of the time underway, while all but one trip had 99 percent of the time underway with power loads of less than 75 percent. Of the eight trips, six fell into a fairly common load pattern. One trip had a significant amount of power loading, between 65 percent and 75 percent, while another had a larger amount of time, with loading from 75 percent to 100 percent.

Table 1: Cumulative Trip Percentage Spent per Engine Load

Trip	Engine Load (%)				
	25%	50%	65%	75%	90%
1p	27.50%	64.80%	96.00%	99.30%	99.50%
1s	36.40%	65.50%	97.50%	99.50%	99.70%
2p	81.30%	96.60%	98.60%	99.10%	99.50%
2s	70.10%	95.90%	98.10%	99.30%	99.80%
3p	38.60%	74.00%	97.90%	99.00%	99.50%
3s	28.40%	72.40%	97.30%	98.90%	99.80%
4p	43.10%	82.30%	90.80%	96.30%	98.10%
4s	43.50%	75.30%	91.20%	96.30%	98.30%
5p	53.30%	97.20%	98.70%	99.20%	99.60%
5s	65.60%	97.20%	99.50%	99.70%	99.80%
6p	53.00%	96.00%	97.40%	98.90%	99.30%
6s	65.00%	96.70%	98.80%	99.80%	99.90%
7p	46.20%	95.30%	96.80%	99.60%	99.90%
7s	46.60%	95.00%	98.70%	99.40%	99.90%
8p	41.70%	68.20%	75.20%	99.80%	99.90%
8s	40.30%	68.20%	75.00%	99.60%	99.90%

p: port engine
p: starboard engine
Source: Crowley

These results indicate that a diesel-powered harbor tug has a disadvantage because its large horsepower engines are required to provide very few minutes of high power for a job, while a great portion of the time the tug is operating at 50 percent power or less. Based on this analysis, designing the power system to be capable of providing maximum power without using an energy storage system would seriously over-size the main propulsion power plant.

The HyZET team also analyzed fuel consumption. The HERCULES uses approximately 3,000 gallons of marine diesel oil per week, which has an equivalent energy content of 2,800 kilograms (kg) of hydrogen. Since the proposed fuel cell tugboat is slightly larger than the HERCULES, it requires more fuel. As a result, a margin of 25 percent was added to the 2,800 kg of hydrogen. Based on this methodology, the tugboat was projected to require 3,500 kg of hydrogen per week. Since the HERCULES normally bunkers once per week, the liquid hydrogen storage tank must be able to hold at least 3,500 kg of hydrogen.

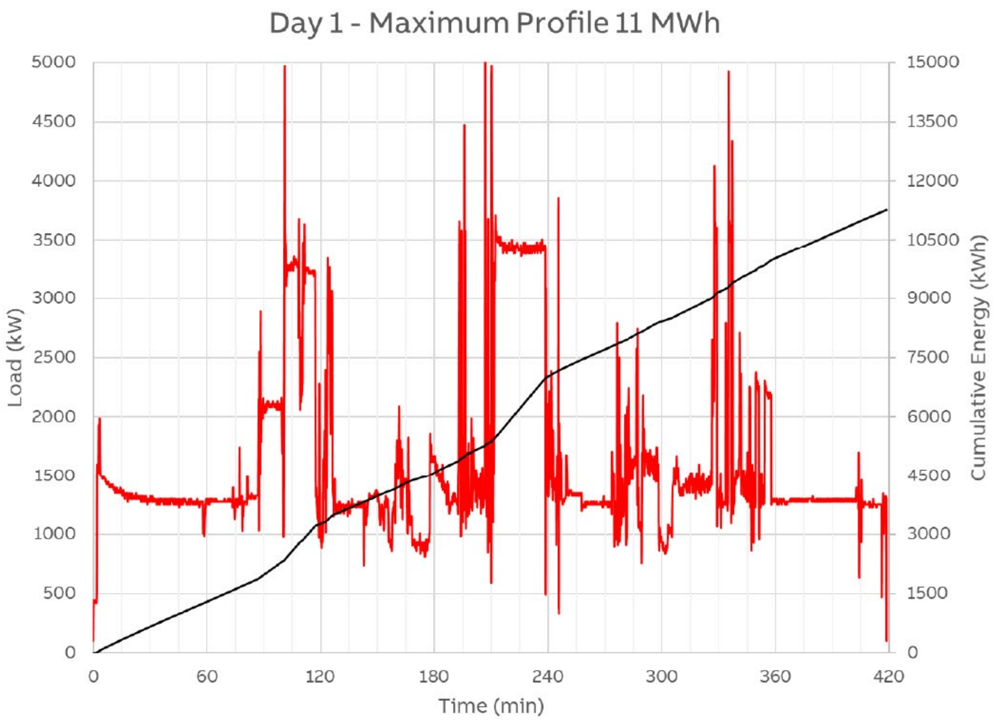
Hydrogen Fuel Cell System Technology and Integration

To be deployed, the tugboat needs to pass a full 90 tons-bollard pull test. The HyZET team specified a Schottel L-Drive (SRP-490LE) system, with a maximum power of 2,450 kilowatts (kW) per engine. Since there is one motor on the port side and one motor on the starboard side of the vessel, this equates to 4,900 kW. In addition, the vessel has a 200-kW hotel load. As a result, the maximum power draw for the tugboat is 5,100 kW. The HyZET team analyzed three operating modes to size the powerplant for the vessel:

- Bollard pull testing: Based on a duty cycle of a 5,100-kW load for 15 consecutive minutes.
- Maximum profile: Based on a duty cycle where the vessel consumes 11 megawatt-hours (MWh) per day. Ninety-five percent of daily duty cycles consume 11 MWh or less.
- Average profile: Based on a duty cycle where the vessel consumes 5.1 MWh a day. Half of daily duty cycles consume 5.1 MWh or less.

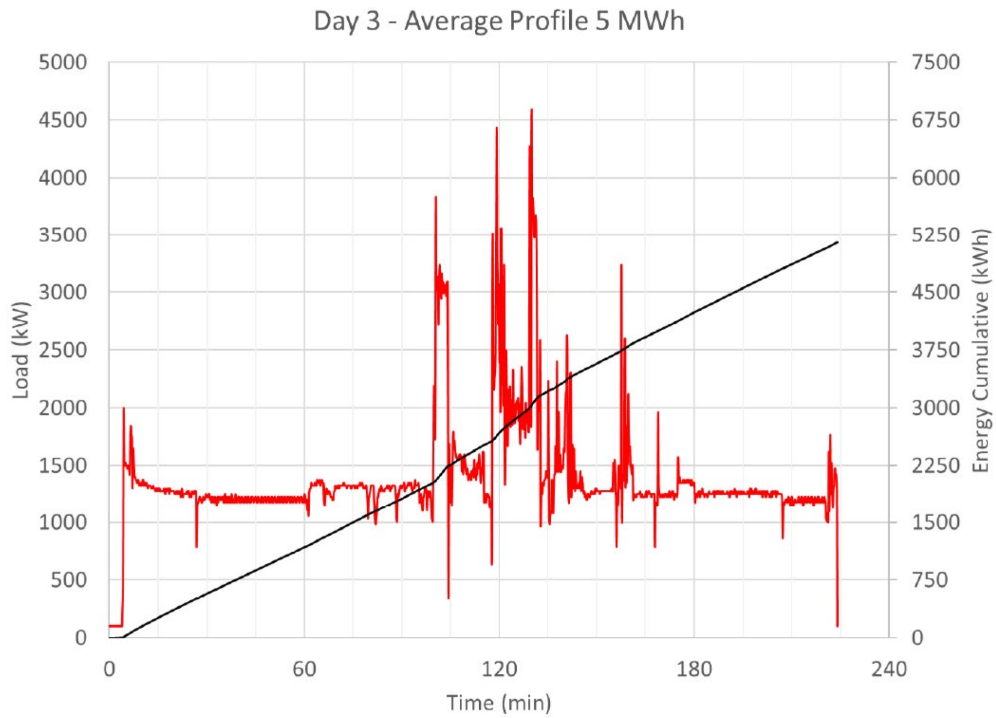
The duty cycles in the maximum profile and the average profile are displayed in Figure 1 and Figure 2, respectively.

Figure 1: Baseline Tug Maximum Power Profile



Source: Crowley

Figure 2: Baseline Tug Average Power Profile



Source: Crowley

The tugboat is designed to employ both fuel cells and battery energy storage systems (BESS) to meet these duty cycles. The fuel cell is used as a baseload, supplying constant power. The BESS is used for peak shaving, providing energy at peak demand and charging when the tugboat's load is less than the power generated by the fuel cells. Additional considerations need to be taken into account when sizing the BESS. The battery should act as a redundant source of power and energy if the fuel cells stop working and it should be able to power the vessel for a certain duration. Sufficient energy and power capacity are required to power the vessel back to shore in the event of an emergency. The mix of fuel cells and BESS is subject to other constraints. Economic factors, primarily the relative cost of fuel cells and the BESS, have a major impact on the optimal mix between the two technologies. Space requirements for the fuel cells and the BESS are also a key factor.

Economic Feasibility

The project team conducted an economic analysis to understand the feasibility of building the vessel. To conduct this analysis, Crowley requested a price estimate from a local shipyard for building the vessel without the major equipment. Then it added pricing for the major equipment (fuel cell, batteries, liquid hydrogen tank) to this figure. Crowley obtained pricing for the major equipment from the members of the consortium and vendors that the company has previously worked with.

Economies of Scale

It is important to note that this is the projected cost for the first vessel. This distinction is important, because the first vessel in a novel design requires additional hours for engineering and design work. Furthermore, more time and resources are used to obtain regulatory approval. These are sunk costs that are required to build the first vessel. As more vessels of the same class are built, fewer hours are required for engineering. In addition, the systems that are deployed on the vessel are new technologies, and their prices can decrease as they benefit from economies of scale; such systems include batteries, fuel cells, and liquid hydrogen storage tanks.

The impact of economies of scale for the fuel cells and the liquid hydrogen storage tanks were modeled using a methodology borrowed from a study conducted by Ruffini and Wei (2018). This study used learning rates to model how price changes in response to increases in production volume. A learning rate is expressed as a percentage. It represents the percent decrease in the price of a good that occurs when production volume doubles. This analysis was used to provide a low estimate and a high estimate for cost reductions. The project team found that the fuel cell had a learning rate of 11 percent for the low estimate and a 39 percent learning rate for the high estimate (representing a scenario where fuel cells have the same learning rate as batteries) (Hydrogen Council, 2020). The project team also set a price floor for fuel cells which assumed that their price would not decrease by more than 50 percent. Based on data from the manufacturer, liquid hydrogen tanks were found to have a learning rate of 5.5 percent. This methodology was used to project the price, based on different production volumes.

Cost-Benefit Analysis

DNV conducted a cost-benefit analysis to compare the life cycle effectiveness of hydrogen fuel cells at reducing GHG and criteria pollutant emissions. Hydrogen fuel cells were compared with other propulsion systems, including battery, hybrid, Tier 4 marine engines, and internal combustion engines powered by alternative fuels. These alternative fuels include liquified natural gas, biofuels, and hydrogen carriers such as ammonia.

DNV calculated the fuel consumption and emissions from Crowley's HERCULES tug, which served as the baseline vessel. The HERCULES consumed 117,900 gallons of marine diesel oil between September 2021 and August 2022. This equates to 388 metric tonnes of fuel. DNV then calculated the GHG emissions from this fuel; it calculated the carbon dioxide, methane, and dinitrogen oxide emissions and adjusted them based on their global warming potential. Based on these figures, DNV concluded that the HERCULES produced approximately 1,249,600 kg of carbon dioxide equivalent emissions per year.

The cost-benefit analysis compared the costs and emissions reduction potential of each fuel type. This analysis examined the capital costs of a vessel for each fuel type. The analysis took into account parameters that affect the techno-economic feasibility of each fuel type. The first parameter was energy density, which reflects the weight and volume of the fuel on the vessel. This factor is important because tugboats are designed to be as small as possible, so that most of the power produced by the propulsion system is used for towing. Any added space and weight would likely lead to a bigger and heavier vessel, which could reduce towing capability. Fuels with lower energy density have higher storage volume and increased weight, which puts them at risk of not meeting performance parameters.

DNV also examined fuel prices because they directly impact operational costs. Prices are greatly affected by factors like supply availability, development of new technologies, infrastructure, and global economic and socio-political factors.

The cost-benefit analysis examined the following fuel types:

1. Battery – Hybrid
2. Battery – Full electric
3. Biodiesel – Fatty acid methyl ester (FAME)
4. Biodiesel – Hydrotreated vegetable oil (HVO)
5. Methanol
6. Liquified Natural Gas (LNG)
7. Hydrogen
8. Ammonia

For each fuel, DNV analyzed the advantages and disadvantages for maritime use, estimated emission reduction potential, assessed fuel availability, and estimated costs. These factors were then compared to the baseline tugboat powered by marine diesel oil.

Vessel Regulatory Analysis

The HyZET vessel, in addition to meeting performance requirements, must also comply with regulatory requirements. These regulatory requirements come from a variety of sources, such as the International Maritime Organization (IMO), classification societies, and governmental regulatory agencies. The majority of these regulatory requirements are related to safety. This is especially important for hydrogen, which has unique safety requirements, especially in the maritime sector. This section outlines the myriad of regulatory requirements that the HyZET vessel needs to meet.

Navigating the DNV Type Approval Process

In the global marine industry, operators rely on official validation that a vessel and its key components meet regulatory, technical, safety, and environmental requirements. Therefore, a sea-going vessel is required to be classified by a classification society, ensuring that the ship's design and components are fully in accordance with the standards set by their class. The components on the vessel pursue type approval. Type approval shows that a product meets a minimal set of regulatory, technical, and safety requirements. While tugboats and many tugboat components already have type approval, the fuel cell system is a new technology for tugboats. As a result, the fuel cell must obtain type approval before it can be deployed on a vessel.

Ballard Power's FCwave™ fuel cell module was selected for the vessel design. Over the course of the HyZET Project, Ballard Power opted to pursue type approval for the FCwave™ through DNV. DNV type approval certifies that the FCwave™ meets safety and reliability standards for the unique demands of the global marine industry. One of the most important functions of type approval is to mitigate any safety concerns and hazards regarding the product. In the context of fuel cells, hydrogen safety, and specifically preventing hydrogen fires and explosions, is one of the most pressing concerns. Type approval is also important for building global market confidence in hydrogen fuel cells and reducing regulatory barriers for adopting fuel cells, by ensuring a one-time design approval that avoids repetitive design reviews.

Ballard Power navigated DNV's type approval process. During this process, DNV typically determines the relevant regulatory, technical, and safety requirements for the product. For established technologies, there are already regulatory, technical, and safety requirements in place. However, the FCwave™ is an innovative technology and, as a result, these requirements were not in place. As a result, DNV used regulatory, technical, and safety requirements for analogous technologies and used them as the basis for evaluating the FCwave™.

The type approval process has several steps. The first stage is the application process. During this stage, the manufacturer submits an application with the necessary technical documentation to the certification body. After the application is received, the certification body reviews the documentation and determines which regulations and codes the product is subject to. Typically, the manufacturer and the classification society have workshops to define and discuss hazardous scenarios and solutions for mitigating these hazards. Once this is determined, the certification body performs tests, inspections, audits, or simulations to verify the compliance of the product or system with the applicable standards and requirements.

After the testing occurs, the certification body reviews the test results and issues a type approval certificate if the product meets the criteria for approval. The certificate is valid for a specific period and may include conditions or limitations. After type approval is awarded, the certification body continues to monitor production and quality control of the approved product. This is carried out to ensure continued compliance with the type approval certificate. If the core functionality or the specifications of the product are changed or updated, DNV can conduct further tests to ensure that the updated product still complies with the type approval certificate.

The FCwave™ module received DNV type approval in April 2022. This marked a major milestone for the zero-emission maritime sector, as the FCwave™ is the first fuel cell to receive DNV type approval. This achievement will help the zero-emission maritime sector, as it will facilitate the adoption of fuel cells on vessels. The FCwave™ module's type approval is valid until May 2027.

Vessel Technology and Regulatory Barriers

To obtain approval for operation, a tug must follow local and international requirements as required by the flag state and the local port authority. These requirements cover the design, construction, and operation of the tugboat. It is important to note that hydrogen is a relatively new type of fuel in the marine sector. As a result, many of the existing regulations were not developed with liquid hydrogen in mind. The project team developed a regulatory matrix to identify the regulations that are most applicable to the HyZET vessel. This section is not intended to be an exhaustive list of regulations.

The United States Coast Guard (USCG) is the main regulatory body for vessels sailing in the United States and has jurisdiction over navigable waters of the United States. Title 46 of the Code of Federal Regulations (CFR) is the main regulation for American-flagged vessels. The most relevant portion of 46 CFR is Subchapter M, which is applicable to all towing vessels. Subchapter M is used by the USCG as a reference during the verification and approval of tugs. The requirements from the subchapter cover a wide range of topics, from fire safety to management systems and machinery and electrical installations. If the requirements of Subchapter M are met, a certificate of inspection is awarded, which is a USCG authorization to operate the vessel. However, 46 CFR does not address the use of hydrogen as fuel or fuel cells. On the other hand, Subchapter M allows for novel designs to follow an alternative design process to demonstrate that an equivalent level of safety is achieved. As a result, the HyZET vessel needs to use the alternative design process to meet the requirements of Subchapter M and to pursue its certificate of inspection.

The HyZET vessel is also subject to applicable IMO regulations. The IMO is the United Nations agency that is responsible for governing shipping, and it has developed many regulations and guidelines for the shipping industry. While there are many IMO publications applicable for a conventional tug, there are several regulations that are most applicable to this vessel. These include the International Convention for the Safety of Life at Sea (SOLAS), the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code), and several other guidelines. SOLAS defines internationally adopted minimum requirements for the construction, equipment, and operation of ships, whether engaging in international trade or when required by the flag for the domestic fleet. The main focus of the convention is the safety of the vessel and those on board. Similar to 46 CFR, there are currently no prescriptive requirements for the use of fuel cells for powering the vessel, but SOLAS provides an "alternative design and arrangements" process that the HyZET vessel can use to pursue approval.

The IGF Code is the main international code for SOLAS vessels using gaseous or low-flashpoint fuels. Currently, the code contains only prescriptive requirements for LNG. All other gaseous or low-flashpoint fueled vessels have to follow an alternative design process to prove that their fuel maintains an equivalent level of safety and meets the functional requirements of the code. The code contains function-based requirements, with the objective of restricting, containing, and venting fuel leakages. The IGF Code also describes considerations for positioning of tanks and separation from other compartments, the arrangement of machinery spaces, the positioning of piping and protection against leakage, and the location and arrangement of the bunkering station. Other safety measures addressed in the code are leakage detections, shutdowns, fire detection, and firefighting. The IGF code is now in the process of being updated to include specific requirements for fuel cells.

The fuel cell and the BESS also have unique safety considerations. Many of these safety considerations can be mitigated through the design of the vessel. There are some guidelines and standards that seek to address this. MSC.1/Circ.1647 addresses safety concerns related to the fuel cells. This set of guidelines applies to vessels using gaseous and low-flashpoint fuels and will be used together with the IGF Code, not replacing it. ASTM F3353-19 addresses safety concerns related to lithium-ion (Li-ion) batteries. This standard contains requirements for onboard arrangement, testing of cells, operation environment, fire safety, design of the system, and studies/assessments to be done for the system.

Hydrogen Infrastructure Analysis

The HyZET vessel needs a supply of liquid hydrogen and a bunkering system to serve the vessel. While hydrogen fueling for on-road vehicles is a mature technology, hydrogen bunkering for the marine sector is still undergoing technological and commercial development. The project team needs to overcome several unique challenges to successful deploy the HyZET vessel. These include securing a supply of hydrogen, developing a liquid hydrogen bunkering system, and understanding the technical and regulatory challenges to deploying the bunkering system. CALSTART investigated these topics to analyze the feasibility of liquid hydrogen bunkering. CALSTART conducted its analysis through interviews with hydrogen suppliers. CALSTART also conducted interviews with companies that are developing liquid hydrogen bunkering systems and facilitating bunkering technologies, to understand the capabilities of the technology and the requirements for deployment.

The project team sought to identify potential technology and regulatory barriers to the operation of hydrogen fuel cells onboard tugs. The project team determined that the vessel needs to undergo an alternative design process to secure approval of the vessel design. Because the alternative design process is a risk-based process, it was agreed among the project members that a hazards identification (HAZID) workshop would be held. The workshop focused on ensuring that the vessel design was compliant with the identified regulatory environment. This workshop aimed to identify the main challenges for the HyZET tug, so potential mitigating strategies could be developed. The outcome of the process should also serve as input to the design basis, to be submitted to the USCG to kick off the alternative design review. The HAZID workshop was held at Crowley's offices in Seattle from October 26 to October 28, 2022.

CHAPTER 3: Results

The project team conducted analysis to develop a vessel, understand the economic feasibility of the vessel, identify technology and regulatory barriers, and identify hydrogen supply and bunkering solutions. This section discusses the results of the analysis.

Hydrogen Fuel Cell System Technology and Integration

Fuel Cell and BESS

The project team sized the propulsion system for the HyZET vessel, including fuel cells and batteries. The fuel cell system was sized to provide a baseload for the vessel. The required baseload was based on the average power demand under both the average profile and the maximum profile. The Ballard Power FCWave™ system was selected for the vessel design. Twelve FCWave™ modules were required to provide the 1,375-kW baseload required by the average profile. The maximum profile had a 1,615-kW baseload requirement, which could also be served by using twelve FCWave™ modules.

The remaining power demand was served by the battery storage system. The HyZET team started by selecting a battery chemistry. There are three types of battery chemistries in the transportation market today, and each type has different properties and is suited for different use cases. The battery chemistries and their properties are displayed in Table 2.

Table 2: Battery Chemistry Properties

Battery Chemistry	Output Power	Energy Density	Cost
Lithium-iron phosphate	Low	High	Low
Lithium nickel manganese cobalt	Medium	Medium	Medium
Lithium titanate oxide	High	Low	High

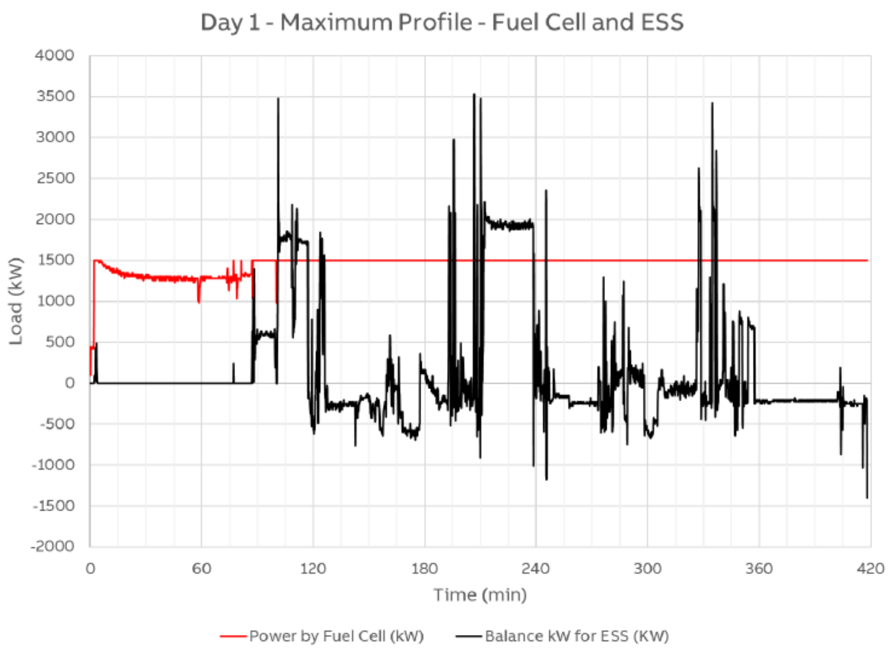
Source: ABB Inc.

The lithium nickel manganese cobalt chemistry was selected because it has a balanced ratio between power and energy. Furthermore, lithium nickel manganese cobalt is the primary chemistry used in the marine sector and the supply chain for this battery type in the marine sector is established.

The primary purpose of the battery storage system is to engage in peak shaving. The battery storage system is designed to provide supplemental power when power demand exceeds the average load and to then recharge from the fuel cells when power demand falls below the average load. This allows the fuel cells to operate in their most efficient range. The ORCA E2250V1 from Corvus Energy was the BESS selected for the vessel design. The Corvus Energy sizing tool was used to determine the optimal size of the battery storage system. The tool determined that the vessel required 1,740 kWh of batteries. These batteries could provide up to 5,220 kW for 13 minutes or 3,480 kW for 20 minutes.

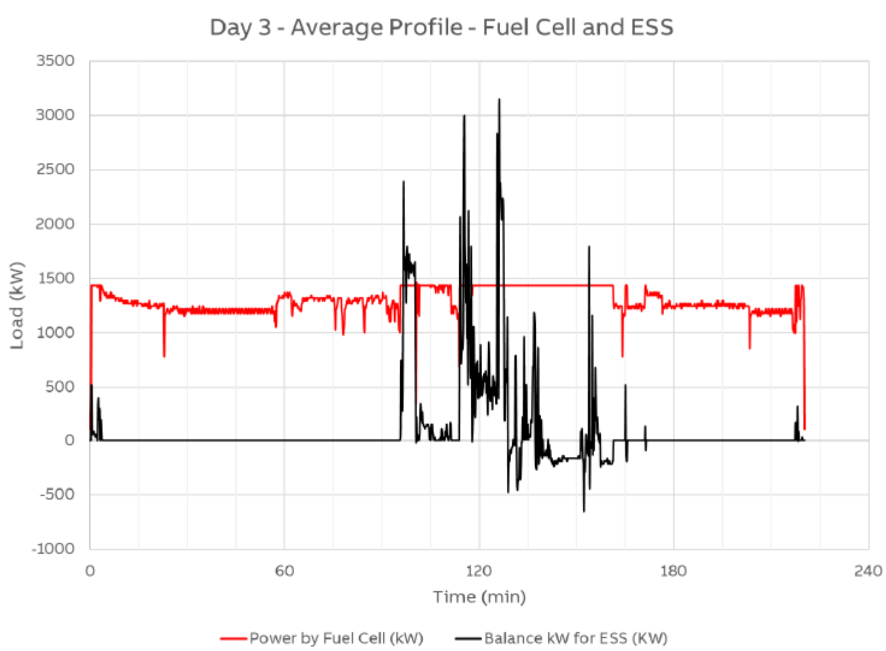
Figure 3 and Figure 4 illustrate how the fuel cell and battery storage systems work in conjunction to meet the power demands of the tugboat for both the Maximum and the Average load profiles, respectively.

Figure 3: Fuel Cell and BESS Operation Under the Maximum Profile



Source: Crowley

Figure 4: Fuel Cell and BESS Operation Under the Average Profile



Source: Crowley

Liquid Hydrogen Storage Tanks

The HyZET team determined that the tugboat requires 3,500 kg of hydrogen per week. The HERCULES tugboat is bunkered once per week. To maintain this operational schedule for bunkering, the vessel needs to be able to store at least 3,500 kg of hydrogen. Since hydrogen is not volumetrically dense and the vessel is space constrained, it is not feasible to store gaseous hydrogen on the tugboat at this scale. As a result, the vessel was designed to bunker with liquid hydrogen. Although the vessel requires 3,500 kg of hydrogen per week, the liquid hydrogen storage tanks cannot be completely emptied without being recommissioned. As a result, the liquid hydrogen storage tanks need to have an additional storage capacity beyond the 3,500 kg that is consumed each week. To meet these needs, the tugboat design calls for two 2,000 kg liquid hydrogen tanks. The liquid hydrogen tanks manufactured by Chart Industries were selected for the vessel design.

Fuel Cell Tugboat Design

The HyZET team developed a general arrangement for the vessel. The design process started with the program . For the general lay-out, the HyZET team aimed to emulate the design of the vessels currently working in the LA harbor as well as the designs under development for updating Crowley's harbor tug fleet. All the new designs currently under consideration employed some amount of BESS to supplement the main propulsion. The trend involved using several generators in a diesel electric configuration. As a result, integrating the BESS into the design was relatively routine.

A key design challenge was integrating the liquid hydrogen storage tanks. The liquid hydrogen tanks are required to be a certain distance from the shell of the vessels, and the vents of the system must be located away from intakes and openings to other parts of the vessel, particularly accommodations spaces. As a result, the tugboat had to be designed to have a length of 105-feet, which was slightly larger than the HERCULES. However, this length still matched well with the current Crowley fleet in the harbor; the lengths of these tugs ranged 82 feet to 105 feet. The current length of the design had to provide sufficient space to allow relevant regulations and guidelines to be met. A hazardous zone plan was developed to determine where areas of potential gas release could affect operations of the vessel.

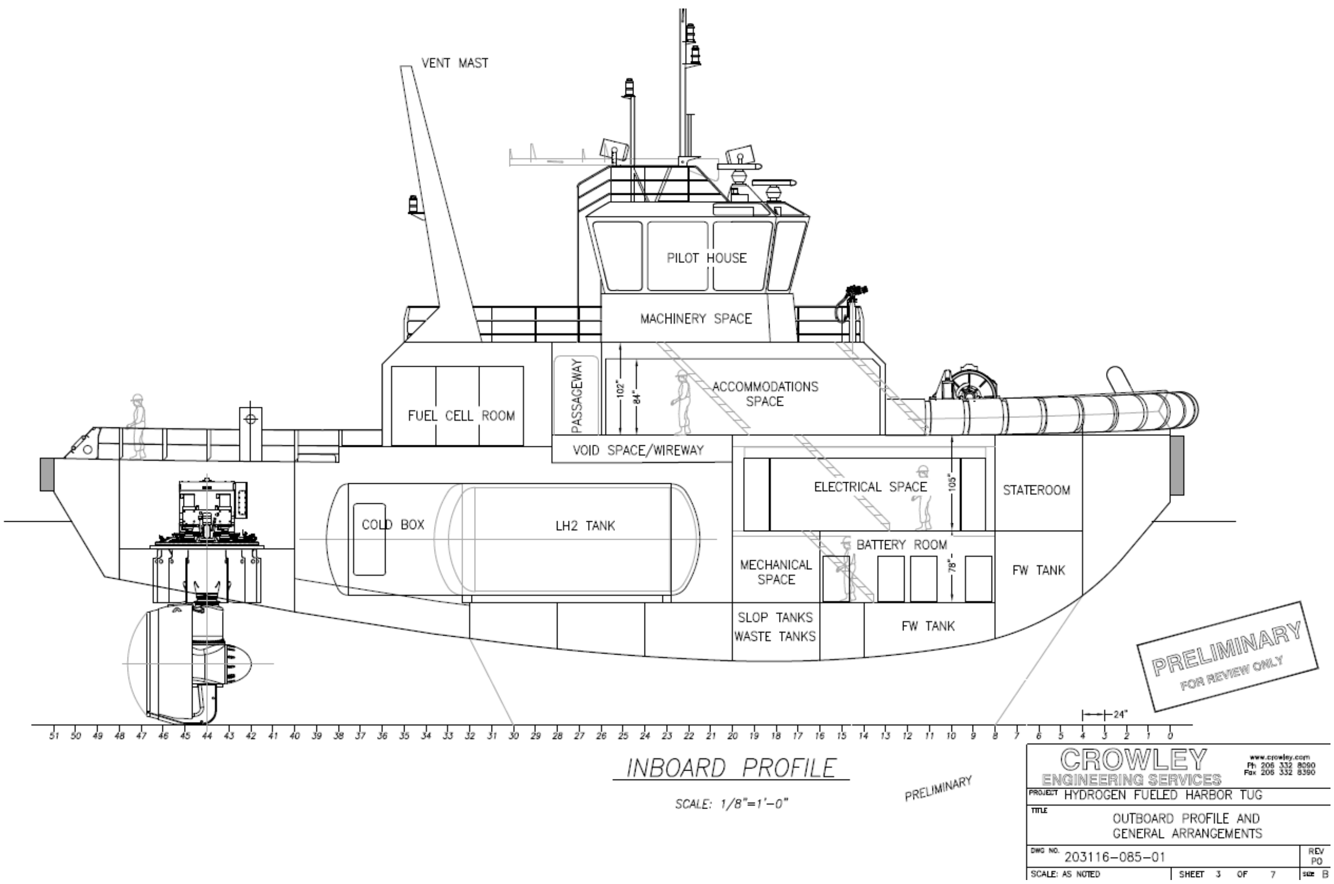
Another aspect of this particular design and electrical propulsion in general was the number of ancillary equipment and control cabinets required to house the DC (direct current) grid and supporting controls and transformers. A side effect of fitting the twin liquid hydrogen tanks into the hull was that it required a slightly deeper hull than typical tugs of this size and power, which provided the opportunity for a two level "machinery/control" space. This provided additional space around equipment and vertical separation for the "wet" machinery (pumps and liquid manifolds) and the "dry" machinery (all the electrical components). This also allowed for the batteries to be located low in the vessel.

Despite these unique design requirements, the HyZET team found that the construction of a hydrogen powered harbor tug appeared to be viable based on available technology. The proposed propulsion system fits within a dimensional envelope that is similar to the existing tugs that operate in the harbor. The power plant provides sufficient energy to obtain the desired bollard pull of 90 short tons for a reasonable amount of time. The design and power that this design can project works well within the framework of the assist tugs currently deployed in POLA and POLB. The tug also fits within the framework of the future fleet Crowley and other companies are looking to field — a high powered zero-emission tug that works no differently than the existing fleet.

While designed to be a harbor craft specific to the operational requirements of the ports of Los Angeles and Long Beach, the vessel has sufficient fuel capacity to transit between ports and operate in different locations. Depending on the specific operational requirements of a particular port, the bunkering intervals may need to be adjusted to maintain the proper levels of liquid hydrogen in the tanks. The vessel's size and bollard pull make it suitable for operations in more open areas, such as the North Puget Sound.

The general arrangement of the HyZET vessel is displayed in Figure 5.

Figure 5: General Arrangement for the HyZET Vessel



Source: Crowley

Economic Feasibility

The cost to build the vessel was expected to be $41.8 million, if it was built in 2022. A breakdown of these costs is included in Table 3.

Table 3: Vessel Cost Estimate

Item	Cost
Hull	$12,500,000
Electronics	$300,000
Liquid Hydrogen Tanks	$8,965,800
ABB System (including fuel cells, batteries, DC drive units, transformers, AC switchboards, motors & thrusters, uninterruptible power supply, pilot automation systems, system integration & project management services)	$16,930,000
Capstan/Windlass	$148,000
Anchor/Chain	$15,000
Hawser Winch	$867,500
Line	$10,000
Engineering	$1,750,000
Class Costs	$350,000
Current Cost (2022)	**$41,836,300**
Cost for 2023 Build	**$46,019,930**
Cost for 2024 Build	**$50,621,923**

Source: Crowley

Inflation is expected to increase the price of the vessel over time. Assuming a 10 percent inflation rate, the cost to build the vessel in 2023 is projected to be approximately $46 million and the cost to build the vessel in 2024 is projected to be approximately $50.6 million. A comparable diesel-powered tugboat costs approximately $17 million.

Economies of Scale

Based on learning rates analysis, the project team calculated the cost reductions that would occur as subsequent vessels are deployed. The calculated cost for a second vessel is displayed in Table 4.

Table 4: Estimated Price Reductions for Second Vessel

Item	Low Estimate	High Estimate
Engineering	$5.00 M	$7.00 M
Batteries	$0.00 M	$0.13 M
Fuel Cells	$0.66 M	$2.34 M
Liquid Hydrogen Tanks	$0.90 M	$0.90 M
Total Cost Reduction	**$6.56 M**	**$10.37 M**

Source: CALSTART

The cost of the vessel in 2022 was estimated at $41.84 million (M). Based on these projections, the cost of the second vessel would be between $31.47 M and $35.28 M. These figures are based on current prices and do not take inflation into account.

The cost reductions for a twentieth vessel were also calculated. The results are displayed in Table 5.

Table 5: Estimated Price Reductions for Twentieth Vessel

Item	Low Estimate	High Estimate
Engineering	$5.00 M	$7.00 M
Batteries	$0.00 M	$0.13 M
Fuel Cells	$2.37 M	$3.00
Liquid Hydrogen Tanks	$1.70 M	$1.70 M
Total Cost Reduction	**$9.07 M**	**$11.83 M**

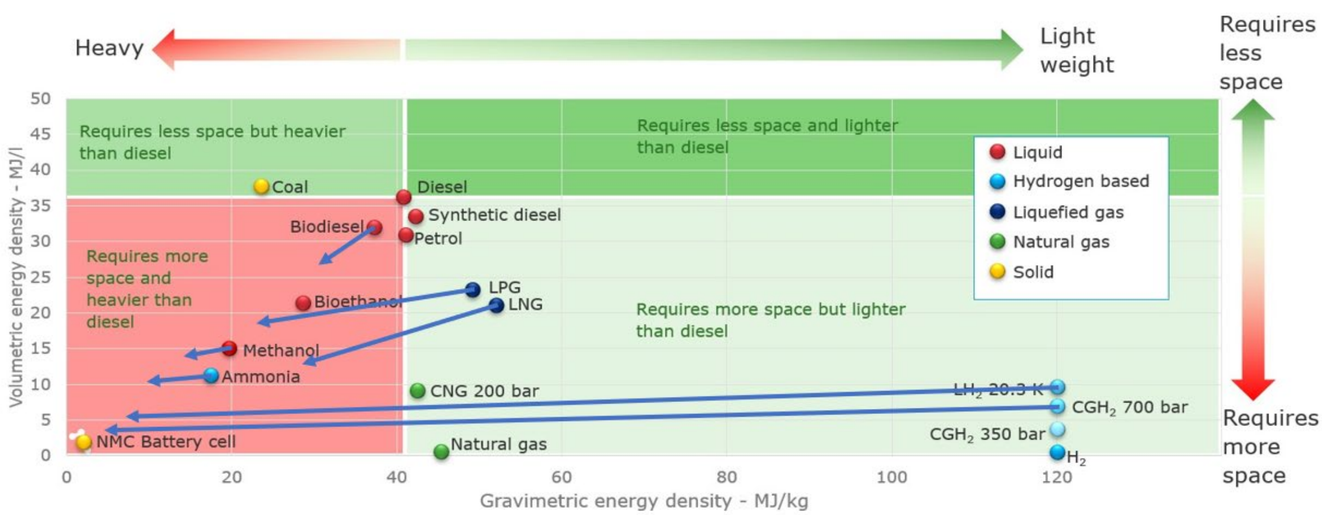
Source: CALSTART

Based on these projections, the cost of the twentieth vessel would be between $30.01 M and $32.77 M. These figures are based on current prices and do not take inflation into account.

Cost-Benefit Analysis

DNV conducted a cost-benefit analysis comparing multiple marine fuels. This analysis examined two metrics. The first metric was energy density. DNV compared the energy density of the fuels examined. The results of DNV's analysis are displayed in Figure 6.

Figure 6: Marine Fuel Energy Density

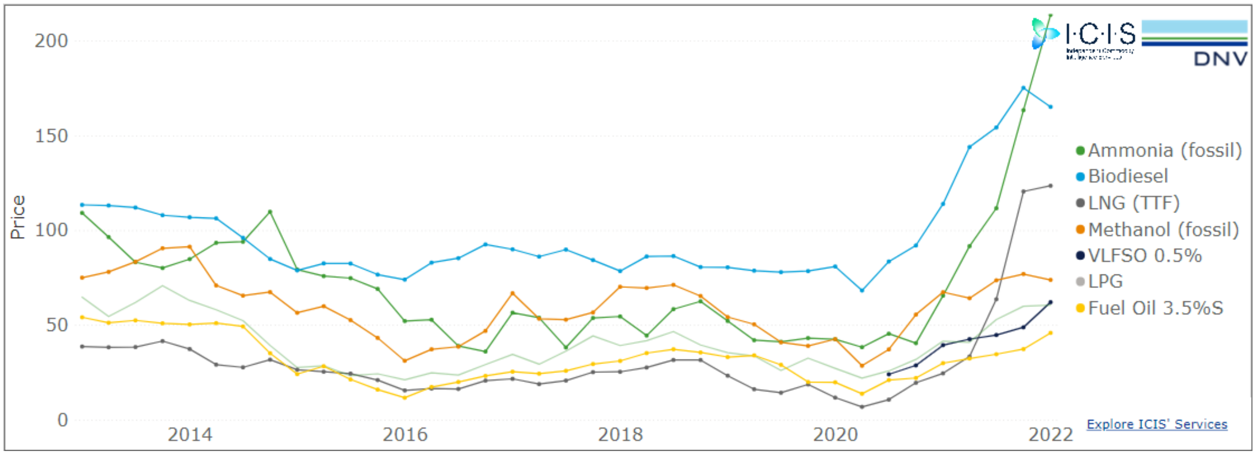


CGH_2 = compressed hydrogen gas
CNG = compressed natural gas
LH_2 = liquid hydrogen gas
LNG = liquified natural gas
LPG = liquified petroleum gas

Source: DNV GL Comparison of Alternative Marine Fuels, 2019

DNV also compared prices for maritime fuels. The comparison of fuel prices is displayed in Figure 7.

Figure 7: Marine Fuel Prices (US$/MWh)



Source: DNV Alternative Fuels Insight

Battery — Hybrid

A BESS can be used in a hybrid configuration in diesel-electric tugs or conventional tugs if the thrusters are powered with electric motors. A BESS contains Li-ion batteries, a battery management system, ventilation/cooling, and a dedicated fire extinguishing system. The BESS must be installed in a dedicated compartment with ventilation. BESS is a mature technology and there are already hybrid tugboats that have been deployed. However, Li-ion batteries have a very low energy density, and large battery installations will entail space and weight costs on the vessel. This is particularly difficult for tugboats, which are space constrained. Fire safety is also a concern, as battery fires can be difficult to extinguish. The lifetime of the BESS is also limited by the number of charge/discharge cycles. The typical BESS lifetime is 8,000 to 12,000 cycles.

While the actual emissions reductions depend on the vessel specifications, DNV estimates that a hybrid tug can reduce GHG emissions by 20 percent. However, the well-to-wake emissions depend on the source of energy used for charging batteries. Charging the batteries from the grid maximizes the renewable content of the electricity. The California grid is currently 33.6 percent renewable (CEC, 2021). A BESS has high GHG emissions during manufacturing. However, these emissions are displaced by GHG emissions reductions from operations within one year. The capital expenses (CAPEX) of a hybrid vessel are expected to be $27 million to $30 million.

Battery — Full Electric

A full electric tugboat is powered entirely with a BESS and electric thrusters. The low energy density of the BESS creates problems similar to those for the battery hybrid configuration. However, since the vessel does not have an internal combustion engine, it would have a shorter range than a battery hybrid vessel and would work best in smaller ports with lower bollard pull requirements. A full electric tugboat would have lifecycle and fire safety concerns similar to those of a battery hybrid vessel. A full electric tugboat would have zero tank-to-wake emissions. However, well-to-wake emissions would depend on the source of energy used to charge the batteries. The CAPEX for a full electric tugboat similar to the HyZET performance requirements is expected to be about $30 million and the shore charging station would cost about $3 million to $5 million.

Biodiesel — FAME

FAME (fatty acid methyl ester) is a biodiesel produced from vegetable or animal sources. It is considered a drop-in fuel, meaning that it can be used with minimal modifications to the engines, the ship, or operations. FAME can be stored in regular diesel tanks. However, integrating this fuel might require adding in fuel treatment systems. Since it is a drop-in replacement, there are no known additional safety concerns when using this fuel, as compared to marine diesel oil. Since its energy density is only slightly less than marine diesel oil, it should not significantly reduce the range or bollard pull of the vessel. However, fuel quality can be an issue. Oxygen degradation can occur, which can cause deposits and peroxides to form. The US is one of the largest producers of FAME, meaning that the fuel is readily available. However, increased demand for FAME as a clean fuel alternative could cause the price to increase. FAME can reduce tank-to-wake emissions by 10 percent. Well-to-wake emissions depend on the source of the feedstock. DNV estimates that well-to-wake emissions can be reduced by up to 80-90 percent. Incorporating FAME into a tugboat would not entail any additional CAPEX. As a result, the price equals that of a standard diesel tug.

Biodiesel — HVO

HVO (hydrotreated vegetable oil) is the third most produced biofuel, behind only ethanol and FAME. The hydrotreating process results in a fuel with main properties similar to those of fossil diesel fuel equivalents, with higher purity and quality than FAME.

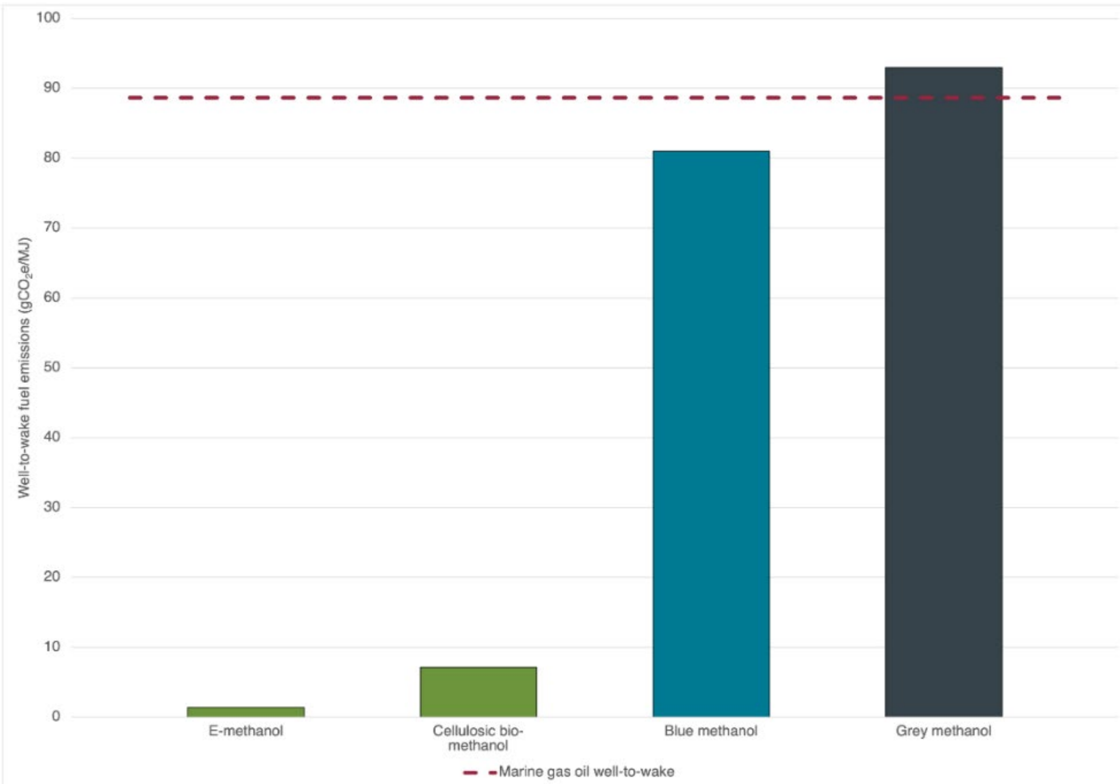
Other than purity and quality, HVO has the same advantages as FAME, including GHG emissions and safety aspects. Its main disadvantage is current availability and potentially higher fuel costs, but global production is expected to increase in the next years, especially in the Americas.

Methanol

Methanol is an alcohol with a low carbon and a high hydrogen content. Methanol can be produced from fossil gas (grey) or agricultural residues and other wastes (green). It can be stored in conventional tanks, as it is a liquid at operating temperatures. Methanol can be used in an internal combustion engine, or it can be converted to hydrogen via cracking and then used to power a fuel cell. However, methanol’s energy density is about half that of marine diesel oil. This affects operations, as it would either have a lower range or require additional storage tanks on the vessel. Methanol is also a low-flashpoint fuel that requires additional safety measures. Methanol can be used as the sole source of fuel or in a dual-fuel arrangement. If used in a dual-fuel arrangement, the vessel requires a diesel after-treatment system.

Methanol reduces tank-to-wake emissions by 10 percent. Well-to-wake emission reductions depend on the source of the methanol. Gray methanol can have higher well-to-wake emissions than marine diesel oil (Figure 8). However, green methanol can substantially reduce well-to-wake emissions. Methanol also eliminates sulfur emissions and significantly reduces PM emissions. Methanol is a widely produced chemical, and it is likely that current production levels can cover demand for shipping until 2030.

Figure 8: Methanol Carbon Intensity



Source: Martin, 2021

A methanol-powered vessel requires a methanol engine. The cost of methanol engines is approximately 50 percent higher than that of diesel engines. As a result, methanol is expected to increase the cost of a vessel by about $2 million to $2.5 million.

Liquefied Natural Gas

Fossil gas or methane is commonly used as an alternative fuel. Fossil gas has a low volumetric energy density as a gas. However, as a liquid, it has a higher energy density. LNG is stored in special tanks in cryogenic conditions, at -259.6ºF (-162ºC). Even as a liquid, its energy density is about 50 percent lower than that of marine diesel oil, meaning that the tanks have to occupy more space on the vessel to obtain the same range. Fossil gas is widely available in California; however, there are few LNG bunkering facilities in California. Bunkering can be carried out via tanker trucks due to the low volume required by a tugboat. LNG eliminates sulfur oxide emissions and significantly reduces PM and NOx emissions. It is also expected to reduce GHG emissions by 10 percent to 25 percent. Emissions can be further reduced if biomethane is used to produce the LNG. The CAPEX for an LNG-powered tugboat is expected to be about $30 million.

Hydrogen

Hydrogen has a very high gravimetric energy density but a very low volumetric energy density. As a result, hydrogen would need to be liquefied to be used in this application. Hydrogen needs to be cooled to -423.4ºF (-253ºC) to be liquefied, which greatly increases the volumetric energy density. However, even as a liquid, it requires 6 to 10 times more volume to obtain the same energy range as marine diesel oil. Hydrogen introduces unique safety considerations, as it has a low ignition energy, has a wide flammability range, and is explosive (this will be discussed further in the Vessel Regulatory Analysis section). Liquid hydrogen can be vaporized into gaseous form and then used in a fuel cell. This method would produce no tank-to-wake emissions and would entirely eliminate NOx, SOx, and PM emissions. However, the well-to-wake emissions depend on the feedstock used to produce the hydrogen. Gray hydrogen, produced from fossil fuels, is most commonly used and has a carbon intensity of 9 to 15 kg of carbon dioxide (CO_2) per kg of hydrogen. Clean hydrogen, as defined in the Inflation Reduction Act, can have a carbon intensity of 0 to 4 kg of CO_2 per kg of hydrogen. As discussed in the Economic Feasibility section, the first liquid hydrogen-powered tugboat is expected to cost approximately $42 million. Subsequent tugs will likely benefit from economies of scale, which will reduce the price.

Ammonia

Ammonia is a colorless gas with characteristics similar to liquefied petroleum gas. The gas is toxic to humans and has irreversible health effects, even causing death at high levels. Ammonia is also corrosive, meaning special care must be given to storage tanks. Released ammonia tends to absorb vapor, making it heavier than air, thus pooling on deck. Ammonia is considered a potential alternative fuel, especially for deep-sea shipping. Ammonia can be used as a fuel in internal combustion engines, or it can be cracked into hydrogen, which can power a fuel cell. Ammonia can likely be used as fuel in large marine engines commonly used onboard ships, and major marine engine manufacturers are currently developing dual-fuel engines that can operate on ammonia. When operating on ammonia, diesel would be required as pilot fuel.

Ammonia's energy density is less than that of marine diesel oil and the tanks need to be about 3 to 3.5 times larger than a marine diesel oil tank to maintain the same range. As a result, ammonia tugboats can be difficult due to space issues. However, ammonia is already commonly transported on ships and ammonia storage tanks are a commercialized technology. The US is the world's largest producer of ammonia. However, ammonia is also commonly used to produce fertilizer, meaning that industrial uses would compete with transportation applications.

Ammonia does not emit any CO_2 during combustion and does not emit sulfur. If it used in an internal combustion engine, the diesel pilot fuel would still produce emissions. However, the pilot fuel is only 5 percent of the total heat input energy. Well-to-wake emissions depend on the feedstock used to produce the ammonia. Green ammonia, produced from renewable energy, has lower emissions. However, brown ammonia, produced from fossil sources, has higher emissions. Brown ammonia produced from fossil gas emits approximately 1.1 kg of CO_2 per kg of ammonia. The CAPEX for an ammonia-powered vessel is approximately $30 million.

Alternative Fuels Comparison

Table 6 displays summarized comparisons of the different marine fuels described above. This comparison outlines the advantages, disadvantages, emission reduction potential, and cost estimates for each fuel.

Table 6: Summary of Alternative Fuels

Fuel	Advantages	Disadvantages	Emission Reduction Potential	Cost Estimates
Battery Hybrid	Can be employed in any port without compromising operations. Not exposed to supply challenges. Allows for operational expenditure (OPEX) reduction.	Higher CAPEX with battery cells Low energy density and limited cycling Safety concerns from battery fires	GHG, NOx, SOx, PM: Up to 30% tank-to-wake, depending on configuration, capacity, and operational profile. Well-to-wake depends on energy source for charging batteries.	CAPEX: Estimated price for vessel is between \$27M and \$30M. OPEX: Potential for 20% reduction in fuel costs.
Full Battery Electric	Demonstrated in the industry as a mature technology, Low maintenance costs	Limited operation range due to low energy density, Safety concerns from battery fires High CAPEX, including battery replacement Cost of charging infrastructure. Costs depend on capacity and potential fees.	GHG, NOx, SOx, PM: 100% reduction tank-to-wake. Well-to-wake depends on the energy source used for charging batteries. In California, less than 35% of the grid is from renewable sources.	CAPEX: Estimated price for the vessel is about USD 27M, with the shore charging station costing about \$3M to \$5M,[1] dependent on the size of the ESS. OPEX: Depends on the cost of charging.
Biodiesel FAME	Drop-in fuel with very low CAPEX. No loss in operational range. Potential for low emissions (well-to-wake) Availability	Quality concerns and potential fuel degradation Price uncertainty	GHG: well-to-wake reduction of up to 80 to 90% for certain types of biofuels, and up to 10% tank-to-wake. Generally, very low Sox emissions. Potential for slightly higher NOx emissions compared to marine gas oil (MGO).	CAPEX: Little impact compared to "baseline tug" costing about \$12M to \$13M. OPEX: Fuel prices depend on feedstock.
Biodiesel HVO	Drop-in fuel with very low CAPEX. No loss in operational range,	Availability and fuel costs		

1 Estimate includes some grant funding to offset the build cost.

OPEX: operational expenditure

Fuel	Advantages	Disadvantages	Emission Reduction Potential	Cost Estimates
	Potential for low emissions (well-to-wake) Fuel quality			
Methanol	Storage in ambient conditions and structural tanks Potentially lower price than most other alternatives	Low energy density and reduced storage due to the requirement of additional cofferdams Safety hazards: toxic, low flashpoint, difficult to detect fires visually Not fully mature technology	GHG: Reduction of up to 10% tank-to-wake. Up to 90% reduction in well-to-wake if using waste as feedstock. Almost eliminates sulfur emissions, and PM emissions are expected to be significantly lower than for MGO. 30%-60% reduction of NOx emissions, depending on the technology used.	CAPEX: Price increase for an engine is about 50% on top of the current cost, plus the additional equipment for handling the fuel. Methanol in a dual-fuel system would raise the cost of a "conventional" tug by about $2M to $2.5M. OPEX: Slightly higher fuel prices. Currently at $575/ton in the US.
LNG	Mature, availability, and demonstrated on tugs. Low fuel costs in the US	High CAPEX and volume required for storage. Methane slip	Up to 25% GHG reduction tank-to-wake. Higher well-to-wake emission reduction once e-LNG and bio-LNG are available. No SOx emissions and very low PM emissions NOx emissions are lower than those of marine diesel oil and heavy fuel oil.	CAPEX: The cost of a pure LNG-powered tug is estimated to be about $30M. OPEX: No significant increase expected but depends on logistics cost.
Hydrogen	Developing supply chain and developing technologies to lower fuel costs	Low energy density requires large storage space. High CAPEX Highly flammable, easily ignited, and high explosion pressures	GHG: Zero emissions. Well-to-wake will depend on feedstock. Used with fuel cells, could eliminate all NOx, SOx, and PM.	CAPEX: Estimated between $40M and $46M. OPEX: Depends on feedstock; potential for competitive prices in the US.

Fuel	Advantages	Disadvantages	Emission Reduction Potential	Cost Estimates
Ammonia	Mature for transport and storage on board ships.	Toxicity and flammability Limited supply and high fuel prices High CAPEX	GHG: Depending on nitrous oxide (N_2O) emissions (not verified yet). Well-to-wake depends on feedstock. Sulfur emissions are virtually eliminated.	CAPEX: Closer to that of an LNG-fueled tug; however, most likely slightly higher. OPEX: Risk of higher fuel prices due to supply concerns.

Source: DNV

Vessel Regulatory Analysis

Vessel Technology and Regulatory Barriers

The project team conducted a HAZID workshop to identify technical and regulatory barriers for the HyZET vessel. The HAZID assessment divided the vessel into multiple nodes, including:

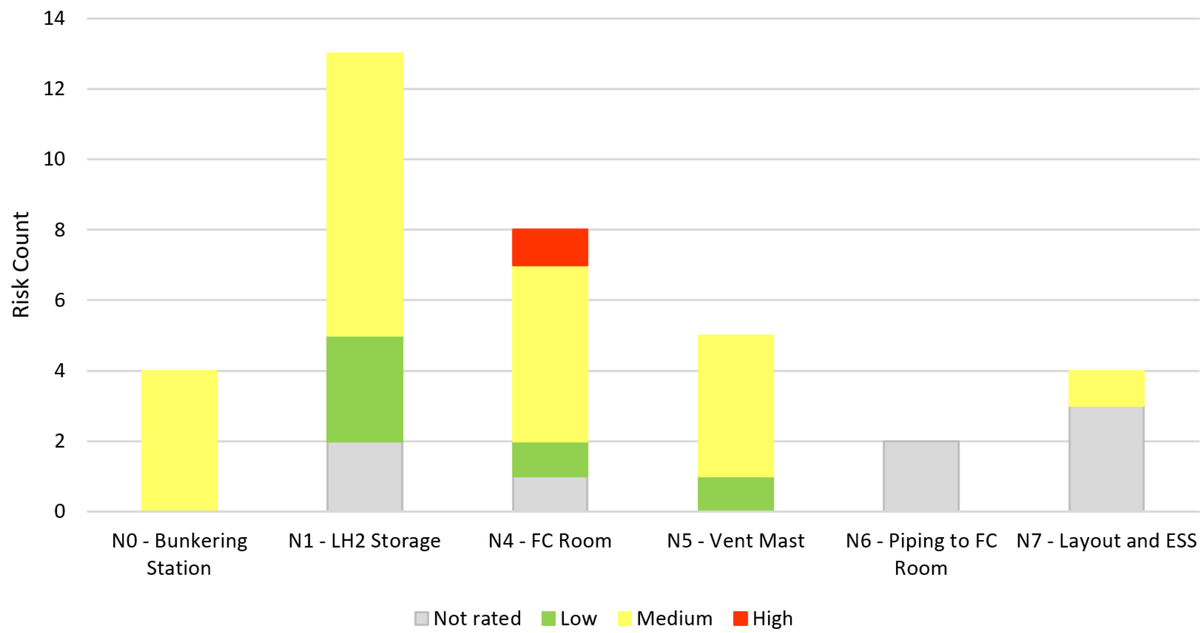
- Node 0: Bunkering station and filling lines to liquid hydrogen tanks
- Node 1: Liquid hydrogen fuel tank (installation and connection to other systems)
- Node 2: Fuel storage hold space
- Node 3: Fuel preparation room (cold box)
- Node 4: Fuel cell room
- Node 5: Ventilation mast – hazardous spaces
- Node 6: Piping between hold space and fuel cell space
- Node 7: General ship layout + BESS

The HAZID assessment then identified potential hazards for each node and scored them based on the frequency and severity of the risks. During the HAZID workshop, Nodes 1 to 3 were consolidated into a single node due to the overlapping nature of the hazards. The hazards were evaluated and rated based on the level of risk they pose to the vessel:

- High (red): Action must be taken to reduce risk to at least the medium level.
- Medium (yellow): Risk reduction measures must be taken if their respective impact on design is not disproportionately high when compared to their attained benefits (as low as reasonably practicable principle); actions need to be taken to manage and measure risk.
- Low (green): Monitoring actions are required to identify whether the risk rises to a medium level.

A summary of the risks is presented in Figure 9.

Figure 9: Risk Exposure per Node



LH_2 = liquid hydrogen gas
FC = fuel cell

Source: DNV

A summary of the most severe hazards is shown in Table 7.

Table 7: Vessel Hazard Descriptions

Node	Hazard	Rating
N4: Fuel cell room	Fire in fuel cell module (electrical equipment)	High
N0: Bunkering station	Contamination of hydrogen	Medium
N0: Bunkering station	Minor piping leakage (hydrogen) — slow leakage	Medium
N4: Fuel cell room	Fuel supply piping rupture	Medium
N5: Vent mast	Water pooling at relief valves	Medium
N4: Fuel cell room	Fire in DC cabling	Medium
N1: Liquid hydrogen storage	Hydrogen in cold box	Medium
N7: General layout and BESS	Loss of thermal insulation (vacuum) in all liquid hydrogen pipes and tanks	Medium
N0: Bunkering station	Major piping leakage (hydrogen) — large volumes	Medium
N1: Liquid hydrogen storage	Liquid hydrogen leakage into annular space	Medium

Source: DNV

The hazards identified in Table 7 are discussed further in Appendix A. Please note that the hazards listed in Table 7 are only the highest-rated hazards. Additional hazards were identified during the HAZID workshop. These are described in the Technology and Regulatory Barriers Report (Task 7).

Hydrogen Infrastructure Analysis

Hydrogen Supply Pathways

Clean renewable hydrogen must be produced and then supplied to the port complex and vessel in liquid form. The HyZET team determined that fueling the tugboat via trucked liquid hydrogen delivery is the most cost-effective method. The HyZET vessel is designed to store up to 4,000 kg of liquid hydrogen and is expected to mirror current bunkering operations by refueling once per week. Since there would be only one vessel deployed at the start, the demand for hydrogen will be relatively low. As a result, there is not enough demand to justify building a liquid hydrogen bunkering station. Also, the tank capacity of the tugboat matches the capacity of a typical liquid hydrogen truck delivery, which simplifies logistics and eliminates the need for fixed infrastructure. Furthermore, there are multiple companies that can supply liquid hydrogen truck deliveries to POLA.

The HyZET team also investigated the potential for onsite liquefaction at or near the port. Typically, liquefaction is done on a large scale at a centralized plant (>30 tons/day). This process typically involves a two-stage process, where the hydrogen is first precooled and then final liquefaction is carried out using helium. However, this process can be scaled down to produce hydrogen onsite. An onsite liquefaction system would need a steady and reliable supply of gaseous hydrogen. Delivering gaseous hydrogen by truck in bulk is not economically efficient and is difficult to scale. As a result, an onsite liquefaction system would likely require gaseous hydrogen that is produced onsite or delivered in bulk via pipeline. While onsite liquefaction is theoretically possible, this would likely require USCG approval and large volumes of concentrated liquid hydrogen demand at the port to justify the infrastructure investment. The evolution of prospective projects within the ARCHES Hydrogen Hub and the Southern California Gas Company’s Angeles Link project may also contribute to the economic feasibility of this supply pathway.

Cryogenic Bunkering Technologies

While gaseous hydrogen has a history of being used as a transportation fuel, industry has only limited experience with using liquid hydrogen. As a result, there are only a few examples of liquid hydrogen bunkering, and this technology is considered to be in earlier stage of technological development. Finding and deploying a suitable liquid hydrogen bunkering system is vital to the success of the HyZET Project.

Liquid Natural Gas Bunkering

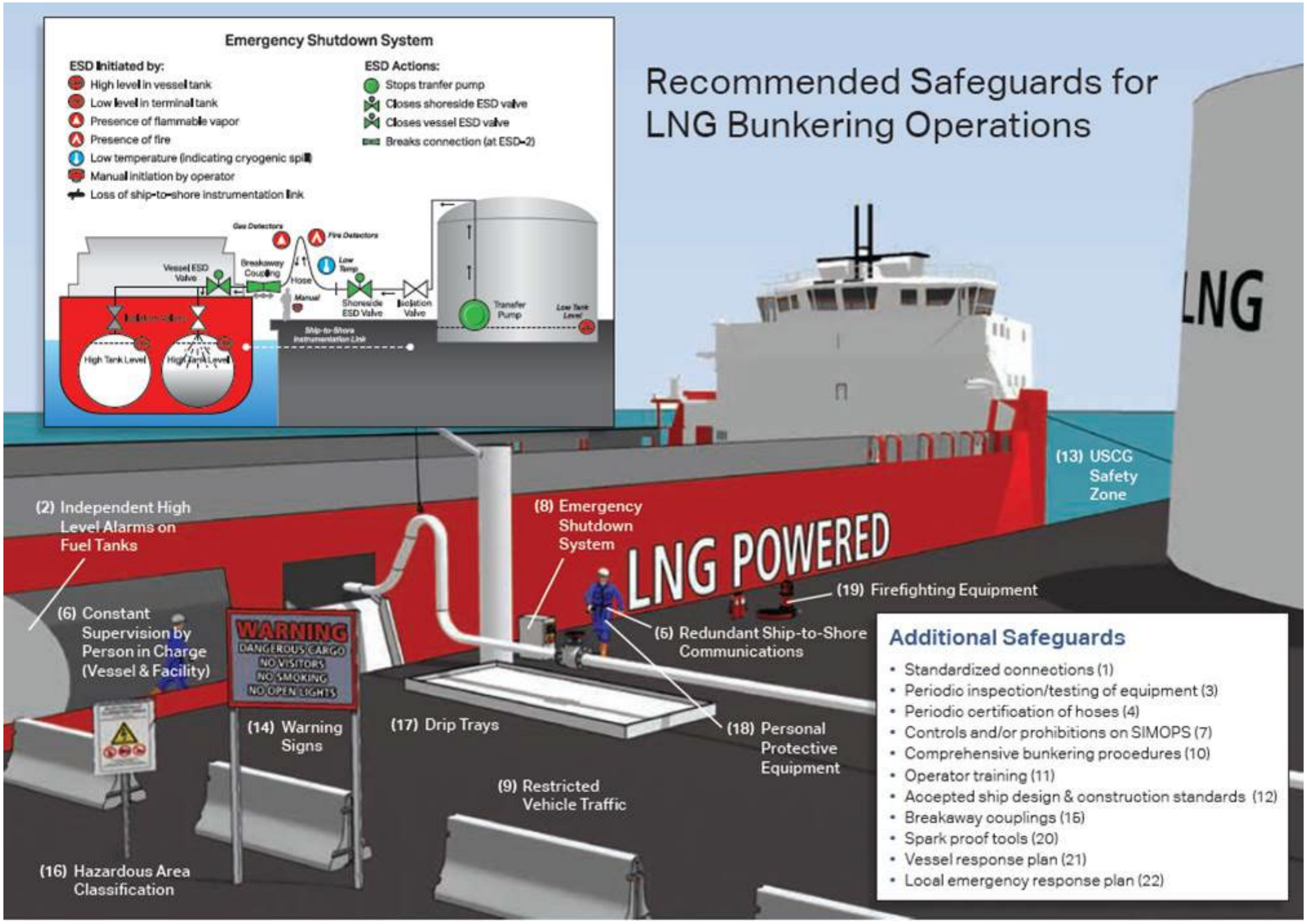
While liquid hydrogen has limited history as a transportation fuel, there are precedents for liquid hydrogen bunkering. LNG has similar properties to liquid hydrogen. Furthermore, LNG has historically been transported in bulk on marine vessels and has recently become a maritime fuel. The maritime industry has extensive experience with handling this fuel, and lessons from handling LNG can be applied to liquid hydrogen.

LNG is comparable to liquid hydrogen because it is also a cryogenic liquid. LNG bunkering typically involves connecting a storage tank that holds LNG to a vessel with a flexible hose. A connector on the flexible hose is used to attach to the vessel's bunkering station. The hose is purged using nitrogen to remove any contaminants. A cryopump is then used to transfer the LNG through the hose to the vessel. Once on the vessel, the LNG travels through double-walled piping until it reaches the onboard storage tank. The hose is then disconnected, and the vessel can resume operations.

There are several models for conducting LNG bunkering. One method is truck-to-ship bunkering. Under this method, an LNG tanker truck parks on the dock next to the vessel and connects using a flexible hose. The bunkering is then facilitated with a cryopump that is located either onboard the tanker truck or on the dock. This method is typically used when demand for LNG is low and there are only a few vessels that require LNG. This method is beneficial because it does not require any permanent infrastructure, meaning that required capital investment is minimal. However, the method does have some drawbacks. Due to the fixed costs of delivering LNG by truck, this method does not scale well when demand increases. Furthermore, this method requires the vessel and the truck to be at the port at the same time, which can complicate logistics. BC Ferries bunkers its vessels using a variation of the truck-to-ship method. Under this method, the LNG tanker truck drives onto the vessel, where it uses a hose to attach to the vessel's bunkering station.

Another method is shore-to-ship bunkering, in which an LNG bunkering station is used to fuel the vessel. Shore-to-ship bunkering is typically used in cases where there is higher demand for LNG at the port. Under this method, a permanent bunkering station is built on the dock. This station typically contains an LNG storage tank. The tank is usually attached to a flexible hose, a bunkering tower, or a loading arm that is used to connect to the vessel's bunkering station. A pump is then used to transfer the LNG (Figure 10). This method is advantageous because the station's storage tank supplies the vessel, meaning that the tanker truck does not need to be present during fueling. This helps to simplify logistics. However, this approach requires capital investment and physical space on the dock. This can be challenging if the port is space constrained. Crowley refuels its vessels at the Port of Jacksonville using this method.

Figure 10: LNG Shore-to-Ship Bunkering Operations



Source: Chart Industries

The last method is ship-to-ship bunkering. This method is typically used when there is high demand for LNG at the port. Under this method, there is a fueling ship that contains an LNG storage tank. The fueling ship approaches the vessel and connects using a flexible hose. A hose saddle is typically used to prevent the hose from sagging excessively into the gap between the two ships, and a pump is typically used to transfer the LNG. This method is advantageous because it allows vessels to be bunkered at their own dock, which minimizes the amount of downtime during the bunkering process.

LNG bunkering has some safety ramifications. One major concern is release of fuel into the environment. Since LNG is a cryogenic fluid, exposure to LNG can cause cold burns to personnel. In addition, released LNG can vaporize, creating a risk of fire and an explosive environment. Fossil gas is also a greenhouse gas, meaning that any releases would contribute to climate change. To prevent these risks, drip trays are used to collect any LNG that leaks. In addition, emergency release couplings are used on the bunkering hose. These couplings are designed to disconnect if the vessel drifts away from the dock while still attached to the bunkering hose. These couplings are dry disconnects, which are designed to minimize or completely prevent release of LNG during the disconnection process.

Liquid Hydrogen Bunkering

Liquid hydrogen and LNG have a similar bunkering process and face similar safety concerns. However, while LNG has a boiling point of -259.6 degrees Fahrenheit (°F [-162 degrees Celsius [°C]), liquid hydrogen's boiling point is at -423.4°F (-253°C). Liquid hydrogen is a colder cryogenic liquid, and this property introduces additional safety concerns. However, these concerns can be mitigated by modifying bunkering operations or equipment.

To accommodate liquid hydrogen, the purging process needs to be modified. In LNG bunkering, the bunkering hose is purged using nitrogen. However, liquid hydrogen's boiling point is lower than nitrogen's boiling point and freezing point. If the bunkering hose is purged with nitrogen and then liquid hydrogen is transferred through it, the liquid hydrogen could cause the nitrogen to liquefy or even freeze. This would contaminate the liquid hydrogen, which could eventually cause damage to the fuel cell. To mitigate this risk, the bunkering hose needs to be purged with a different gas. Helium would be a good candidate for this because its boiling point is even lower than that of hydrogen.

Another safety issue concerns the bunkering hose. Since liquid hydrogen is a colder cryogenic liquid, it is important to ensure that the bunkering hose is insulated. If the hose is not insulated, heat ingress will cause the liquid hydrogen to boil off at a greater rate. The hose can be insulated by using a double-walled hose. However, even with this insulation, there are weak points on the hose at the couplings and the emergency release couplings where thermal infiltration can occur. Current couplings and emergency release couplings are designed for use with LNG. However, if these same couplings are used with liquid hydrogen, there will not be sufficient insulation. This is problematic because liquid hydrogen is so cold that it can dramatically decrease the temperature of the air near the coupling. This can cause oxygen in the atmosphere to liquefy and form droplets of liquid oxygen (O_2). This creates a serious fire hazard. Furthermore, the cold temperatures can cause moisture in the atmosphere to condense or even freeze. This creates the potential for nozzle freeze, which can impede the disconnection process. This is especially problematic if it occurs on the emergency release coupling. To mitigate this problem, insulated couplings need to be deployed. There are coupling manufacturers that have developed vacuum-insulated liquid hydrogen couplings to address this issue. These couplings need to be deployed on liquid hydrogen bunkering systems.

Although liquid hydrogen bunkering is an early-stage technology, there are some solutions that are already being developed by manufacturers such as Norled, Unitrove, and Zero Emission Industries.

These bunkering systems are discussed in more depth in Appendix B.

Facilitating Technologies for Liquid Hydrogen Bunkering

Liquid hydrogen bunkering introduces several novel safety considerations that need to be addressed. The main issue is the need for insulation, which can be solved by applying new technologies to the bunkering system.

Connectors

Connectors are a vital technology for liquid hydrogen bunkering systems. Connectors that facilitate LNG bunkering have already been developed. However, since liquid hydrogen has different properties than LNG, these existing connectors are not sufficient. The exposure of uninsulated components in the liquid hydrogen bunkering system to air can create a fire hazard by liquefying oxygen. Insulating the connector prevents the oxygen liquefaction problem. Connectors also promote safety by preventing the release of hydrogen into the air. Since hydrogen is flammable, releases into the environment can create fire risks. Connectors are important for preventing such releases during the connection/disconnection process and during bunkering operations. Emergency release couplings are also a vital part of the bunkering transfer line. This system is important because it prevents vessels from causing damage by drifting away from the dock during bunkering.

Dry break couplings ensure safe and easy routine connections between the bunkering system and the vessel. Emergency release couplings ensure that the bunkering system is released from the vessel in case of an unintended vessel drift or other emergency events. The bunkering system for the HyZET vessel requires connectors that can provide all of these functionalities.

Industry has taken steps to develop liquid hydrogen bunkering components and systems. For example, ARTA designs and distributes connectors that are compatible with bunkering for cryogenic fluids, such as LNG. ARTA also developed a line of couplings that facilitate bunkering for liquid hydrogen. ARTA's connector is vacuum insulated to prevent oxygen liquefaction and nozzle freeze. The couplings connect to the vessel by turning in a clockwise motion and are designed to be light enough so they can be operated manually by a person. The connector is also designed to prevent spills and releases of hydrogen to the environment.

The ARTA bunkering system consists of couplings, hoses, control and power units, and accessories such as hose saddles. The control systems are used to manage the bunkering process. One of the key functionalities of the control system is to engage the emergency release couplings. ARTA's control system can detect if the vessel is starting to drift away from the dock during bunkering. If the vessel drifts too far away, the system activates the emergency release couplings. This process allows the vessel to disconnect from the bunkering system to prevent damage. ARTA's system uses several systems to detect separation from the dock. Its core system is based on a steel traction cable that mechanically activates the emergency release coupling. The extended system uses a sensor-based control unit to detect the vessel drift. The emergency release couplings are then activated by pneumatics or hydraulics.

Loading Arms

A loading arm is an assembly of articulated pipes that is used to transfer liquid and gaseous products from or into ships. Loading arms are typically used to transfer large quantities for cargo purposes but can also be used to facilitate bunkering of bulk LNG shipments with a smaller diameter transfer pipe. Among the advantages of a loading arm over a typical flexible hose solution is that the former provides a higher transfer flow rate, easier and safer maneuverability of the system, and a longer lifespan. Loading arms typically do not contain their own pump to transfer fuel. Instead, they are added to a bunkering system and facilitate fuel transfer by serving as a conduit through which the fuel can be pumped. As a result, if a loading arm is employed, it would serve as the point of connection with the vessel and would be located between the vessel and the bunkering system.

Typically, a loading arm product line is not insulated, even for cryogenic applications such as LNG transfer. When it is mandatory to reduce heat ingress, thermal or vacuum insulation can be added on the piping. However, for liquid hydrogen transfer application at -423.4°F (-253°C), the full product line would be vacuum insulated, including dynamic components such as swivel joints, the emergency release system, and the ship connector. Not Insulating parts of the transfer line can result in fire hazards, with the liquification of the ambient air enriched with oxygen on the outer face in addition to high heat ingress to the system that causes high gas boiloff. Technip Energies is currently developing a loading arm that would transfer liquid hydrogen to vessels.

Bunkering System Technology and Regulatory Barriers

The project team used the HAZID workshop to identify potential technology and regulatory barriers for the liquid hydrogen bunkering system. During the HAZID workshop, the project team identified the following potential barriers.

- **Loss of Insulation:** Loss of insulation (most likely the loss of a vacuum in the annular space) in the transfer piping leads to ice formation and pipe blocking. At very cold temperatures, liquid O_2 could also be formed, which would increase the flammability of materials exposed to it.
- **Trapped Liquid Hydrogen Between Valves:** Once bunkering is finished (or when interrupted, in an emergency), trapped liquid hydrogen between valves could expand, risking an eventual leak into the atmosphere. This could happen both on the supply/ port side and onboard, but it could be mitigated through system design and operational measures, including flushing of lines. Pressure relief valves should also be installed in critical areas and vented to a safe location (vent post onshore and vent mast onboard).
- **Undetected Leak:** Leakages in flanges and valves in the bunkering system can lead to a release of hydrogen, which creates a flammable atmosphere risk. The technology design should include the installation of sensors in critical locations and could also include a means of monitoring both the inner and the outer annulus (temperature, pressure, etc.) to alert for potential leakages. A precheck of all connections in the system should be done prior to each bunkering.
- **Fuel Contamination:** Improper purging leads to contamination of fuel with humidity, oxygen, nitrogen, and other gasses. This could lead to the formation of ice inside pipes and a risk of limiting the operation of safety valves and even preventing the manifold from disengaging. Ultimately, contaminated fuel could damage fuel cells.
- **Seal Failure:** If a seal is not achieved at the interface between the ship and the bunkering system, hydrogen would leak into the environment. Potential causes of seal loss are damage during connection, poor maintenance, misalignment due to tug movements, and weather exposure (water, salt, and temperature variation). An

improper seal is also a concern for the connection between components of the bunkering system.

- **Sudden Bunkering Stop:** A sudden stop in bunkering would most likely happen in an emergency, when the emergency shutdown (ESD) system is engaged. At a minimum, it's expected that valves in the bunkering line would close immediately, but it should be determined whether the bunkering pump(s), if applicable, can be immediately stopped without damaging the system. It should also be confirmed that the lines can be safely vented.

POLA Liquid Hydrogen Bunkering Regulatory Environment

The USCG is the authority that regulates bunkering systems at ports. Most maritime fuels have regulations to ensure that they are handled, bunkered, and used in a safe manner. Many of these regulations are codified in the CFR and enforced by the USCG, which has a section at ports to enforce these regulations locally. The USCG has a section with jurisdiction over POLA and POLB. The USCG regulates both the vessel itself and the bunkering system. Since liquid hydrogen is a relatively new marine fuel, the regulatory environment is still in the early stages of development, and there are currently no regulations in the CFR that specifically regulate liquid hydrogen bunkering. However, the CFR does have regulations for similar fuels, such as LNG, and the USCG has issued several policy letters clarifying how LNG will be regulated as a maritime fuel. A major part of the regulatory environment for LNG bunkering is under 33 CFR Part 127. It regulates waterfront facilities handling LNG and liquefied hazardous gas. An owner or operator that intends to build a new facility handling LNG or liquified hazardous gases that is planning new construction to expand marine terminal operations, or that is planning construction that will result in an increase in the size or frequency of marine traffic to a facility must submit a letter of intent to the captain of the port. The letter of intent must be submitted at least one year prior to the start of construction.

The facility can be approved under 33 CFR Part 127 as a Waterfront Facility Handling LNG (Waterfront Facility) or an LNG Fuel Facility. The facilities are distinguished by the ability to transfer fuel in bulk. A Waterfront Facility has a bulk storage tank, whereas an LNG Fuel Facility does not. This distinction is important because it determines how the facility is approved by the USCG. If a facility owner or operator is planning to deploy a Waterfront Facility, it needs to submit a Waterway Suitability Assessment, whereas an LNG Fueling Facility requires either the Waterway Suitability Assessment or an Operational Risk Assessment. The Operational Risk Assessment is generally considered to be a lower regulatory barrier. In general, a permanent shoreside facility with a bulk storage tank would almost certainly be regulated as a Waterfront Facility. There may be an exception if the bulk storage tank is located inland. However, a facility that bunkers vessels using a tanker truck will likely be regulated as an LNG Fuel Facility.

Maritime security for facilities is regulated under 33 CFR Part 105, which applies to, among other things, any facility subject to 33 CFR Part 127. This regulation outlines security requirements for applicable facilities. The facility owner or operator is required to conduct a Facility Security Assessment for the site, submit a Facility Security Plan, and ensure that the facility operates in compliance with the Facility Security Plan. The facility owner or operator must also designate a Facility Security Officer, who ensures that the Facility Security Assessment is carried out and the Facility Security Plan is implemented. The requirements for facility security personnel, security training, drill and exercises, and recordkeeping are outlined in 33 CFR Part 105.

Since liquid hydrogen is a new maritime fuel, there are no laws or regulations that apply directly to liquid hydrogen bunkering. However, USCG Sector Los Angeles-Long Beach confirmed that, due to its similarities to LNG, liquid hydrogen will be subject to the same regulatory requirements as LNG. This means that the liquid hydrogen bunkering location will be regulated under 33 CFR Part 127. Initially, bunkering is expected to be carried out via liquid hydrogen tanker truck. USCG Sector Los Angeles-Long Beach stated that bunkering from a tanker truck would likely be treated as an LNG Fuel Facility. As a result, tanker truck bunkering would most likely require an Operational Risk Assessment. After the assessment is submitted, the USCG provides feedback on the assessment and raises any concerns that it may have. If a bunkering facility with a bulk storage tank were to be pursued in the future (either shoreside or on a bunkering barge), that would likely be treated as a Waterfront Facility, which would require a Waterway Suitability Assessment. The bunkering site would also need to meet the requirements of 33 CFR Part 105. The owner or operator of the facility would need to have a secured and restricted area to carry out bunkering. The USCG indicated that sites with public access will have a difficult time meeting the requirements of 33 CFR Part 105.

Furthermore, the USCG stated that bunkering equipment must be deployed on a concrete or steel dock.

CHAPTER 4: Conclusion

This study found that a tugboat powered entirely with liquid hydrogen, using fuel cells and a BESS, can be designed around a 90 ton bollard pull rating and meet the duty cycle requirements for assist tug operations in POLA. The fuel cell and the BESS are commercially available technologies that have obtained type approval for maritime applications, so they can be easily integrated into a vessel.

While the design is feasible, there are some challenges that need to be overcome to deploy the vessel. The cost of the first HyZET vessel is projected to be approximately $41.8 million, which is significantly higher than the $17-million cost of an equivalent conventionally-powered tugboat. Much of this premium comes from the zero-emission components on the vessel and from one-time engineering and Class certification costs. The cost for subsequent vessels would likely decrease, as the zero-emission components benefit from economies of scale. The second challenge relates to the technology and regulatory risks identified during the HAZID meeting. However, these risks can be overcome using existing technologies and changes to the final design of the vessel.

The HyZET vessel requires a bunkering solution. This study found that there are feasible pathways for supplying liquid hydrogen to the vessel and deploying a liquid hydrogen bunkering system. Liquid hydrogen can be provided by tanker trucks. This is the most appropriate solution because one vessel will not use enough liquid hydrogen to justify building a permanent bulk storage tank at the bunkering facility. The liquid hydrogen capacity of the tanker trucks also matches the amount of hydrogen that the vessel requires. New technologies such as insulated connectors have emerged to address novel safety challenges pertaining to liquid hydrogen bunkering.

There are viable pathways to obtain regulatory approval for the vessel design and the bunkering system from the USCG. The operator of the vessel needs to prove that the bunkering system is at least as safe as that of an LNG equivalent, because the system will be regulated under the same regulatory environment as LNG bunkering.

This project marks a major advancement towards zero-emission harbor craft. At the time of writing, there are very few zero-emission tugboats in existence. The eWolf, which is a battery electric tugboat rated for 70 tons of bollard pull, has been deployed at the Port of San Diego (Crowley, 2024). However, there are no hydrogen fuel cell tugboats in existence. Furthermore, since the HyZET vessel is rated for 90 tons of bollard pull, it would expand the types of duty cycles that zero-emission technology can serve. Despite there being relatively few tugboats, they produce a disproportionate amount of criteria pollutants and are responsible for nearly 20 percent of PM emissions from the harbor craft sector (CARB, 2021). As a result, deploying zero-emission harbor craft can significantly reduce pollution around ports.

Lessons learned from the HyZET Project can also be informative for other vessels with rigorous duty cycles where liquid hydrogen and fuel cells may be an appropriate zero-emission technology. At the time of writing, there are only a few vessels using liquid hydrogen that were deployed or are under development, including the MF Hydra in Norway (Blenkey, 2023) and the hydrogen-hybrid California Coastal Research Vessel to be built for UC San Diego's Scripps Institution of Oceanography (Wood, 2022).

The HyZET Project also contributes to the maritime sector by developing a design with liquid hydrogen tanks located below deck. This design is necessary for smaller vessels like tugboats, which do not have sufficient space to deploy liquid hydrogen on deck. As of 2022, there are 32 assist tugboats operating in POLA and POLB that could potentially transition to fuel cell technology, leveraging the design developed under this project. Together, these vessels produce 3.4 tons of PM10, 3.3 tons of PM2.5, 165 tons of NOx, and 35.3 tons of CO emissions per year. Transitioning these 32 tugs to zero-emission technology would eliminate these emissions and improve air quality of portside communities and the broader South Coast Air Basin. Lessons learned from this project could also be applicable to other ports and similar vessel types, such as towboats and articulated towing barges.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
BESS	battery energy storage system — a device that stores energy and produces electric current by chemical action.
CAPEX	capital expenditures — funds used by a company to acquire, upgrade, and maintain physical assets
CARB	California Air Resources Board
CEC	California Energy Commission — California's primary energy policy and planning agency.
CFD	computational fluid dynamics
CFR	Code of Federal Regulations — the codification of the general and permanent regulations enforced by the executive departments and agencies of the US federal government
CGH_2	compressed hydrogen gas
CHC	commercial harbor craft — commercial vessels that are used in harbors or inland waterways. Commercial harbor craft include tugboats, towboats, crew and supply boats, fishing vessels, ferries, excursion vessels, and workboats.
CNG	compressed natural gas
CHIRP	Cryogenic Hydrogen Infrastructure Replacement Product
CO	carbon monoxide
CO_2	carbon dioxide
DC	direct current
ESD	emergency shutdown
FAME	fatty acid methyl ester — a biodiesel that can be produced with vegetable or animal fats through a process called transesterification
FC	fuel cell
GHG	greenhouse gas — any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane, nitrous oxide (N_2O), halogenated fluorocarbons, ozone, perfluorinated carbons, and hydrofluorocarbons.
HAZID	hazards identification — risk assessment technique used to identify potential hazards to the vessel, the crew, or other property
HI-FIVED	Hydrogen Innovation – Future Infrastructure & Vessel Evaluation and Demonstration
HVO	hydrotreated vegetable oil — a biodiesel that can be produced with vegetable oil through a process called hydrocracking
HyZET	Hydrogen Zero-Emission Tugboat Project
IMO	International Maritime Organization

Term	Definition
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
kg	kilograms
kW	kilowatt
LH_2	liquid hydrogen gas
LNG	liquefied natural gas — natural gas or methane that has been converted to liquid form by cooling to at least -259.6°F (-162°C). This process greatly increases the volumetric density of natural gas, as it takes up only 1/600th the volume of natural gas in gaseous form.
Li-ion	lithium-ion battery — a type of rechargeable battery. In the batteries, lithium ions move from the negative electrode to the positive electrode during discharge and back when charging.
LPG	liquified petroleum gas
M	million
MGO	marine gas oil
MWh	megawatt-hour
N_2O	nitrous oxide
NOx	nitrogen oxides (oxides of nitrogen, NOx) — a general term pertaining to compounds of nitric oxide (NO), nitrogen dioxide (NO_2), and other oxides of nitrogen. Nitrogen oxides are typically created during combustion processes and are major contributors to smog formation and acid deposition. NO_2 is a criteria air pollutant and may result in numerous adverse health effects.
OPEX	operational expenditure
PM	particulate matter — unburned fuel particles that form smoke or soot and stick to lung tissue when inhaled. These are a chief component of exhaust emissions from heavy-duty diesel engines.
POLA	Port of Los Angeles — a seaport managed by the Los Angeles Harbor Department. It is located in San Pedro Bay, approximately 20 miles south of downtown Los Angeles. POLA handles approximately 20 percent of all cargo entering the United States.
POLB	Port of Long Beach — a container port that is adjacent to POLA. It is located in San Pedro Bay, near Long Beach.
SOLAS	safety of life at sea
SOx	sulfur oxides — pungent, colorless gases (sulfates are solids), formed primarily by the combustion of sulfur-containing fossil fuels, especially coal and oil. Considered major air pollutants, sulfur oxides may impact human health and damage vegetation.
USCG	United States Coast Guard
ZEMFS	Zero-Emission Multi-Fuel Station

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Project Deliverables

The deliverables for this project include:

- Baseline Harbor Craft Report
- Hydrogen Fuel Cell System Technology and Integration Report
- Fuel Cell-Powered Harbor Craft Design and Safety Report
- Type Approval for Hydrogen Fuel Cells in the Marine Sector Report
- Critical Project Review Report #1
- Economic Feasibility Analysis Report
- Cost-Benefit Analysis Report
- Technology and Regulatory Barriers Report
- Technology Assessment Report
- Hydrogen Feasibility Roadmap
- Critical Project Review Report #2
- Kick-off Meeting Benefits Questionnaire
- Mid-term Benefits Questionnaire
- Final Meeting Benefits Questionnaire
- Initial Fact Sheet
- Final Project Fact Sheet
- Final Presentation Materials
- Technology/Knowledge Transfer Plan
- Technology/Knowledge Transfer Report

Project deliverables are available upon request by submitting an email to pubs@energy.ca.gov.

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Vessel Technology and Regulatory Barriers

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APPENDIX A: Vessel Technology and Regulatory Barriers

The HAZID workshop identified several technology and regulatory barriers for the HyZET vessel, as well as potential methods for mitigating these risks. The highest-rated risks are discussed in more detail in this section. It is important to note that there are risks beyond those discussed in this section. These risks can be found in the Technology and Regulatory Barriers Report (Task 7).

Fire in Fuel Cell Module (Electrical Equipment) — High Risk

If a fire has started by a failure (e.g., short circuit) in any of the electrical equipment inside the enclosure, it should not go undetected to a point where it would cause leakage — and ignition — of hydrogen. Since this is a sealed enclosure, access for firefighting might be challenging.

The enclosures are fitted with smoke detectors and firewire, which would trigger an alarm in the control room. This most likely would cut the hydrogen supply to the fuel cell, but this needs to be checked. As follow-up actions, the project team should investigate which fire-fighting measures would be in place for the enclosure to avoid the progression of fire to other modules. The type of fire or gas detection inside the cabins must also be clarified.

This risk is considered high because the situation could cause total loss if it leads to the ignition of hydrogen. The frequency might be reduced once more details are available about the approval and testing of equipment inside the fuel cell enclosure but, until then, this is the highest-rated risk identified in the workshop.

Contamination of Hydrogen — Medium Risk

Contamination of hydrogen with water and other gases could happen due to high humidity inside the piping and/or insufficient purging. Liquified hydrogen is stored at temperatures lower than the freezing point of many gases (-436ºF [-260ºC]), including oxygen (-360.4ºF [-218ºC]), nitrogen (-346ºF [-210ºC]), and CO_2 (-108.4ºF [-78ºC]). The presence of these gases and humidity could lead to the formation of crystals, which could prevent valves and sensors from operating properly. In severe cases, it could lead to blockage of fuel and relief piping.

To mitigate this risk, a procedure must be in place to ensure that purging is done correctly. The project team should also investigate whether the presence of moisture could damage the fuel cells.

Minor Leakage in Fuel Piping — Medium Risk

The space between the inner and the outer annulus in the double-walled piping is kept in a vacuum to avoid thermal losses and heating of the fuel. A small leak might be harder to detect than a major leak, as the pressure inside the outer annulus would increase slowly. Some icing could form in the area of the leakage due to the rapid expansion of hydrogen during evaporation. Eventually, this could lead to a pressure increase in the annulus, which should be vented to a safe area to avoid further leakages. Given hydrogen's wide explosivity range, even a small leak could ignite and cause an explosion. If not detected in time, hydrogen could be sucked into nearby areas (including the steering gear room). Operators in the region could also be exposed to health risks, including suffocation and cold burns. Some possible causes for small leakages are:

- Mechanical impact from other equipment/material.
- Fatigue of material and equipment.
- Poor maintenance, including seals and valves.
- Human error during bunkering.
- Sudden vessel movements during bunkering.
- Thermal behavior of materials due to low temperatures.
- Fabrication (poor welding quality).

The main safeguards considered in the design are using "Ex-rated" equipment in the bunkering area and ensuring a safe radius during bunkering, preventing ingress of crew and operators. (Ex-rated equipment means that the electrical energy within the equipment is restricted to a level that is below what may cause an ignition.) Other possible actions discussed in the workshop were:

- Investigate what sensors should be installed on deck.
- Consider thermal cameras to detect cryogenic leaks.
- Define zone rating during bunkering.
- Use breakaway coupling to disconnect the bunkering line quickly in case of emergency.
- Use ESD to shut down fuel transfer manually or automatically in case of leakage.
- Analyze CFD (computational fluid dynamics) to understand the consequences of leakages from inner to outer annulus.
- Conduct a CFD study to understand H_2 dispersion and identify a need for rearrangement of openings (ventilation, air pipes, etc.).
- Monitor pressure for loss of vacuum in the outer annulus.
- Investigate the safety philosophy and strategy for containment of leakages.
- Investigate what types of firefighting equipment are required.

Fuel Supply Piping Rupture — Medium Risk

A pipe rupture in the fuel cell room could happen from an impact from external elements. It could also happen from vibration/acceleration combined with poor maintenance or improper installation. Most of the piping inside the fuel cell room is located under a false floor that protects against impacts, but it could also make leakages difficult to detect if ventilation is insufficient under the flooring and/or there are not enough sensors in that area. If not detected in time, hydrogen leakages could pool and eventually ignite.

All fuel piping under the false floor is double-walled, though it should be clarified whether the outer annulus is filled with an inert gas or continuously vented. The fuel cell room is also under continuous forced ventilation to ensure that there are enough air changes, but airflow under the false floor should be checked to determine if additional fans and/or gas detectors are required. Another identified action is to assess the consequences of external damage (navigation impacts).

Water Pooling at Relief Valves — Medium Risk

The fuel storage tanks are fitted with two or more pressure relief valves to vent hydrogen in case the pressure inside the tank exceeds safe levels. Depending on the location and arrangement of these valves, water (from rain, waves, and condensation) could pool on the valve's outlet and prevent its operation in an emergency. It could also lead to corrosion and seal loss, impacting its operation.

The tug's maintenance plan should include a procedure to check the vents regularly, but the design and arrangement of the vent and the stack topper should minimize exposure to weather. Low-point drains should also be provided.

Fire in DC Cabling — Medium Risk

This was raised due to the concern that a fire caused by a short circuit in DC cabling would not be controlled in time, impacting fuel piping and risking leakage of hydrogen. The room is fitted with smoke sensors (as well as fire/heat sensors), which would trigger a shutdown, and it is also protected against short-circuit, but the firefighting strategy needs to be clarified because the type and medium used are not yet known.

Hydrogen Leakage in the Cold Box — Medium Risk

The details and arrangement of the cold box are not fully known yet but, due to the number of fittings, valves, and components, there's a concern that hydrogen could leak due to fatigue, vibration, or improper installation, forming a hydrogen-rich atmosphere and risking ignition.

All piping inside the cold box is expected to be double-walled, but the details of the arrangement and connections with valves and heat exchangers are not clear yet. If fully enclosed, the cold box should have a vent directing any leakages to a safe area. It's also expected that any instruments in the area are approved for use in a potentially hazardous atmosphere.

Three actions were identified in the workshop:

- Verifying the consequences of venting at port if it could risk other vessels.
- Vibration analysis of annular lines.
- Explosion analysis to understand the consequences of ignition inside an enclosed cold box.

Loss of Thermal Insulation (Vacuum) in All Liquid Hydrogen Pipes — Medium Risk

All liquid hydrogen piping and storage tanks are vacuum insulated to limit heat exchange with outside air. If the vacuum is lost, ice would form around piping, valves, and fittings, potentially damaging sensors, materials, and structures not designed to be in contact with such low temperatures. It could also lead to the heating of the fuel and a pressure increase due to the formation of gas.

Loss of vacuum could happen due to damage to outer piping, fatigue, faulty flange, poor maintenance, and human error during installation.

Major Piping Leakage — Large Volumes — Medium Risk

Major leakage is very similar to the "minor leakage in fuel piping" risk previously described, except that the volume leaking from the inner annulus would be much greater and the rapid expansion of the fuel evaporating would cause a sudden pressure increase on the walls of the outer annulus, risking rupture if the pressure relief valves were not activated in time. Spillage/cryogenic leakage of fuel on deck could also happen for a short period. All other consequences from the "minor leakage in fuel piping" risk would apply here, as would the identified safeguards and proposed actions. One additional action identified was the possibility of using drip trays to protect the tug's structure.

Internal leakage Into Annular Space — Medium Risk

A leakage in any piping between fuel tanks and cold boxes would cause a loss of vacuum in the outer annulus. The first consequence of vacuum loss would be the freezing of piping, valves, and equipment, preventing proper operation and causing potential damage. If this causes the temperature inside the liquid hydrogen piping to rise above boiling point, there would be a sudden pressure increase. If the relief valves were not activated in time, the outer annulus could rupture, causing leakage of hydrogen to the cold box and fuel tank room.

A leakage in the inner annulus could be caused by many different factors, such as:

- Manufacture quality and installation issues.
- Material fatigue due to thermal cycling.
- Vibration.

While details of the cold boxes are not clear, these are expected to be fitted with pressure and temperature sensors that would alert the crew of any potential failure and allow for system shutdown. Loss of vacuum inside tanks was not considered, as this is part of the approval and testing done by a recognized classification society.

A decision has to be made on a strategy for handling any leakages detected in the cold box, to shut down or continue operation to avoid a blackout, and to understand how to safely vent. It's important to note that hydrogen is considered an indirect greenhouse gas and any leakages are considered air pollution.

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix B: Liquid Hydrogen Bunkering Systems

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APPENDIX B: Liquid Hydrogen Bunkering Systems

There are several liquid hydrogen bunkering systems that can be used to fuel the HyZET vessel and other liquid hydrogen-powered vessels. Descriptions of these systems follow.

Norled

Norled is a marine company that provides ferry service in Norway. Norled operates multiple passenger and car ferries and provides service to destinations such as Rogaland, Vestland, Sunnmore, and Trondheim Fjord. The company developed the MF Hydra, which is the first liquid hydrogen ferry. The MF Hydra entered service in April 2023. The vessel has a 4,000-kg cylindrical liquid hydrogen tank that is 10 meters in length and 3.5 meters in diameter. The vessel uses approximately 170 kg of hydrogen per day and is fueled about every 3 weeks. The bunkering system is capable of transferring up to 3,000 kg per hour.

Norled developed a bunkering system to fuel the MF Hydra. The MF Hydra is fueled through a truck-to-ship system. Since there is a major height difference between the quay and the bunkering station on the MF Hydra, bunkering is facilitated by a tower that is about 10 meters tall. The tower has an electric motor that allows it to be driven to the fueling position under its own power. Once it is in place, a liquid hydrogen tanker can attach to it with a vacuum jacketed hose. The tower also has a loading arm on the top. The loading arm has a counter-weight so it can be manually attached to the ship's bunkering station. The tower also has a vent mast that is used during the purging process. The bunkering process is controlled from a panel on the tower.

After the system is set up, the bunkering process begins with a pressure check to ensure that there are no leaks, whereas low-pressure, warm hydrogen is kept in the pipes between two bunkering operations. After that, cold gas and afterwards liquid hydrogen are introduced into the line to create cryogenic conditions in the tower pipe system. Liquid hydrogen is then transferred from the tanker to the ship via the tower. The transfer process is facilitated through differential pressure between the tanker and the onboard liquid hydrogen tank, which is kept at a pressure of 4-5 bar. Pressure in the liquid hydrogen tanker is increased to 8–9 bar. This pressure differential pushes liquid hydrogen from the tanker to the ship. Once the bunkering process is completed, there is remaining hydrogen left in the pipe. Most of this is transferred to the vessel, but a very small volume is left in the tower pipe system. This is done so that part of the system does not have to be purged at every bunkering. As a result, only the hose from the tanker truck to the tower has to be purged. This reduces the amount of helium required for purging.

To address the safety issues associated with hydrogen, Norled had to adapt some of the components to handle liquid hydrogen. One adaptation was on the connectors. To prevent ambient air/oxygen from liquefying, Norled used insulated connectors. These connectors are vacuum insulated, which is a novel technology. Norled is also modifying the purge process.

liquified nitrogen gas (LNG) bunkering can use nitrogen as the purge gas. However, to prevent liquefaction or freezing of the nitrogen, Norled uses helium as the purge gas.

Norled expects that cryotransfer will be the normal method for bunkering liquid hydrogen. It anticipates that the maximum cryotransfer rate will increase to 4,000 to 5,000 kg per hour.

Unitrove

Unitrove is a technology and renewable energy company based in the United Kingdom. It delivers zero-emission fueling infrastructure for heavy-duty transport and industry, with a keen focus on developing the supply chain for liquid hydrogen within the maritime sector.

Unitrove initially unveiled the world's first liquid hydrogen bunkering facility at the United Nations Climate Change 26 conference in Glasgow in November 2021 (see Figure B-1). The system consists of a skid that contains a cryopump for transferring liquid hydrogen. It is a fully safety-instrumented system that includes flame and gas detection, monitored breakaway couplings, and a pre-break-away alarm system. It is also equipped with Coriolis mass flow metering to ensure accurate measurement of two-phase flow hydrogen. The system comes with ground-mounted vent stack to safely accommodate any potential hydrogen discharges (for instance, in the case of overpressure). Finally, the system has a portable control panel with multi-way plug sockets for rapid installation.

The skid measures approximately 5 meters by 2.5 meters by 1.5 meters and weighs about 1.5 metric tons. It can be moved with a forklift, or it could potentially be put on a trailer and towed by a car. The portable control panel has a physical footprint of approximately 1 meter by 1 meter.

The bunkering skid can accept liquid hydrogen from a tanker truck, an intermodal shipping container, a stationary storage tank, or directly from a hydrogen liquefaction plant. It then uses a hose to transfer the liquid hydrogen to the vessel. The bunkering system has a flow rate of around 500 liters per minute, although it could be sized for higher flow rates. The system can also be attached to a loading arm to facilitate bunkering.

Figure B-1: Unitrove Liquid Hydrogen Bunkering System

Source: Unitrove

The Unitrove bunkering system uses principles and operations similar to LNG bunkering. The bunkering process starts by connecting the bunkering skid to a tanker truck or stationary tank. The skid is then attached to the vessel with a vacuum-insulated cryogenic hose. The hose connects to the vessel's bunkering station with either an open-ended liquid hydrogen bayonet connector or a quick-connect/disconnect coupling.

Once the connections are complete, the system begins the purging process. The purge gas is fed into the overall fueling line and is held for five minutes for a pressure check. This pressure check is done to detect leaks in the fueling line. Once the pressure check is completed, liquid hydrogen is introduced into the hose. The liquid hydrogen cools the hose until it is as cold as the liquid hydrogen. Once the cooldown process is complete, the bunkering process begins and liquid hydrogen is transferred to the vessel. Any liquid hydrogen that boils off or flashes during the cooldown or fueling process is generally pushed to the vessel. This boil-off can, however, be recovered using a vapor return line.

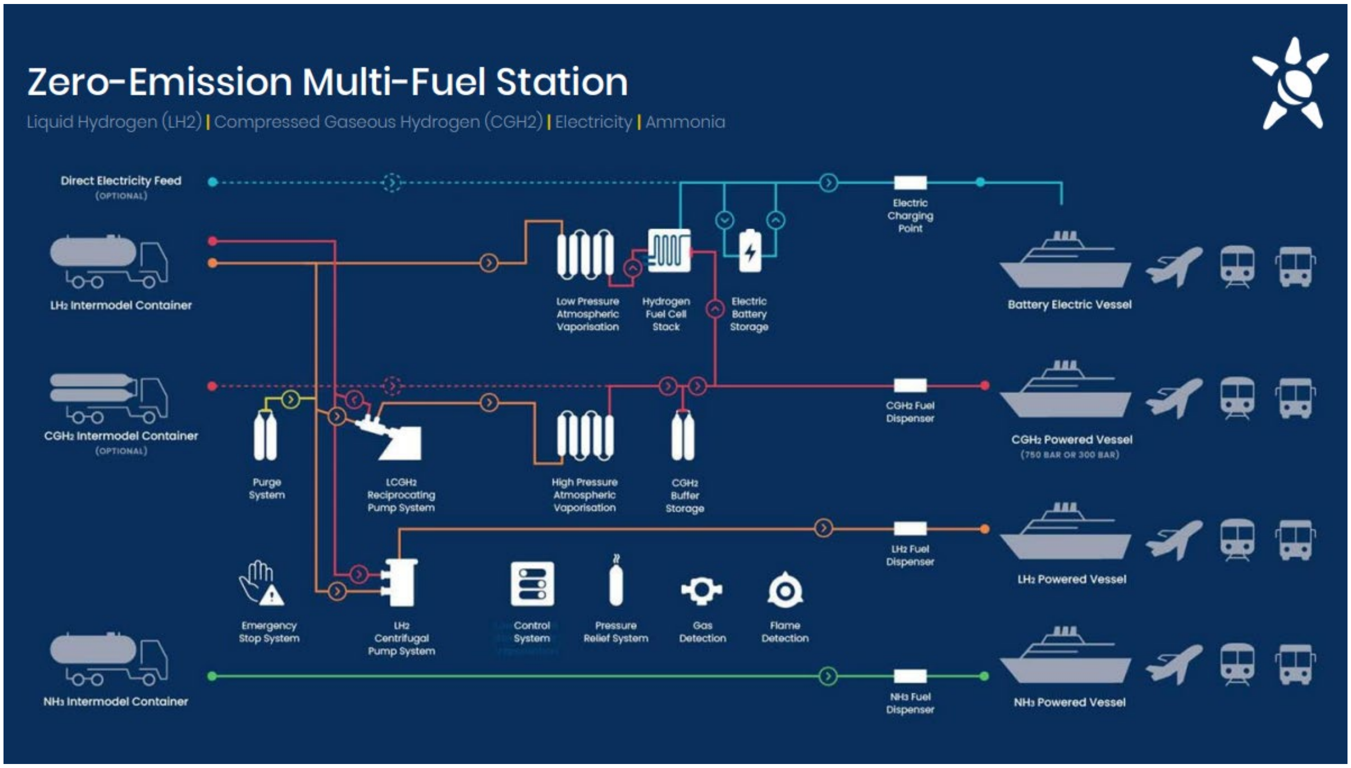
To address the safety issues associated with hydrogen, Unitrove had to adapt some of the components to handle liquid hydrogen. One adaptation was on the connectors. To prevent ambient air/oxygen from liquefying, Unitrove used insulated connectors. These connectors are vacuum insulated.

Unitrove is also modifying the purge process. LNG bunkering can use nitrogen as the purge gas. However, to prevent freezing of the nitrogen at liquid hydrogen temperatures (the freezing point of nitrogen is -346°F (-210°C), compared with liquid hydrogen at -423.4°F (-253°C), a different purging mechanism must be used.

Unitrove is considering using gaseous or liquid helium to purge the hose before bunkering. However, due to concerns about helium scarcity, the company is considering using gaseous hydrogen. Unitrove also had to make modifications to the cryopump. The cryopump it uses is like those used for pumping LNG. However, since liquid hydrogen is a lighter fluid, the pressure differential that a pump can create with liquid hydrogen is lower. As a result, the pump needs to have an increased number of stages to generate enough differential pressure to transfer the hydrogen.

Unitrove is also developing the Zero-Emission Multi-Fuel Station (ZEMFS). ZEMFS is a bunkering system that can provide liquid hydrogen, gaseous hydrogen, and electricity to ships (Figure B-2). ZEMFS combines Unitrove's liquid hydrogen system with other equipment to provide bunkering for multiple fuels. The liquid hydrogen bunkering system can be combined with a high-pressure cryogenic reciprocating pump and a high-pressure ambient-air vaporizer to convert the liquid hydrogen to gaseous hydrogen. This hydrogen can then be bunkered to a gaseous hydrogen vessel through cascade filling. This system can also be combined with a fuel cell stack to convert hydrogen to electricity. Boil-off hydrogen, which is recovered via a vapor return line, could potentially be used to produce electricity. This electricity can be used to charge battery electric vessels.

Figure B-2: Unitrove ZEMFS Schematic



Source: Unitrove

Unitrove has received funding from the UK to deploy its liquid hydrogen bunkering system. This deployment is funded as part of the Hydrogen Innovation – Future Infrastructure & Vessel Evaluation and Demonstration (HI-FIVED) consortium. Through this project, zero-emission vessel provider ACUA Ocean will receive funding to build and deploy a liquid hydrogen-powered autonomous vessel that will provide shipping service between Aberdeen and the Orkney and Shetland Islands. Unitrove will deploy its liquid hydrogen bunkering system at the Port of Aberdeen to support the vessel. This project is expected to be completed by the end of 2024 (Unitrove, 2023).

Zero Emission Industries

Zero Emission Industries is a hydrogen fuel cell technology company that develops hydrogen power and refueling systems. The company previously developed the propulsion and fueling system for vessels such as the Sea Change and is currently developing a liquid hydrogen bunkering system. Zero Emission Industries was awarded funding from the CEC, under solicitation GFO-22-502, which funds the development of hydrogen fueling solutions for medium- and heavy-duty on-road and off-road vehicles.

Zero Emission Industries is developing a containerized liquid hydrogen bunkering solution, the Cryogenic Hydrogen Infrastructure Replacement Product (CHIRP). The CHIRP system will consist of a container that holds a liquid hydrogen manifold and a control system. The container is connected to a liquid hydrogen tanker truck and then to the vessel. The manifold accepts liquid hydrogen from the truck and facilitates transfer to the vessel. Liquid hydrogen can be transferred with either a cryopump or through differential pressure. A unique feature of CHIRP is that it is a zero boil-off system. Typically, liquid hydrogen transfers generate a large amount of gaseous hydrogen as the cold liquid hydrogen encounters warm piping and tanks, and this gaseous hydrogen is almost always vented to the atmosphere. This results in increased cost as well as potential usability constraints due to flammable gas venting. CHIRP accepts and processes boil-off hydrogen gas from the piping and from the vessel. CHIRP contains a compressor that can compress the boiloff hydrogen gas and store it in hydrogen tanks within the container. The container also holds a fuel cell that uses the boil-off gas to produce electricity that can be exported and/or stored in a battery. The battery can be used to power the compressor, the control system, and the liquid hydrogen manifold. Depending on the design, it can also be used to power charging for electric trucks or port equipment.

CHIRP addresses many problems faced by liquid hydrogen bunkering systems. Ports are oftentimes space constrained and, as a result, cannot host permanent infrastructure. CHIRP addresses this because it is portable. The container can be moved to the dock when it is needed and transported to storage after bunkering is completed. CHIRP is also aiming to facilitate fast refueling times, and the design goal of the project is a solution that can transfer 3,500 kg of liquid hydrogen in 90 minutes or less.