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Decarbonizing Harbor Craft: The Hydrogen Zero Emission Tug Project

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Executive Summary

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 Commision funded the Hydrogen Zero Emission Tug (HyZET) project to develop a design for a liquid hydrogen (LH2) fuel cell tugboat and to analyze its commercial viability. This project also investigated the technical, safety, and regulatory requirements that this vessel must meet and the feasibility of LH2 bunkering. This paper outlines the results of this project and the technical specifications for the tugboat.

Keywords: marine, off-road, port, fuel cell, hydrogen, boat

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1 Introduction

The San Pedro Port Complex, which includes the Port of Los Angeles (POLA) and Port of Long Beach (POLB) is one of the busiest port complexes in the United States, handling 40% of America's containerized imports and 30% of America's exports [1]. Large numbers of onroad and offroad vehicles, including Class 8 trucks, cargo handling equipment, commercial harbor craft, and container ships, operate at this port complex. Unfortunately, these vehicles produce a large amount of emissions. The San Pedro Port Complex produces 100 tons of smog per day, as well as large amounts of particulate matter (PM), nitrogen oxides (NOx), and greenhouse gas (GHG) emissions. The San Pedro Port Complex is the single largest source of air pollution in the Southern California region, producing 100 tons of smog and NOx per day [2]. As a result, many of the areas surrounding the port complex have elevated levels of air pollution. This has public health ramifications for these communities as it has caused increased levels of asthama, respiratory illness, and cancer [3].

The State of California has responded to this problem in a variety of ways. One method has been to encourage industry to transition to zero emission transportation technology. The State of California has provided funding for demonstration projects and incentive programs to support the adoption of zero emission medium- and heavy-duty vehicles, like battery electric or fuel cell buses and trucks. These technologies have experienced rapid technological development and some fleets have begun to adopt these vehicles. However, some transportation segments have proven harder to transition to zero emission because of high energy requirements, rigorous duty cycles, unpredictable operating schedules, or design constraints on the vehicle. The harbor craft sector is an example of a transportation segment that is difficult to transition to zero emission technology.

Transitioning the harbor craft sector to zero emission is important because marine vessels contribute to climate change and poor air quality. According to the International Maritime Organization, marine vessels are responsible for nearly 3% of global GHG emissions [4]. In addition, since harbor craft typically consume diesel, they are responsible for PM and NOx emissions. The State of California aims to mitigate these emissions by developing and deploying zero emission harbor craft. Since, this sector is still in early stages of commercialization, the State of California has focused primarily on vessels like tugboats and ferries. Since these vessels have predictable duty cycles and return to base at the end of each day, they were deemed to be promising “first movers” for transitioning to zero emission. To promote commercialization of this technology, the California Energy Commission funded the Hydrogen Zero Emission Tug (HyZET) project.

2 Project Background

The HyZET project is being carried out by a consortium that is led by CALSTART. ABB Marine & Ports, Ballard Power Industries, Chart Industries Inc., Crowley Engineering Services, DNV, the Port of Los Angeles, and the Southern California Gas Company. The HyZET consortium consists of leading maritime stakeholders 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, LH2 system integration, and upstream hydrogen production. The HyZET consortium was formed in the summer of 2020 to seek funding opportunities to develop a zero emission. The California Energy Commission awarded funding for the HyZET project under solicitation GFO-20-604.

The HyZET project is intended to produce an actionable design for a hydrogen fuel cell tugboat that is designed to operate in the Port of Los Angeles; evaluate the costs of constructing, operating, and maintaining the tugboat; identify technology and regulatory barriers to hydrogen fuel cells in marine applications; and develop supporting plans for refueling infrastructure. If the design is deemed to be viable, the consortium can collaborate to seek funding to build the vessel.

3 Vessel Design

The fuel cell tugboat was designed to provide escort and docking service in the Port of Los Angeles, 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 LH2 storage system. Based on these system requirements, a general arrangement for the vessel was then developed. This general arrangement then served as the basis for estimating the cost of the vessel.

3.1 Tugboat Duty Cycle

The HyZET team analyzed data from Crowley’s HERCULES tugboat to understand its duty cycle. 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. The team examined the loading of the individual main engines. Engine loads were then broken into 5% increments of total engine power to obtain a distribution of loading over each trip.

This analysis indicates that the vast majority of the time the vessel is underway, power use is less than 50% of the maximum engine loading. Of the eight trips analyzed, four trips had engine loads of 50% or less at least 95% of the time underway, while all but one trip had 99% of the time underway with power loads of less than 75%. Of the eight trips, six fell into a pretty common load pattern. One trip had a significant amount of power loading in between 65% and 75%, while another had a larger amount of time with loading from 75% to 100%. These results indicates that a diesel powered harbor tug has a serious disadvantage because large horsepower engines are required to provide that very few minutes of high power required for a job, while a great portion of the time, the tug is operating at 50% power or less. Based on this analysis, designing the power system to be capable of providing maximum power without utilizing 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 equates to 2,800 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% 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 LH2 storage tank must be able to hold at least 3,500 kg of hydrogen.

3.2 System Sizing

To be deployed, the tugboat will need 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 kW per engine. Since there will be one engine on the port-side and one engine 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 5,100 kW load for 15 consecutive minutes
- Maximum profile: Based on a duty-cycle where the vessel consumes 11 MWh per day. 95% of daily duty cycles consume 11 MWh or less
- Average profile: Based on a duty-cycle where the vessel consumes 5.1 MWh in 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.

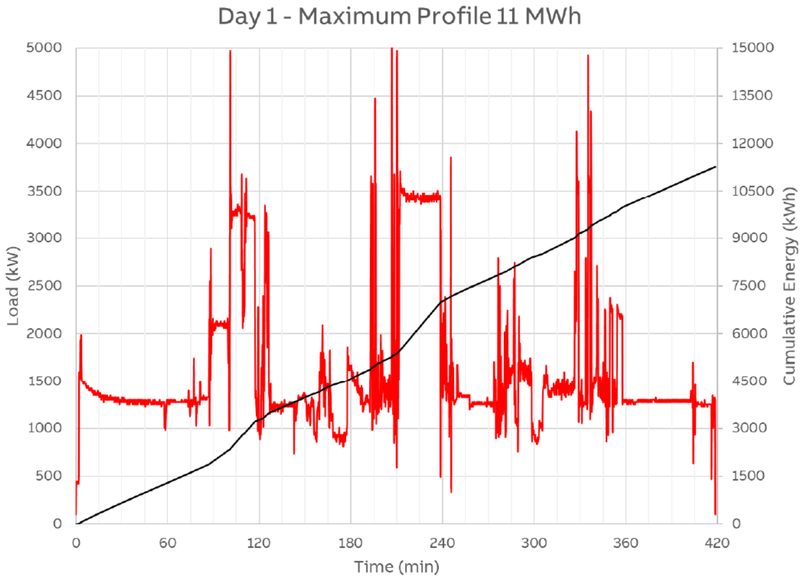

Figure 1: Maximum Profile

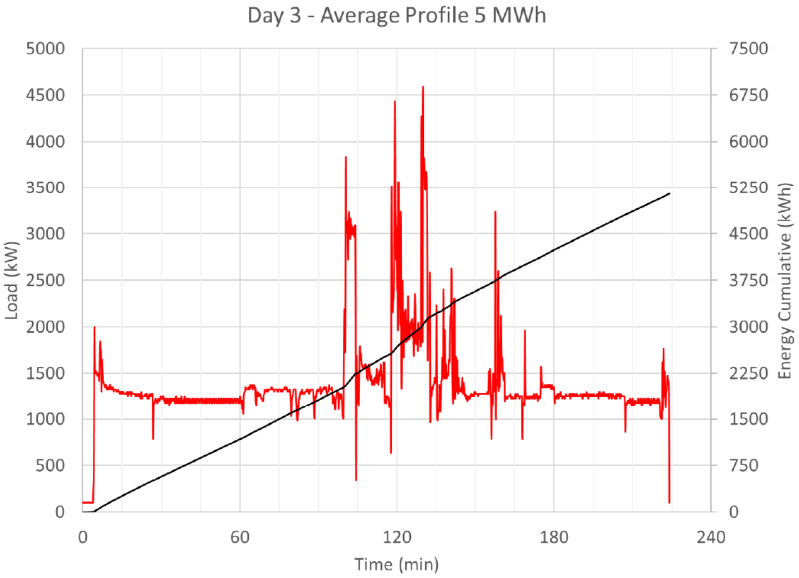

Figure 2: Average Profile

The suggested philosophy of operation for the tugboat is to employ both fuel cells and battery storage. The fuel cell is used as a baseload, supplying constant power. The battery storage system is used for peak shifting, 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 battery storage system. The battery should act as a redundant source of power and energy should the fuel cells stop working and 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. This approach was used to size the major components of the vessel.

3.2.1 Fuel Cell and Battery Storage System Sizing

The fuel cell system was sized to provide a baseload for the vessel. The required baseload is based on the average power demand under both the Average Profile and the Maximum Profile. The Ballard Power FCWave^{TM} system was selected for the vessel design. Twelve FCWave^{TM} modules are required to provide the 1,375 kW baseload required by the Average Profile. The Maximum Profile has a 1,615 kW baseload requirement which can also be served using twelve FCWave^{TM} modules.

The remaining power demand is 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. These battery chemistries have different properties and are suited for different use cases. The battery chemistries and their properties are displayed in Table 1.

Table 1: 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

The lithium nickel manganese cobalt chemistry was selected because it has a good 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 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 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 requires 1,740 kWh of batteries. These batteries can 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 Average profiles.

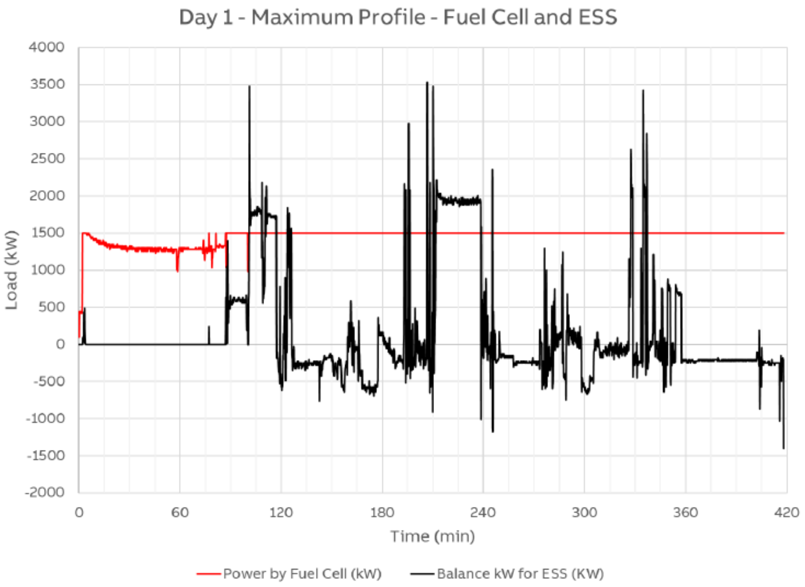

Figure 3: Fuel Cell and Battery Storage System Operation under the Maximum Profile

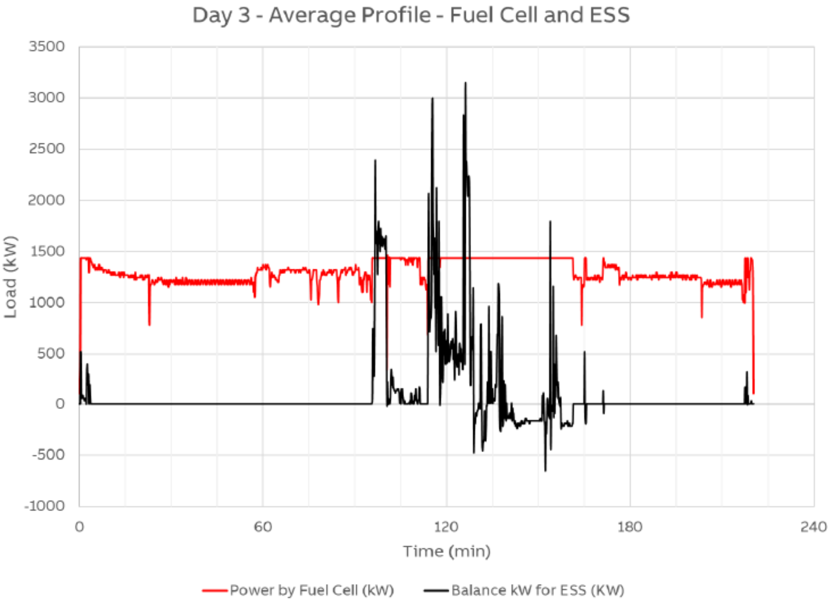

Figure 4: Fuel Cell and Battery Storage System Operation under the Average Profile

3.2.2 Liquid Hydrogen Storage Tanks

The HyZET team determined that the tugboat will require 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 LH2. Although the vessel requires 3,500 kg of hydrogen per week, the LH2 storage tanks cannot be completely emptied without being recommissioned. As a result, the LH2 storage tanks will need to have additional storage capacity beyond the 3,500 kg that will be consumed each week. To meet these needs, the tugboat design calls for two 2,000 kg LH2 tanks. The LH2 tanks manufactured by Chart Industries were selected for the vessel design.

3.3 General Arranagement

The HyZET team developed a general arrangement for the vessel. The design process starts with the Program Requirements and then proceeds to see how those can be achieved. For the general lay-out, the HyZET aimed to emulate the current vessels that work in the LA harbor as well as the designs currently under development for updating Crowley's harbor tug fleet. All the new designs currently under consideration employ some amount of battery storage to supplement the main propulsion, with the current trend to using several generators in a diesel electric configuration. As a result, integrating the battery storage system into the design is relatively routine.

A key design challenge is integrating the LH2 storage tanks. The LH2 tanks are required to be certain distance from the shell of the vessels, as well as locating the vents of the system 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 is slightly larger than the HERCULES. However, this length still matches well with the current Crowley fleet in the harbor, which run from a length of 82-feet to 105-feet. The current length of the design should 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 is the number of ancillary equipment and control cabinets that are required to house the DC Grid and supporting controls and transformers. A side effect of fitting the twin LH2 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. Not only did this provide additional space to allow generous space around equipment, but allowed 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 appears 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 within the harbor. The power plant provides sufficient energy to obtain the desired bollard pull of 90 short 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 Port of LA 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 LH2 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.

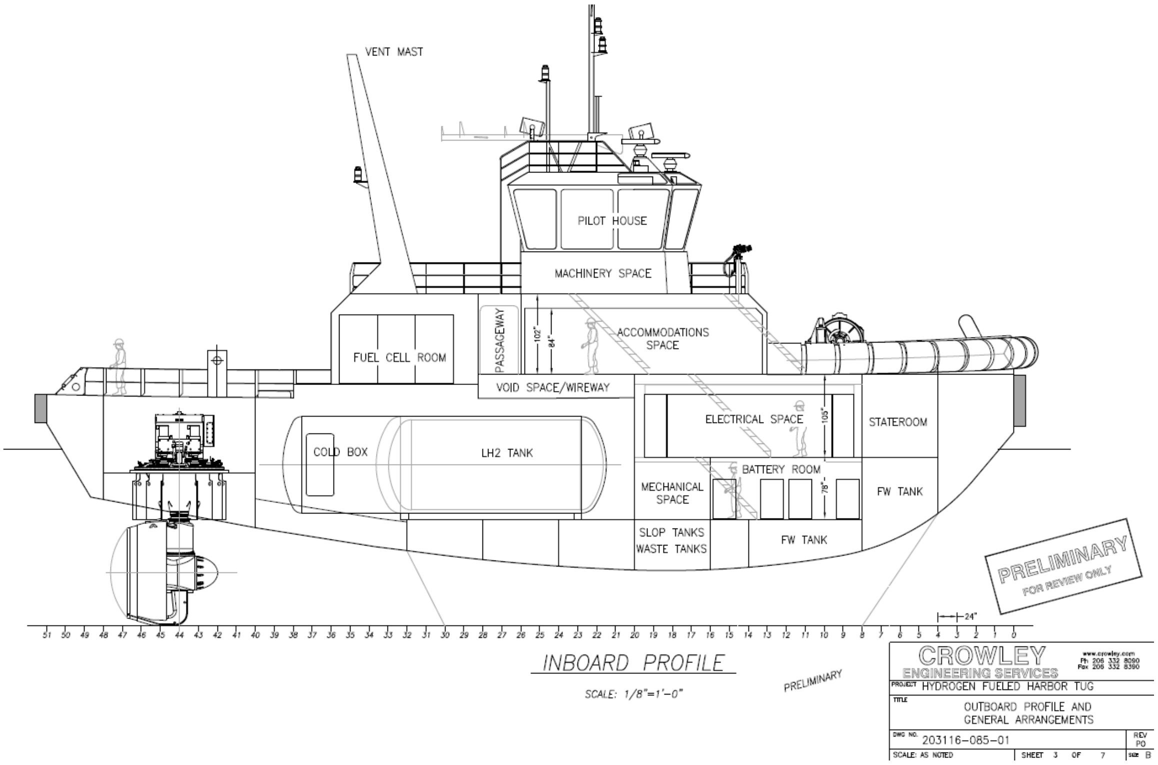

Figure 5: General Arranagement for the HyZET Vessel

3.4 Vessel Costs

The HyZET consortium conducted an economic analysis to understand the feasibility of building the vessel. To conduct this economic analysis, 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, LH2 tank) was added to this figure. Pricing for the major equipment was obtained from the members of the consortium and vendors that Crowley has previously worked with. Based on this method, the cost to build the vessel is expected to be $41.8 million, if it was built in 2022. A breakdown of these costs is included in Table 2.

Table 2: Approximate Vessel Cost

Item	Total Cost
Hull	$12,500,000
Electronics	$300,000
LH2 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**

Inflation is expected to increase the price of the vessel over time. Assuming a 10% 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.

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 will require 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 will be 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. The main systems that can benefit from economies of scale include batteries, fuel cells, and LH2 storage tanks.

The impact of economies of scale for the fuel cells and the LH2 storage tanks were modeled using a methodology borrowed from a study conducted by Elenora Ruffini and Max Wei [5]. 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 fuel cell was found to have a learning rate of 11% for the low estimate and 39% learning rate for the high estimate (representing a scenario where fuel cells have the same learning rate as batteries) [6]. A price floor for fuel cells was also set, which assumed that the price of fuel cells would not decrease by more than 50%. Based on data from the manufacturer, LH2 tanks were found to have a learning rate of 5.5%. This methodology was used to project the price based on different production volumes.

Based on this analysis, the price for subsequent vessels has been calculated. Based on this analysis, the cost reductions for the for the second vessel is displayed in Table 3.

Table 3: 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
LH2 Tanks	\$0.90 M	\$0.90 M
Total Cost Reduction	**\$6.56 M**	**\$10.37 M**

The cost of the vessel in 2022 is estimated at \$41.84 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 4.

Table 4: 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
LH2 Tanks	\$1.70 M	\$1.70 M
Total Cost Reduction	**\$9.07 M**	**\$11.83 M**

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.

4 Regulatory Environment

To obtain approval for operation, a tug must follow local and international requirements as required by the flag state and 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 LH2 in mind. As a result, it remains unclear how some of the existing regulations will be enforced for a LH2 powered vessel. This section outlines the regulations that are most applicable to the HyZET vessel. This section is not intended to be an exhaustive list of regulations.

The US Coast Guard 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 46) is the main regulation for American-flagged vessels. The most relevant portion of CFR 46 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 will 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 a US Coast Guard authorization to operate the vessel. CFR 46 does not address the use of hydrogen as fuel nor fuel cells. However, 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 will need to use the alternative design process to meet the requirements of Subchapter M and to pursue its Certificate of Inspection.

The HyZET vessel will also be subject to International Maritime Organization (IMO) regulations. The IMO is the United Nations agency that is responsible for governing shipping and 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 convention has as its main focus the safety of the vessel and those on board. Similar to CFR 46, 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 only contains prescriptive requirements for LNG. All other gaseous or low-flashpoint fuelled vessels would 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, arrangement of machinery spaces, positioning of piping and protection against leakage, and 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 battery storage system 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 shall be used together with the IGF Code, not replacing it. ASTM F3353-19 addresses safety concerns related to 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.

5 Liquid Hydrogen Supply and Bunkering

The HyZET vessel will require large amounts of hydrogen to operate. This is especially true if multiple fuel cell tugboats are deployed in the future and if other types of harbor craft transition to fuel cell technology. As a result, a LH2 supply chain will need to be established to serve the HyZET vessel and other LH2-powered marine vessels. Furthermore, a bunkering solution needs to be developed to transfer LH2 to the vessel. This section will discuss options for supplying LH2 and LH2 bunkering technology.

5.1 Liquid Hydrogen Supply

Hydrogen is expected to be supplied to POLA via delivery truck. Hydrogen can be delivered as a liquid. After the hydrogen is produced, it must be converted into LH2 through a process called liquefaction. Gaseous hydrogen must be cooled to -253°C to become a cryogenic liquid. The liquefaction process cools hydrogen by exposing it to other cold materials. Many producers use liquid nitrogen or other cryogenic liquids to precool the hydrogen. The liquefaction process is then completed by exposing the hydrogen to cooled helium. It is important to note that the liquefaction process consumes a large amount of energy, which adds to the cost of the hydrogen production process. The LH2 is then pumped onto a truck with a LH2 tank. A typical LH2 tanker truck can hold more than 4,000 kg of LH2. The truck is then driven to the end user, where the hydrogen is offloaded. The hydrogen can be offloaded using a cryopump. Alternatively, if the LH2 tanker has a vaporizer, the hydrogen can be transferred using differential pressure. Under this method, the vaporizer is used to gasify some of the LH2. The vaporized hydrogen in the tanker truck will create pressure in the tank. If this pressure exceeds that of the storage tank on the vessel, the pressure differential will push the LH2 out of the truck and onto the vessel.

The HyZET team determined that fueling the tugboat via truck is the most cost effective method. Since there would only be one vessel deployed at the start, demand for hydrogen will be relatively low. As a result, there is not enough hydrogen demand to justify building a bunkering station. The tugboat can also be fueled with a single LH2 tanker truck, which simplifies logistics. Space at POLA is limited and employing truck-to-ship bunkering eliminates the need for permanent equipment. Furthermore, there are multiple companies that can supply LH2 to POLA.

5.2 Liquid Hydrogen Bunkering

A LH2 bunkering system will need to be developed to facilitate bunkering for the HyZET vessel. Although there is not an off-the-shelf bunkering product, there are some solutions that are being developed. LH2 bunkering borrows many principles from liquid natural gas (LNG) bunkering.

5.2.1 Liquid Natural Gas Bunkering

LNG is comparable to 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. Then 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, a 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, it 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.

Another method is shore-to-ship bunkering, in which a 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 will typically contain a LNG storage tank. The LNG storage tank is usually attached to a flexible hose, 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. 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 simply logistics. However, this approach requires capital investment and physical space on the dock. This can be challenging if the port is space-constrained.

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 a 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. 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, releasead LNG can vaporize creating a risk of fire and explosive environment. Natural 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.

5.2.2 Liquid Hydrogen Bunkering

LH2 bunkering is similar to LNG bunkering. LH2 and LNG have a similar bunkering process and face similar safety concerns. However, while LNG has a boiling point of -162°C, LH2's boiling point is at -253°C. LH2 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 LH2, the purging process needs to be modified. In LNG bunkering, the bunkering hose is purged using nitrogen. However, LH2's boiling point is lower than both nitrogen's boiling point and freezing point. If the bunkering hose is purged with nitrogen and then LH2 is transferred through it, the LH2 could caue the nitrogen to liquefy or even freeze. This would contaminate the LH2 which can 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 it's boiling point is even lower than hydrogen's. Alternatively, hydrogen boil off (in gaseous form) can be used in the purging process.

Another safety issue concerns the bunkering hose. Since LH2 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 LH2 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 LH2, there will not be sufficient insulation. This is problematic because LH2 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. 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 LH2 couplings to address this issue. These couplings will need to be deployed on LH2 bunkering systems.

Conclusion

This study found that a fuel cell powered tugboat can feasibly meet the duty cycle for tugboat operations in POLA. This is an important finding because it provides a pathway towards reducing emissions at the San Pedro Port Complex. Tugboats are responsible for approximately 19% of PM emissions from the commercial harbor craft sector [7]. As a result, transitioning tugboats to zero emission will help to improve air quality around POLA and POLB. This study is also applicable to many vessels. As of 2018, there were 55 tugboats in the San Pedro Port Complex and 229 tugboats and towing vessels in California [8]. Furthermore, the HyZET vessel is suitable for operations in other regions, like the Pacific Northwest. As a result, this study will help to enable adoption of zero emission tugboats beyond the San Pedro Port Complex. It is important to note that there are very few hydrogen powered vessels in existence. The Sea Change ferry in San Francisco and the MF Hydra ferry in Norway are examples of hydrogen-powered vessels that have been built. As a result, this project is an early-mover in the hydrogen marine sector. Lessons learned from early-mover projects can help to inform other marine projects and enable the adoption of zero emission technology in other commercial harbor craft segments.

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Presenter Biography

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