

# ***MV Sea Change: Fuel Cell, Emissions, and Hydrogen Fueling Performance***

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## **Abstract**

The Sea Change Project, managed and financed by SWITCH Maritime, produced the first zero-emission 100% hydrogen fuel-cell powered commercial ferry in the world. The *MV Sea Change* is a 70-foot catamaran equipped with a 360-kW fuel cell powertrain and a 250-bar 246 kg capacity hydrogen storage system. The 75-passenger vessel began public passenger service in July 2024 as part of the San Francisco Bay Ferry system. Summarized here are aspects of the design of the vessel, its construction, and vessel bunkering with high-pressure hydrogen. Results from a fuel cell performance analysis are also presented, along with estimates of the greenhouse gas (GHG) and criterial pollutant emissions assuming different sourcings of hydrogen. Lessons learned from the project will be briefly reviewed.

## Introduction

The International Maritime Organization (IMO) established in 2023 a greenhouse gas (GHG) reduction strategy with a goal to reach net-zero GHG emissions by 2050 [1]. This reduction will require a change in vessel fuel, away from traditional fossil-derived fuels to alternative fuels that can reduce or eliminate both GHG emissions as well as criteria pollutant emissions ( $\text{NO}_x$ , hydrocarbons (HC) and particulate matter (PM)) that immediately impact human health [2]. Prior work has summarized possible alternative fuels [3 - 5] with individual studies examining specific candidate fuels such as dimethyl ether (DME) [6], methanol [7], ammonia [8], liquid natural gas [9], and biodiesel [10].

Hydrogen ( $\text{H}_2$ ) has great potential for replacing fossil hydrocarbon fuels in maritime. As summarized by Klebanoff et al [11], Foster [12] and Kickulies [13] explored the applicability of  $\text{H}_2$ , both in fuel cells and internal combustion engines (ICEs), for shore power, as well as for marine vessel propulsion and auxiliary power. In 2016, van Biert et al. [14] reviewed different types of fuel cells for their use on vessels, and also assessed different methods of storing hydrogen or producing it on-board. Bicer and Dincer considered using hydrogen or ammonia in internal combustion engines (ICEs) as replacements for burning heavy fuel oils on transoceanic vessels [15]. The IMO prescriptions [1] have increased the interest in using hydrogen fuel cell technology to power ships. Since then, a number of studies have been published with a focus on lifecycle emissions [16,17], maritime fuel cell thermodynamics [18], safety [19], and investigations of the varying types of fuel cells and  $\text{H}_2$  storage approaches available to future low-emission shipping [20 - 22]. Supplemental to these studies, a review of the safety-related physical and combustion properties of hydrogen in the maritime context has been published by Klebanoff and co-workers [23].

Since 2016, there have been several studies examining the feasibility of introducing hydrogen fuel cell power to ships, with a particular focus on ship attributes and performance. Pratt and Klebanoff at Sandia National Laboratories examined the feasibility of a high-speed ferry called the *SF-BREEZE* [24]. The feasibility and attributes of a zero-emission  $\text{H}_2$  fuel-cell coastal oceanographic research vessel named the *Zero-V* were investigated [25], along with that of a  $\text{H}_2$  Hybrid research vessel as a follow-on project [11]. Detailed vessel designs incorporating hydrogen technology demonstrated that the combination of hydrogen and proton-exchange membrane (PEM) fuel cells could provide the basis for very capable vessels. These studies examined feasibility in terms of vessel performance (speed, range, passenger complement), safety (the placement of hazardous zones), fueling (speed of refueling and available quantities) and local acceptance (Ports). These studies also included the United States Coast Guard (USCG), naval architects, Ports of call (for both ferries and research vessels), and Class Societies, introducing them to the safety-related properties of hydrogen and how to properly manage hydrogen technology in the design of vessels and shore side refueling facilities. In other work, The Hornblower Group company Alcatraz Island Services, LLC (AIS), organized a project named “Nautilus” to retrofit an existing diesel-battery hybrid passenger ferry named *Discover Zero* with a hydrogen fuel cell [26].

Due to the commercial implementation for hydrogen fuel cells in automobiles, and also in part to the feasibility of hydrogen fuel-cell vessels shown in these prior studies, hydrogen-powered vessels are starting to be realized. The first commercial hydrogen powered ferry was the *Hydroville* [27] built by CMB.Tech. The 16-passenger *Hydroville* used dual fuel ( $\text{H}_2$ /diesel) internal combustion engines

supplied with 36 kg of useable hydrogen stored in 200-bar hydrogen tanks. The top speed of the vessel was 27 knots (cruising speed 22 knots), and it operated on the River Scheldt in the Port of Antwerp as a commuter ferry.

As a follow-on to the *Hydroville*, CMB.Tech built a hydrogen powered work boat [28]. The *Hydrocat 48* is a dual-fuel (H<sub>2</sub>/diesel) vessel, with the hydrogen stored as compressed gas. The *Hydrocat 48* contains 210 kg of compressed hydrogen and has a cruising speed of 30 knots. Very recently, the MF *Hydra*, built by Norled, has entered service along the Hgelmeland-Nesvik route in Norway [29]. The *Hydra* uses PEM fuel cells, fueled with hydrogen gas provided by a 4000-kg LH<sub>2</sub> tank. The *Hydra* also has a battery-based propulsion system, with the vessel operating 50% of the time on batteries and 50% of the time on fuel cells. The *Hydra* can carry 299 passengers, 80 cars, 10 cargo trailers and has a top speed of 9 knots.

In 2021, The Scripps Institution of Oceanography (SIO) received \$35M in funding from the State of California [30] and \$4M from the Office of Naval Research to build the H<sub>2</sub> Hybrid oceanographic research vessel [11]. Currently named the *Coastal Class Research Vessel (CCRV)*, the ship has been designed and very recently received an approval in principle (AIP) from the American Bureau of Shipping [31].

Against the backdrop of this prior work, the MV *Sea Change* has advanced the state of hydrogen vessel technology by being the first operational commercial ferry in the world that is 100% powered by hydrogen fuel cells, with no supporting diesel power or significant battery power.

The key goals and objectives of the Sea Change Project are:

- Translate the prior Sandia feasibility studies [11, 24, 25] to practice, proving the viability of fuel cell powertrains in commercial maritime applications.
- Design, construct and operate the first-of-its-kind zero emission fuel-cell ferry.
- Engage with the USCG to certify the vessel design, safe operational procedures, fueling practices, and establish a regulatory framework for future hydrogen-fueled zero-emissions vessels.
- Collect and analyse data to produce valuable lessons for the broader maritime industry.
- Provide opportunities for outreach and education, supporting the dissemination of information about zero-emission vessel options to local Bay Area authorities, the Port of San Francisco staff, the public and market, and future hydrogen mariners.
- Commercialize the fuel cell electric ferry, creating a proof point for existing operators and supporting their ability to integrate similar vessels into their fleets.

A full account of the *Sea Change* Project, which also includes the financial course of the project, is available through the California Air Resources Board (CARB) [32].

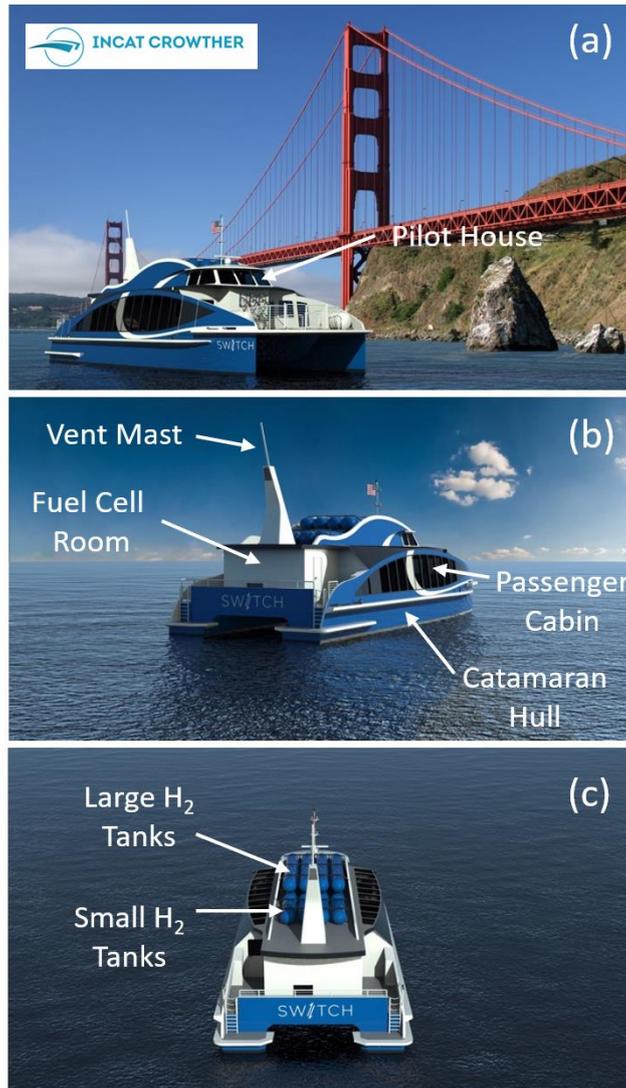
At a high level, the project's development consisted of the following key features:

1. The MV *Sea Change* was inspired by the Sandia *SF-BREEZE* study [24] that found H<sub>2</sub> fuel cell ferries to be technically feasible.
2. Joe Pratt left Sandia and founded the company GGZEM, later renamed Zero Emission Industries (ZEI), to commercialize the Sandia research on marine fuel cell propulsion and fueling systems.
3. CARB funded GGZEM for the project, including the design/construction of the world's first 100% hydrogen powered commercial fuel cell ferry, the MV *Water-Go-Round* (later renamed the MV *Sea Change*). The funding totalled \$3M, administered by Bay Area Air Quality Management District (BAAQMD).
4. SWITCH Maritime joins the effort and eventually purchases the MV *Sea Change* from ZEI. SWITCH provides and arranges additional funding for completing the project.
5. Construction of the aluminum vessel commenced at Bay Ship & Yacht in Alameda CA and was subsequently moved to All American Marine (AAM) in Bellingham WA for completion.
6. As with all new vessels, the USCG reviewed the design of the vessel in a hazard identification (HazID) workshop.
7. Once the vessel was completed and delivered to SWITCH Maritime, the MV *Sea Change* was certification-tested by stakeholders, including in Sea Trials by the USCG Sector San Francisco.
8. Upon completing all certification tests, the MV *Sea Change* received a Certificate of Inspection (COI), allowing it to enter public service along the SF waterfront on July 12, 2024 in a 6-month deployment with the San Francisco Water Emergency Transit Authority (WETA).

## Vessel Design

### *Renderings*

The *Sea Change* design was led by naval architect Incat Crowther and was informed by the prior Sandia feasibility studies [11, 24, 25]. The *Sea Change* is a 70-foot catamaran ferry equipped with a 360-kW proton exchange membrane (PEM) fuel cell from Cummins/Accelera, and a 250-bar 246 kg capacity hydrogen storage system from Hexagon Purus. Hydrogen from the storage tanks flows through a pressure control valve (PCV), which steps down the pressure from the rated storage pressure of the hydrogen tanks (up to 250 bar) to the much lower rated pressure required by the fuel cells of ~ 7 bar. The low-pressure hydrogen enters the 360-kW fuel cell system, where electricity is produced to power electric motors driving the propellers. The fuel cells are thus zero-emission power sources that are also very quiet and produce little vibration. 3D renderings of the *Sea Change* are shown in Figure 1.



**Figure 1:** (a) 3D engineering renderings of the *Sea Change*, (a) showing the location of the Pilot House; (b) identifying the Vent Mast, Fuel Cell Room, Passenger Cabin and Catamaran Hull and (c) showing the locations of the Large H<sub>2</sub> Tanks and the Small H<sub>2</sub> Tanks.

Certain high-level safety-oriented design decisions for the *Sea Change* include: (1) locating hydrogen tanks on the open top deck (although this location is not required by regulations), (2) creating an “A-60” (60 minute) fire boundary between the passenger cabin and hydrogen per USCG prescriptive requirements, (3) locating fuel cells in an emergency shutdown (ESD)-protected Fuel Cell Room, (4) hydrogen, smoke, and fire detection systems throughout the vessel with automated shutdowns if triggered, and (5) classified electronic equipment in hazardous zone areas. The *Sea Change* design establishes an important baseline for safety from which future iterations of zero-emission hydrogen fuel cell vessels can build and evolve.

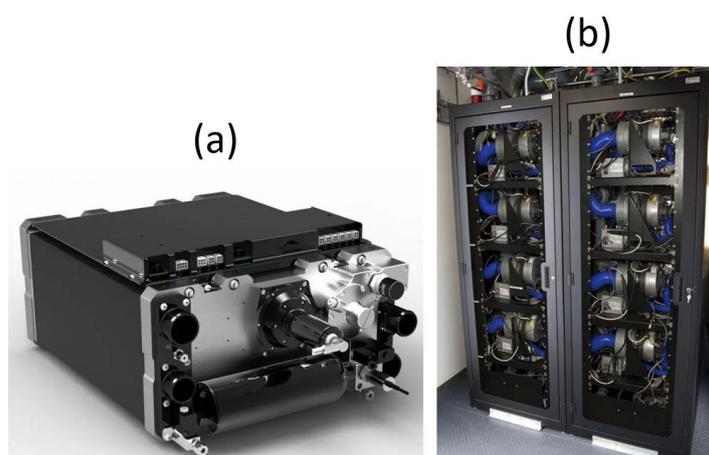
### *H<sub>2</sub> Storage*

The *Sea Change* has ten (10) Type IV composite storage tanks that are located on the top deck of the ferry (Fig. 1(b)). There are eight “Large” tanks and two “Small” tanks, with nominal H<sub>2</sub> storage capacities (per tank) of 28 kg and 11 kg, respectively. Thus, the total *Sea Change* hydrogen capacity is 246 kg at a pressure of 250 bar (3600 psi). 250 bar storage was selected because the

large form factor of the available tanks from Hexagon resulted in the lowest cost, weight, and volume storage method per kilogram of hydrogen stored. In normal *Sea Change* operation, hydrogen is drawn from all tanks at once when the fuel cells are powered on, and the *Sea Change* is underway.

### *Fuel Cells*

Several “hydrogen conversion” technologies are available for hydrogen-based power production [33]. A Proton Exchange Membrane (PEM) fuel cell is particularly well-suited for maritime applications because it provides zero emissions of greenhouse gases (GHGs) or criteria pollutants at the point of use, rapid response, high thermal efficiency in converting hydrogen fuel energy, and a compact physical footprint. In these fuel-cell power “racks” used on the *Sea Change*, individual HD 30 fuel-cell power modules from Cummins/Accelera of nominal power ~30 kW each are integrated together into stacks of four modules per rack, giving a combined power of 120 kW per rack. For maintenance purposes, the individual fuel cell modules within each rack are easily removed and replaced. Figure 2 shows the individual Cummins/Accelera HD 30 fuel cell module, and their integration into fuel cell racks.



**Figure 2:** Cummins/Accelera Fuel Cell Power System for the *Sea Change*, (a) an individual 30 kW HD 30 power module; (b) eight power modules assembled into two HyPM-R HD 120 kW Racks. The *Sea Change* has three HyPM-R HD 120 kW Racks, for a total installed fuel cell propulsion power of 360 kW. Photo Credit: R. Sookhoo, Cummins/Accelera.

### *Batteries*

When the vessel is idling or traveling at low speeds, excess energy can be generated by the fuel cells. This excess electricity is stored in the 100-kWh lithium-ion battery storage system supplied by XALT Energy (XALT). Note that the 100 kWh of energy stored in the XALT battery is negligible compared to the usable stored propulsion energy available from the hydrogen supply, which is ~ 4100 kWh, assuming the fuel cells are ~ 50 % thermally efficient.

## Vessel Construction

After partial construction of the vessel superstructure at Bay Ship & Yacht, the vessel was moved to AAM in Bellingham WA as discussed in the Final Project Report [32]. Most of the vessel construction and all the equipment outfitting was performed at AAM. AAM installed all required supporting mechanical and electrical systems. Figure 3 shows the vessel having been placed in the water for the first time at AAM.



**Figure 3:** *Sea Change* berthed at Bellingham WA for initial in-water certification and first fueling. Photo Credit: E. Van Sickle.

Once AAM had completed construction, the vessel was ready for initial certification testing and eventually Sea Trials. There are several such certifications required. For example, AAM had to certify to SWITCH Maritime that the ship was substantially complete prior to SWITCH taking vessel delivery. SWITCH then had to undergo extensive testing with the USCG to certify that the vessel's systems were performing safely and as designed. Additionally, SWITCH also helped facilitate crew training in order to ready the vessel operator, Blue & Gold, to safely enter public passenger service within the Water Emergency Transportation Authority (WETA) and its SF Bay Ferry fleet.

Upon completion at AAM and initial certification with SWITCH, the *Sea Change* was transported to San Francisco for Sea Trials with USCG Sector San Francisco, as well as operational crew training. During Sea Trials, the vessel's mechanical and electrical systems were tested to ensure proper function and safety. A multitude of tests were conducted for the USCG to witness and certify that the vessel was ready to safely enter passenger service with a crew that was knowledgeable and competent. During its Sea Trials, the *Sea Change* underwent bunkering (fueling) activities, performance testing, and data collection to evaluate the hydrogen and battery-electric propulsion functionality.

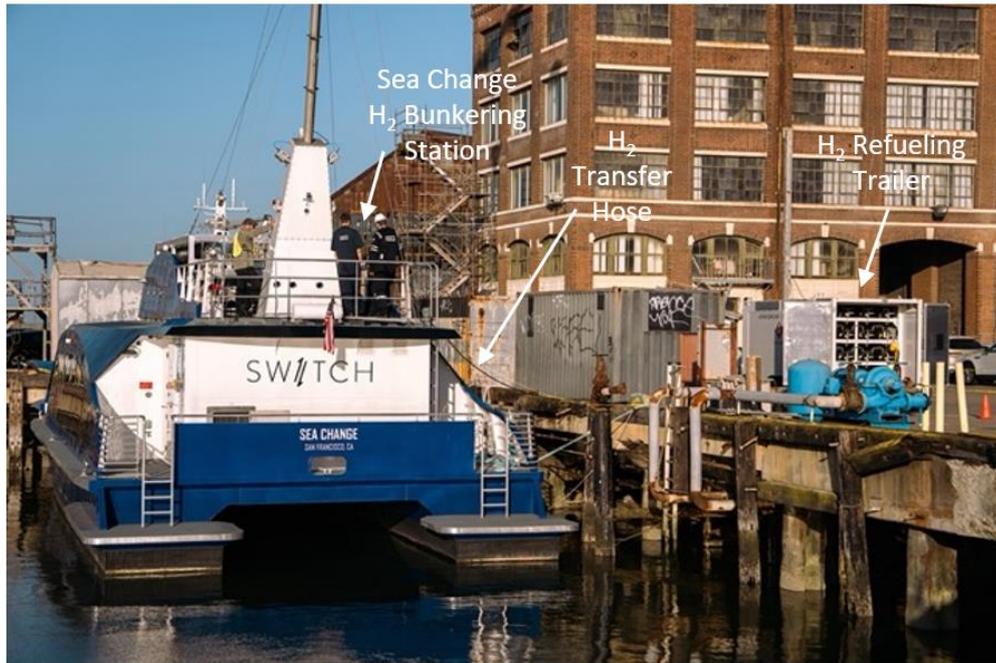
## Sea Change Bunkering

The *Sea Change* has been refueled with hydrogen at Pier 68 at the Port of San Francisco, as shown in Figure 4. This location was reviewed and approved by the USCG Sector San Francisco and the Port of San Francisco Fire Marshal.



**Figure 4:** H<sub>2</sub> Refueling in SF Bay. (Top) Location of the *Sea Change* refueling site at Pier 68 at the Port of San Francisco; (Bottom) Blow-up satellite image of Pier 68 in San Francisco, showing the H<sub>2</sub> refueling location. Images courtesy of Google Earth.

The requirements for the fueling process are dictated by the USCG and are similar to the requirements for fueling with conventional diesel fuels [32]. Fuel distribution to the *Sea Change* is managed by West Coast Clean Fuels (WCCF). Figure 5 shows the *Sea Change* bunkering at Pier 68.



**Figure 5:** H<sub>2</sub> Refueling at Pier 68, showing the connection of the H<sub>2</sub> Refueling Trailer to the *Sea Change* Bunkering Station via a high-pressure H<sub>2</sub> Transfer Hose. Photo Credit: E. Van Sickle.

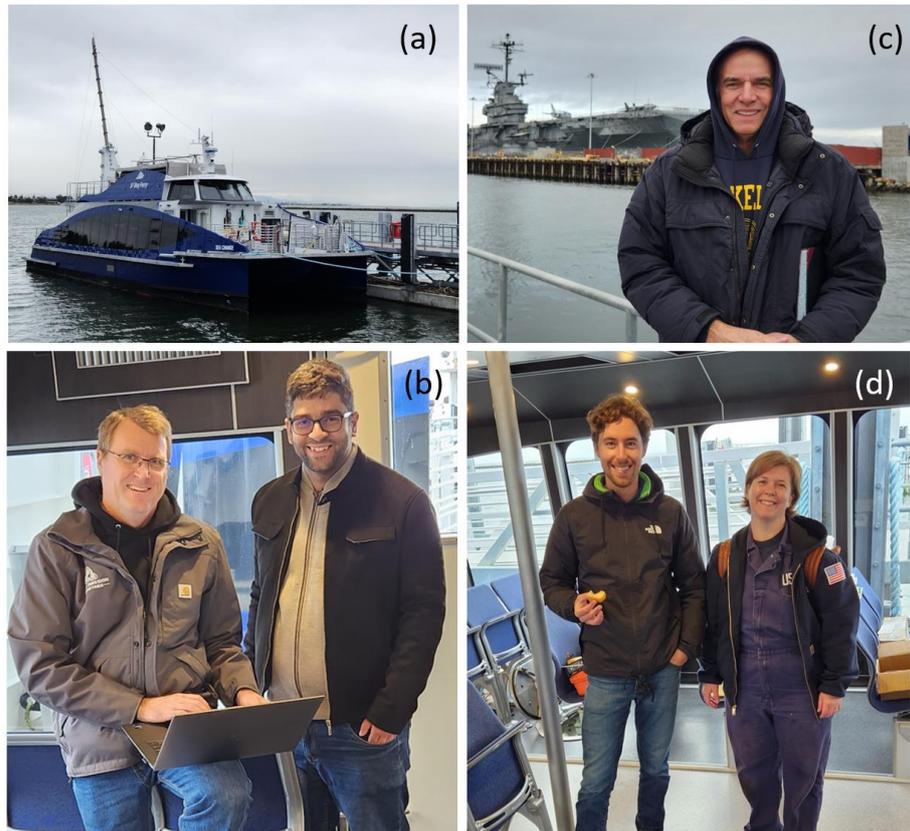
Supplying the *Sea Change* with hydrogen (i.e., bunkering) occurs via a truck-to-ship fueling, paralleling established industry practices. Hydrogen transfer occurs via “cascade filling,” where one tank of the high-pressure hydrogen refueling trailer (typically at 450 bar) is connected to the *Sea Change* bunkering station, and the H<sub>2</sub> pressure is allowed to equalize between a (full) H<sub>2</sub> trailer tank and the *Sea Change* H<sub>2</sub> tank array. Then, that first trailer H<sub>2</sub> tank is closed off, and a new trailer tank is opened to the (now fuller) *Sea Change* H<sub>2</sub> storage tank array. Set up and breakdown each take around 30 minutes before and after fueling events, respectively. Fueling frequency has varied during the commissioning period with bunkering events generally occurring 1 – 2 times per week. Currently, the *Sea Change* receives its hydrogen from the First Element Hydrogen Distribution Facility in Livermore CA which is 49 miles from Pier 68. One resulting benefit of the Sea Change Project is that ZEI has commercialized the unique fueling method developed for the MV *Sea Change*, where no landside fueling infrastructure is required, into a portable fueling product for all kinds of hydrogen vehicles and equipment.

## ***Sea Change* Performance Analysis**

Here, we give some essential results related to the *Sea Change* performance with a focus on H<sub>2</sub> fuel cell performance, “well-to-waves” (WTW) pollution emissions, H<sub>2</sub> refueling, maintenance, safety and a brief review of some lessons learned.

## Fuel Cell Efficiency

Figure 6(a) – (d) shows pictures from the fuel cell analysis activity. The vessel was temporarily berthed at Alameda Island at WETA headquarters. The Fuel cell data collection was performed by Lennie Klebanoff (Sandia), Joe Pratt (ZEI) Yazan Arafat (ZEI) and Elias Van Sickle (SWITCH Maritime).

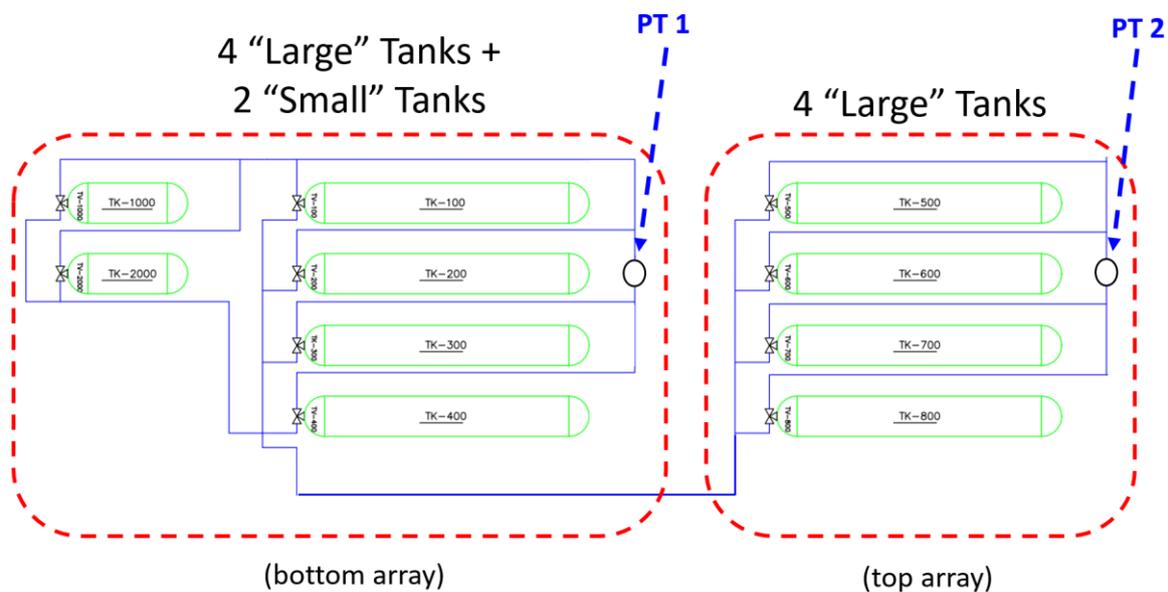


**Figure 6:** The Fuel Cell performance activity (a) *Sea Change* berthed at Alameda Island, (b) Joe Pratt (L) and Yazan Arafat from ZEI, (c) Lennie Klebanoff (Sandia) and (d) Elias Van Sickle (L) and Megan Torres (USCG Sector SF). Photo Credit: L.E. Klebanoff.

The Fuel Cell performance study requires measurement of the PEM fuel cell output power as a function of time, with corresponding measurement of the hydrogen pressure in the tank arrays, which will yield the hydrogen mass consumed by the fuel cell powerplant by using the Abel-Noble real gas equation of state for hydrogen [33]. An important concern for the data is the absolute and relative time bases recorded on the vessel. The hydrogen storage system (HSS) software captures data for the pressure and temperature of the hydrogen tanks. The Fuel Cell Data Logger (FCDL) records fuel cell output power and status. An important first step was to check the time relationships of these databases to make sure the fuel cell power output (FCDL) is synchronized with the hydrogen pressure measurement (HSS). Ideally, these time bases would agree with each other, and agree well with official Pacific Daylight Time (PDT).

The HSS system time was found to agree precisely with PDT. However, a discrepancy was found between the time base of the FCDL and the HSS. Specifically, the FCDL lagged the HSS time by 3 minutes and 31 seconds. This discrepancy was accounted for and used to correct the FCDL time basis for the data analysis.

A second important input is the hydrogen tank pressures. The hydrogen tanks on the *Sea Change* are distributed into two general arrays as shown in Figure 7.



**Figure 7:** Arrangement of hydrogen storage tanks on the MV *Sea Change*. For simplicity, many valves are not shown. The bottom array holds 4 “Large” hydrogen tanks and 2 “Small” hydrogen tanks. The top array holds 4 “Large” hydrogen tanks.

One array towards the bottom, consists of 4 “Large” Tanks and 2 “Small Tanks.” The total volume of these 6 hydrogen tanks is  $4 \times 1532.5 \text{ L} + 2 \times 576 \text{ L} = 7282 \text{ L}$ . The second array on top consists of 4 “Large” Tanks, with total volume of  $4 \times 1532.5 \text{ L} = 6130.0 \text{ L}$ . PT 1 is a pressure transducer (PT) measuring the hydrogen pressure in the bottom array; PT 2 is a pressure transducer measuring the hydrogen pressure in the top array. We checked to make sure the pressure transducers were reading properly, and in good agreement with the manual pressure gauges on the *Sea Change*

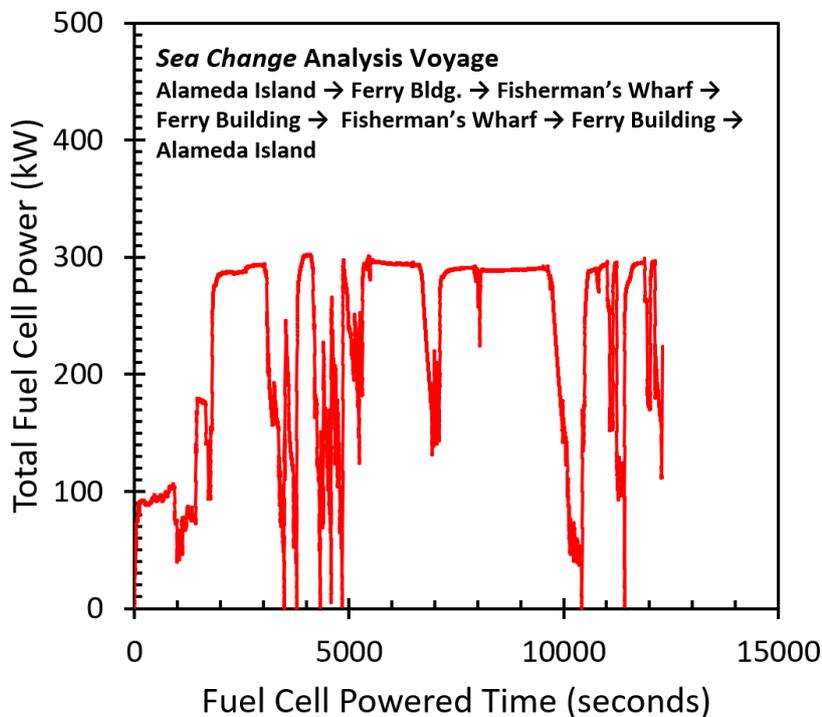
system. PT 1 and PT 2 agreed with each other and with the manual pressure gauges to within 3.4%. This test shows that the HSS system pressures (which report pressure transducer readings), are in agreement with visual checks of manual gauges to within 3.4%, which was deemed satisfactory.

A similar check was made of the data logging to make sure that the PT 1 and PT 2 readings were being accurately captured by the data logging system. The data logger was storing the PT 1 and PT 2 readings to within 0.3% accuracy. This provides confidence the measurement of hydrogen pressures on the vessel are handled well and are being captured by the HSS correctly.

With confidence that the pressures were being properly recorded, we can then convert changes in hydrogen pressure readings to “hydrogen mass consumed” by using the Abel-Noble real gas equation of state for hydrogen [34].

Here we present analysis results for the *Sea Change* fuel cell power system, in terms of the fuel cell thermal efficiency as well as the “well-to-waves” (WTW) pollution emissions that includes emissions from hydrogen fuel production and transport (i.e., the “lifecycle emissions”). We analyse a 5-hour and 25-minute voyage involving transit from Alameda Island to the SF Ferry Building, then up to Fisherman’s Wharf, back to the Ferry Building, back up to Fisherman’s Wharf, back down to the Ferry Building, then return to Alameda Island. This is a total voyage distance of ~ 15 nautical miles (NM).

Figure 8 plots the total fuel cell output power (all loads) versus the time when the Fuel Cells are turned on, eliminating from the data down time when the *Sea Change* is loading and unloading passengers and the fuel cells are turned off.



**Figure 8:** Total Fuel Cell Power Output (kW) plotted against time the fuel cells were turned on for the *Sea Change* Voyage indicated. The voyage took place February 7, 2024, and covered ~ 15 NM.

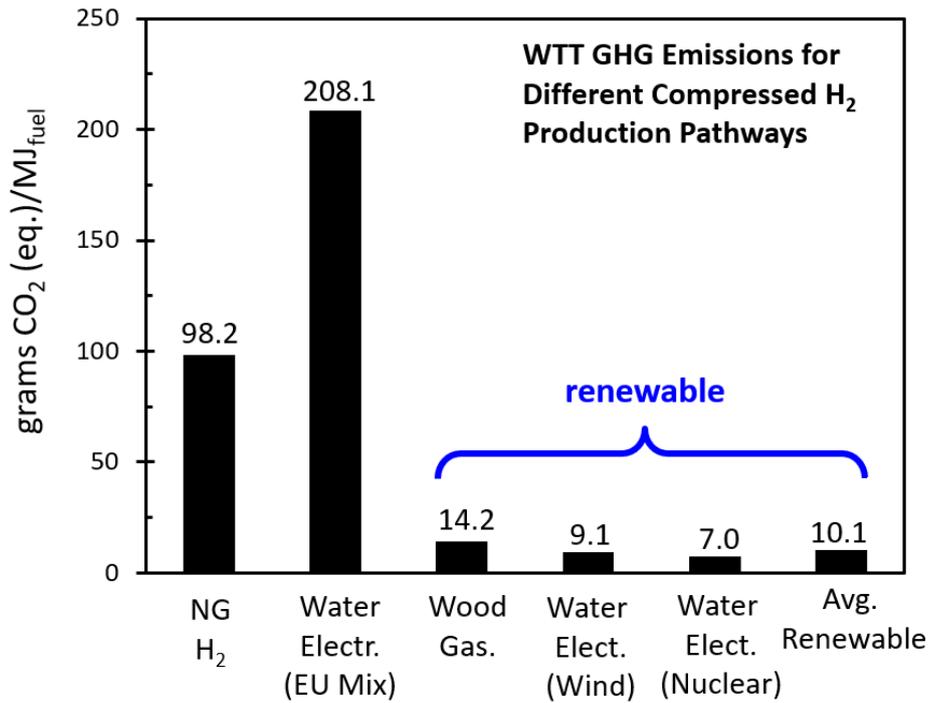
During this voyage, the total H<sub>2</sub> mass consumed was 50.12 kg, corresponding to a LHV energy consumed of 1670 kWh (adopting a LHV of 1kg of H<sub>2</sub> = 33.33 kWh). The time-averaged Fuel Cell Power output during the voyage was 224 kW. Since the maximum rated power of the Fuel Cells is 360 kW, this voyage, on average, had the fuel cells running at  $224 \text{ kW}/360 \text{ kW} = 0.622$  or 62.2% of the full-rated power. The fuel cells were turned on during the voyage a total of 3.41 hours. As a result, the total fuel cell electrical energy output during the voyage was 764 kWh. Thus, the average Fuel Cell thermal efficiency during the ~ 5-hour voyage was:  $764 \text{ kWh}/1670 \text{ kWh} = 0.457 = 45.7\%$

## GHG and Criteria Pollutant Emissions Estimates

Water is the only product of PEM fuel cell operation. There is zero formation of CO<sub>2</sub>, NO<sub>x</sub>, HC, SO<sub>x</sub>, or PM, making the PEM fuel cell a zero-emissions power plant at the point of use. Thus, the *Sea Change* eliminates exposing the crew, passengers and surrounding communities to the toxic criteria emissions as well as GHGs of the incumbent diesel technology. However, a full accounting of emissions associate with the *Sea Change* requires consideration of the emissions associated with the production and transport of hydrogen to the vessel, also known as the “well-to-tank” (WTT) fuel pathway emissions. Adding emissions from the use of the fuel on the vessel to the WTT emissions defines the WTW emissions. For zero-emission PEM fuel cells, WTT emissions equals the WTW emissions. This differs from emissions associated with the use of diesel fuel, which not only has emissions from diesel fuel production and distribution, but also emissions from fuel combustion on the vessel. As a result, WTW GHG and criteria emissions from a diesel powertrain have two contributions: the WTT production and delivery of the diesel fuel plus combustion of the fuel onboard the vessel. Here we consider the emissions benefits of the *Sea Change* taking into account these full fuel lifecycle emissions and comparing to an equivalent vessel operating on hydrocarbon fuel.

Our GHG and criteria pollutant estimates follow the formalism described previously by Klebanoff and co-workers [17]. The hydrogen WTT production methods considered here are via steam reforming (SMR) of fossil natural gas (NG), and conventional electrolysis of water using grid power [17]. “Renewable Pathways” of hydrogen production are those that don’t involve the release of carbon, including wood gasification, using offshore wind power to electrolyze water and using zero-carbon nuclear generated electricity to electrolyze water, in all cases ultimately producing hydrogen compressed to 880 bar for transport.

The results for the total WTT GHG emissions in CO<sub>2</sub> (eq.) for the compressed hydrogen production and delivery pathways are reported in Figure 9.



**Figure 9:** Total fuel pathway (WTT) GHG emissions in grams CO<sub>2</sub> (eq.)/MJ<sub>fuel</sub> for the compressed hydrogen production pathways considered in this study: (L-R); NG reforming, electrolysis of water using the European Union (EU) grid mix, wood gasification, water electrolysis using wind-based electricity, water electrolysis using nuclear-based electricity, and the average of the renewable paths. The figure reports the GHG emissions associated with producing one MJ of finished hydrogen fuel on a LHV basis, MJ<sub>fuel</sub>, with final compression to 880 bar.

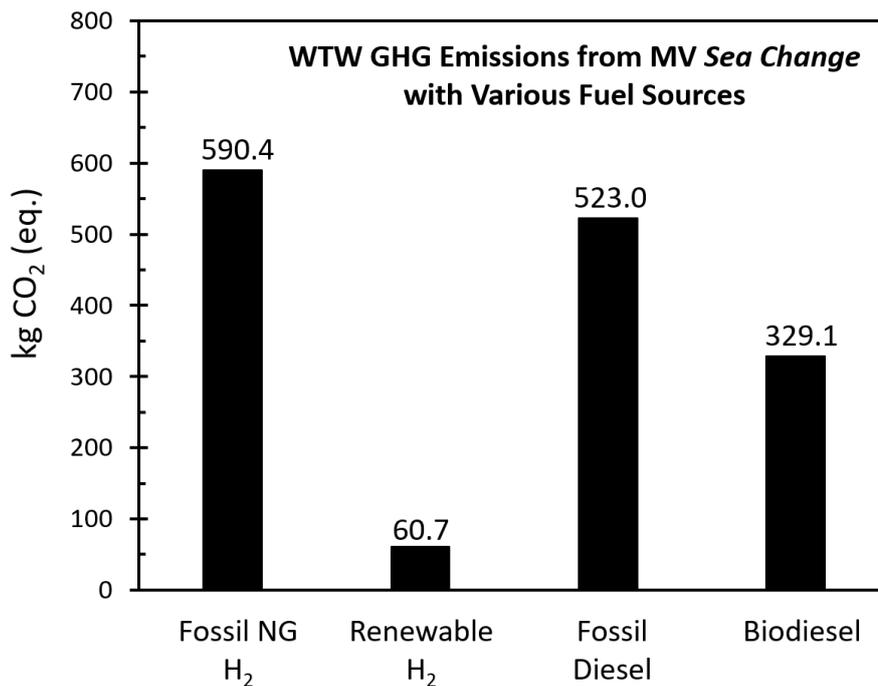
Figure 9 shows that NG-based SMR production of hydrogen followed by compression to 880 bar produces 98.2 grams of CO<sub>2</sub> (eq.) per megajoule of compressed hydrogen on a LHV basis. Water electrolysis using conventional grid power produces 208.1 grams of CO<sub>2</sub> (eq.)/MJ<sub>fuel</sub>, significantly worse than the fossil NG reforming route. This is because water electrolysis is very energy intensive. We will not consider water electrolysis via the grid further but will assess water electrolysis GHG and criteria pollutant emissions when low-carbon (renewable) sources of electricity are available.

Figure 9 shows that the renewable sources of hydrogen dramatically reduce WTT GHG emissions. Taking the average of these renewable paths, we get an average renewable GHG emissions for the production and delivery of renewable compressed hydrogen as 10.1 grams CO<sub>2</sub> (eq.)/MJ<sub>fuel</sub>. Since PEM fuel cells produce no emissions of any kind at the point of use, these WTT hydrogen production numbers provide the entire basis for estimating GHG emissions from the *Sea Change* using hydrogen produced in these different ways. In other words, the WTW emissions equals the WTT emissions for the PEM fuel cell use.

To understand the WTW emissions from the *Sea Change*, we will need some context, which we provide by comparing to a hypothetical replacement of the hydrogen fuel cells with a diesel powertrain [35] that provides the equivalent power to the propellers, while burning either diesel fuel or biodiesel fuel. The total (pathway + engine) WTW GHG emissions from making and burning 1.0

MJ (LHV) of fossil-derived diesel fuel is 87.4 g CO<sub>2</sub> (eq.)/MJ<sub>fuel</sub> [17]. Biodiesel can be the “renewable” “drop-in” biomass replacement for diesel fuel. The WTW GHG emissions associated with making, distributing, and using biodiesel are estimated to be 55.0 g CO<sub>2</sub> (eq.)/MJ<sub>fuel</sub> [17]. Biodiesel and “renewable diesel” are expected to have very similar WTW GHG emissions [17].

With this information in hand about the GHG emissions associated with making and delivering compressed hydrogen and the GHG emissions associated with making, delivering and burning fossil diesel and biodiesel, we can now assess with proper context the WTW GHG emissions from the *Sea Change* on the voyage depicted in Figure 8. The results are shown in Figure 10.



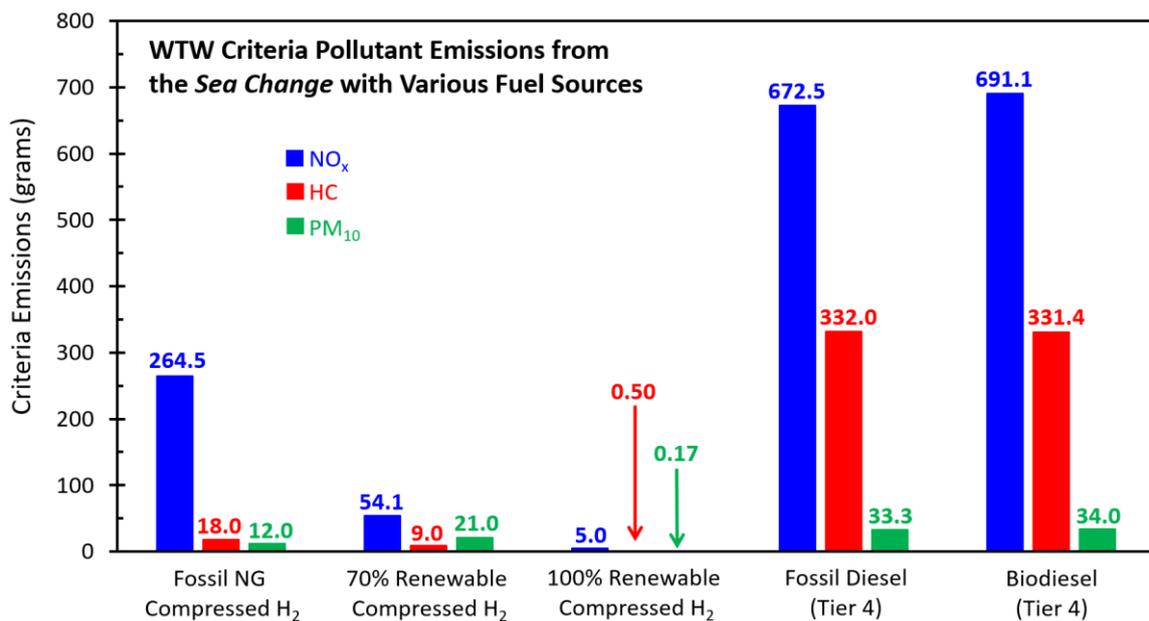
**Figure 10:** Predicted well-to-waves (WTW) GHG emissions for the MV *Sea Change* for the voyage depicted in Figure 8 for fossil-NG derived hydrogen and renewable hydrogen. These emissions are compared to hypothetical diesel and biodiesel engine substitutes for the fuel cell power.

Figure 10 shows that the GHG emissions from *Sea Change* fueled with compressed hydrogen from fossil NG would be 590.4 kg CO<sub>2</sub> (eq.), produced entirely during the production and delivery of the hydrogen fuel. This is worse than from the hypothetical diesel engine replacement powertrain running on fossil diesel fuel, with GHG emissions of 523.0 kg CO<sub>2</sub> (eq.). This GHG emissions increase arises because making hydrogen by steam methane reforming is energy intensive in the first place, and since fossil NG is the source, carbon in the fossil methane is released as CO<sub>2</sub>. The situation is dramatically improved using renewable hydrogen. Taking the average value of the WTT renewable production pathway emissions, 10.1 g CO<sub>2</sub> (eq.)/MJ<sub>fuel</sub> in Figure 10, Figure 10 shows the GHG emissions from the *Sea Change* running on renewable hydrogen drop to 60.7 kg CO<sub>2</sub> (eq.). This is an 88% reduction from that which would be produced by using fossil diesel fuel. Thus, figures 9 and 10 show that the real ability of hydrogen technology to reduce GHG rests with using renewable hydrogen, and that reduction is large.

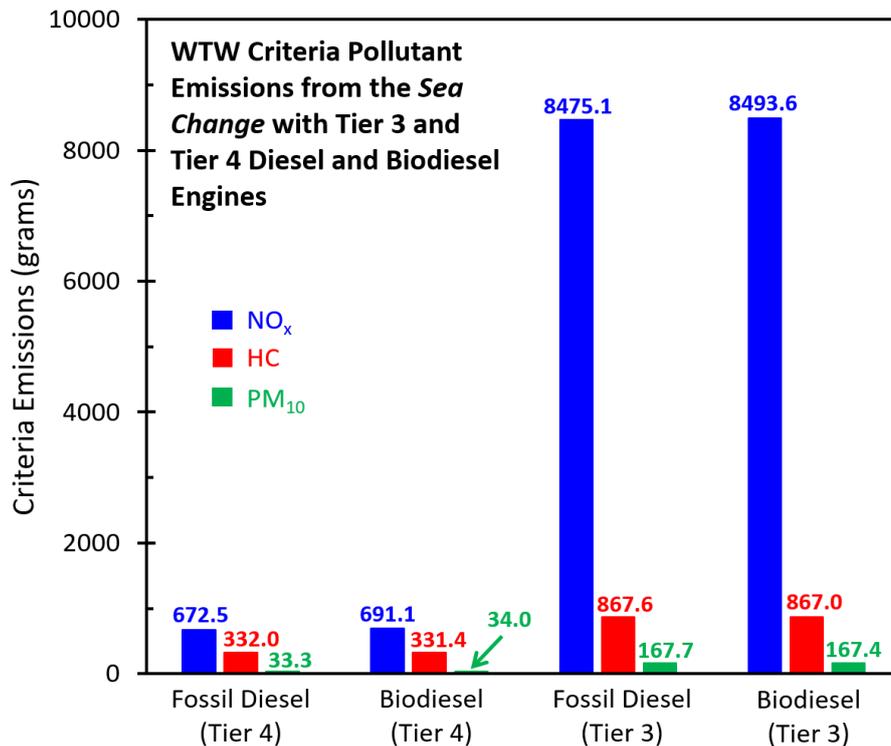
Considering using biodiesel as a drop-in renewable fuel for the hypothetical combustion powertrain, Figure 10 shows that the GHG emissions would be 329.1 kg CO<sub>2</sub> (eq.). The persistent

GHG emissions even from biodiesel arise because biodiesel fuel is energy intensive to make, which leads to emissions [17]. Summarizing the GHG results of Figure 10, The *Sea Change* operating on renewable hydrogen demonstrates the powerful ability of hydrogen fuel cell technology to dramatically reduce GHG emissions compared to the incumbent diesel or biodiesel technology.

Criteria pollutant emissions from the combustion of fossil fuels, among them nitrogen oxides (NO<sub>x</sub>), hydrocarbons (HC) and particulate matter (PM) continues to be of concern due to their immediate adverse health effects. Any criteria pollutant emissions associated with the hydrogen fuel cell technology on the *Sea Change* arise entirely from the production and transport of compressed hydrogen to the vessel, namely the WTT criteria pollutant emissions. The criteria pollutant emissions associated with the hypothetical diesel/biodiesel powertrain involve two sources: (1) production and delivery of the diesel/biodiesel fuel and (2) combustion of the diesel/biodiesel fuel onboard the vessel. Following the prior analysis methods [17], we calculate the WTW criteria pollutant emissions for the *Sea Change* using fossil-NG H<sub>2</sub>, 70% renewable H<sub>2</sub> (water electrolysis using 70% zero-carbon electricity), 100% renewable hydrogen and for the hypothetical replacement of the fuel cells with combustion powertrains utilizing fossil diesel or biodiesel, with the results shown in Figure 11. We initially constrain the diesel and biodiesel engine emissions to be at the Environmental Protection Agency (EPA) Tier 4 criteria pollutant emission limits [17], although the actual applicable criteria emissions would be constrained to the Tier 3 limits [36] for the *Sea Change* engine power level. Figure 12 compares the hypothetical *Sea Change* diesel/biodiesel criteria emissions assuming Tier 4 and Tier 3 limits, revealing how much more criteria pollution is produced by a Tier 3 engine compared to a Tier 4 engine.



**Figure 11:** Predicted well-to-waves (WTW) criteria pollutant emissions for the *Sea Change* running on hydrogen fuel cells, or the propeller power equivalent powertrain running on diesel combustion engines fueled with fossil diesel and biodiesel. The combustion engine emissions are limited to the EPA Tier 4 standards in the comparison.



**Figure 12:** Comparison of the MV *Sea Change* criteria emissions if it were, hypothetically, to be running on Tier 3 or Tier 4 constrained engines, utilizing either fossil diesel or biodiesel fuels.

The first aspect of Figures 11 and 12 to notice is that the WTW criteria pollutant emissions for the hypothetical *Sea Change* running on diesel fuel or biodiesel are very nearly the same. Although the WTT criteria pollutant emissions for the production and delivery of biodiesel are higher than those for fossil diesel [17], the WTT criteria pollutant emissions are small compared to the quantities of emissions coming from either the Tier 3 or Tier 4 combustion engines. Figures 11 and 12 show that the *Sea Change* operating on hydrogen derived from any source goes far beyond both the Tier 3 and Tier 4 criteria pollutant emissions requirements for new ferry construction in the U.S. As expected, the more “renewable” the hydrogen production becomes, the smaller the WTW criteria pollutant emissions.

We note here that the comparisons in Figures 10 - 12 between hydrogen power technology and diesel/biodiesel technology are semiquantitative. A more accurate comparison could be obtained comparing the *Sea Change* running on hydrogen fuel cells to a mission-equivalent vessel with diesel or biodiesel powertrains, with a vessel design optimized for using internal combustion engine technology. To our knowledge, such a mission-equivalent vessel does not exist, making necessary the assumptions inherent in Figures 10 - 12 concerning the required hypothetical diesel/biodiesel combustion engines and fuel consumption. However, the overall conclusions are unaffected, namely that renewable hydrogen is required to make large reductions in WTW GHG emissions from the *Sea Change*, but that hydrogen with any sourcing dramatically reduces criteria pollutant emissions.

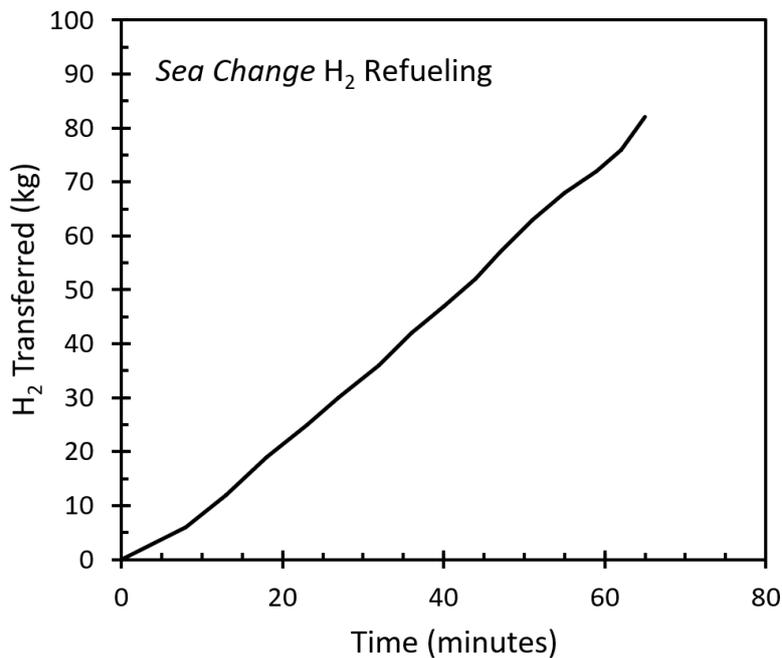
To date, most implementations of hydrogen technology, such as light-duty vehicles, trucks, and vessels (*Sea Change*), have used NG-derived hydrogen associated with elevated GHG emission like that shown in Figure 10. However, it’s been well understood in the hydrogen community that these

implementations have allowed field-testing, deployment and improvement of hydrogen fuel cell technology systems that will be able to take full advantage of the dramatic GHG reductions afforded by renewable hydrogen (e.g., Fig. 10) when it becomes more widely available.

### *H<sub>2</sub> Fueling, Maintenance, Safety and User Experience*

The high pressure compressed gas trailer delivering hydrogen to the *Sea Change* has proven to be very reliable, with the fueling very analogous to refueling a diesel vessel from a diesel tanker trailer. On the *Sea Change*, almost all of the fueling events progressed smoothly and without any issues. Fueling frequency has varied during commissioning period with bunkering events generally occurring 1-2x per week. An example of a hydrogen fueling event is described below, with a more comprehensive discussion of the refueling activity given in the Final Project Report [32].

On February 8, 2024, the *Sea Change* was cascade filled with 82 kg of hydrogen using a single trailer fueling. The total duration of the hydrogen transfer was 65 minutes. The average fill rate was 1.26 kg/minute. The overall time the *Sea Change* was at the Pier 68 refueling site 2 hours and 15 minutes, which includes all hose connection, hydrogen transfer, and hose disconnections. Figure 13 shows the time dependence of the transferred hydrogen.



**Figure 13:** Mass of hydrogen transferred to the *Sea Change* hydrogen storage system versus time. The delivery from Pierside refueling trailer occurred on February 8, 2024.

Hydrogen market conditions have fluctuated during the vessel’s operations in the San Francisco Bay Area, but prices for delivered hydrogen have averaged around ~\$30/kg of hydrogen. Currently this cost of hydrogen translates to approximately 10 times the cost of diesel. While it’s currently a significant premium to diesel, that cost premium represents only around a ~20% increase in the annual operating cost of the vessel relative to a diesel baseline operation [32]. Like other aspects of the project, the high fuel cost reflects the time the project was conducted and can be attributed to

temporary supply chain disruptions. It's likely that with increased demand for hydrogen in the near future, the \$/kg of hydrogen will come down significantly.

The high pressure compressed gas trailer delivering hydrogen to the *Sea Change* has proven to be very reliable. On the *Sea Change*, the majority of fueling events progressed smoothly and without reliability issues. However, on two occasions, an issue impeded progress on bunkering and required maintenance or troubleshooting before being able to proceed. On one occasion, a solenoid valve on the top deck of the *Sea Change* was determined to be “sticky” and not opening fully. This limited the hydrogen mass flow rate from the refueling trailer to the *Sea Change*. The solenoid valve was rebuilt and the problem did not re-occur. On another occasion, a nitrogen gas leak was identified on a swivel fitting near the bunkering hose reel. No hydrogen was flowing at the time (only a pre-fill leak with nitrogen gas) and no danger was present. The gas fitting was successfully replaced a day later enabling bunkering to be rescheduled.

As a first-of-its-kind vessel, commissioning the *Sea Change* entailed undergoing a learning process for understanding novel issues as they arose and fine tuning the vessel system, just as with any new build vessel. Very few of the issues involved the hydrogen propulsion systems, but instead involved issues associated with the control software, recirculation pumps and battery connections. The Project Final Report [32] gives a more complete account of the *Sea Change* maintenance history.

Regarding Safety, no notable incidents occurred where safety was compromised.

One of the primary differences in the *Sea Change* passenger experience is the reduced noise and vibration due to the fuel cell propulsion. The lack of diesel fumes makes for a much-improved passenger experience. For the captain, the responsiveness of the electric propulsion system is a significant positive feature of the *Sea Change*. This immediate powerplant response enhances the vessel's operational safety characteristics.

## Some Lessons Learned

Successfully completing the *Sea Change* project required the coordination of many project participants to navigate challenges, both foreseen and unforeseen. The Final Report [32] provides a full account of how these challenges were navigated. In addition, a new understanding was acquired on several topics. Illustrative examples of Lessons Learned are described here, which fell into several broad categories, including shipyard selection, Acts of God, regulations, and H<sub>2</sub> fueling. This learning has created a technical foundation for further integration of zero-emission powertrain technology for commercial harbor craft and beyond, accelerating maritime decarbonization goals.

**Shipyard Selection:** Similar to conventional vessel construction, the intricacies of US shipbuilding are best managed by a team of construction management experts with deep industry knowledge. Changing shipyards creates a time-consuming shipyard selection process, as well as the need for barges for vessel and equipment transportation to the new shipyard, with all the attendant added (and unbudgeted) costs.

**Acts of God:** Just as the team was shipping the partially constructed vessel hull on a barge to the new shipbuilder, COVID-19 shut down specific states and eventually, most of the entire world. While the immediate impact of the shipyard shutdown was relatively short-lived, the larger, more serious COVID-related challenges emerged over time, including supply chain issues, increased cost

of materials and equipment, travel restrictions and quarantine mandates, and negative impacts to vessel commercialization prospects as the passenger ferry industry was decimated overnight. Although these are hopefully rare events in the future, it speaks to providing a budget margin for Acts of God that can mitigate the impact of such events on schedule and budget.

**Regulations:** Navigating regulatory challenges and establishing a framework for future hydrogen-fueled vessels was undoubtedly one of the most impactful accomplishments of the project. While codes and standards exist for transfer and use of hydrogen on land (e.g., NFPA 2 [37]) and in other low flashpoint fuels like LNG for the maritime industry (e.g., IGF Code [38]), prior to this project no regulatory framework for hydrogen in maritime had existed in the U.S. Consequently, the process of achieving a USCG approved vessel requires continuing the USCG collaboration that had already been started with the Sandia feasibility studies, only this time encountering and overcoming very specific design issues that only a buildable vessel design could generate.

While future projects will benefit from the regulatory pathway created by the *Sea Change* project, including vessel design, operation and fueling, adding ample time to project schedules to accommodate extended review processes would be a wise precaution.

**Hydrogen Fueling:** The *Sea Change* cannot go anywhere without a robust hydrogen fuel supply chain to deliver hydrogen to the vessel. Unlike electric charging infrastructure, hydrogen affords vessels a great locational flexibility for fueling. We found that bunkering the *Sea Change* with hydrogen largely parallels existing, well-established truck-to-ship diesel fueling practices in the maritime industry. Aside from locational considerations, sourcing compressed hydrogen from the market at this point in time sometimes requires transporting the fuel over long distances which can add to the delivered hydrogen cost. Such costs need to be anticipated and budgeted for. This situation is not unusual for new H<sub>2</sub> vessels. In Norway, the MF *Hydra* gets its liquid hydrogen (LH<sub>2</sub>) fuel from Germany, a drive of ~ 20 hours [39].

## Conclusions:

The MV *Sea Change* is the first zero-emission 100% hydrogen fuel cell powered commercial ferry in the world. The project to develop the *Sea Change* was unique in that it captured and documented lessons learned throughout as a requirement of its State of California funding. These project phases captured include the vessel design, construction, testing, fueling and entry into the public ferry fleet in San Francisco. Performance data indicates overall fuel cell efficiency of 45.7%. An emissions analysis showed a 88% reduction in GHG emissions (using renewable hydrogen) compared to a fossil-fueled diesel equivalent. No matter how the hydrogen is produced, dramatic reductions in lifecycle criteria pollutant emission are achieved by the MV *Sea Change*. The lessons learned from the project are covered in greater detail in the Project Final Report [32], but included lessons associated with selecting shipyards, anticipating the unexpected Acts of God, navigating maritime regulations and anticipating fueling price increases.

## Acknowledgements

The *Sea Change* Project was funded in part from the California Air Resources Board Grant CARB-G16-DEMO-05-ZEH2F for the project titled, ‘Zero-Emissions Hydrogen Ferry Demonstration Project.’”

Funding for the *Sea Change* fuel cell performance and emissions analysis came from the U.S. Department of Energy (DOE) Hydrogen Fuel Cells Technologies Office (HFTO) under their Market Transformation program. The author thanks Pete Devlin at DOE for his support of this work.

The author thanks Joe Pratt (ZEI) and Elias Van Sickle (SWITCH Maritime) for their assistance with the fuel cell data collection and hydrogen consumption data. Many thanks to Robin Madsen of Glosten for discussions on the comparable diesel engine technology for the GHG and criteria pollutant emissions analysis. The contributions of Todd Sterling (CARB), Andrew Damiano (CARB), Chengfeng Wang (BAAQMD), John Del Arroz (BAAQMD) and Pace Ralli (SWITCH Maritime) are gratefully acknowledged.

Sandia National Laboratories is a multi-mission laboratory managed by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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