Commercial Harbor Craft Technology Assessment- Review of Tier 4 Engine Technology and Zero Emission Technology

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Disclaimer

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Abstract

This report provides an update on the commercial status of low emission engine technology (including those compliant with Tier 4 regulations), aftertreatment technology, zero emission capable hybrids, and zero emission technology for commercial harbor craft. The report supports the Amendments to the Commercial Harbor Craft Regulation adopted by CARB on December 30, 2022. Trade journals, DNV, CARB, and IMO databases were used along with discussions with various organizations and individuals to gain awareness of recent projects involving these technologies. The report includes a brief description of the commercial harbor craft vessels of interest along with a summary of diesel fuel to reduce criteria pollutant emissions and accelerate decarbonization. The resulting information provided is an assessment of evolving low or zero emissions technologies. The inventory of engine technologies available that can meet Tier 4 emissions requirements has expanded since 2020 and 27 marine engines are now commercially available (up from one in 2014). Of note are four additional engines in the <600kW size range vs none in 2018. After treatment remains a key strategy for meeting NOx and particulate emissions standards for diesel engines. These systems are generally offered by OEMs and are often offered with different geometric configurations to provide flexibility in installation. A small number of zero emission capable hybrids and zero emission vessels are in service or planned in California and the U.S. for vocations including ferries, tugs, excursion vessels, fishing boats, pilot boats, dredges and others. There are potentially feasible opportunities for converting additional CHC to ZEAT in California, and these opportunities are likely to grow as technical advancements and enhanced commercialization of vessel and infrastructure technologies is achieved. However, because vessels have unique designs, duty cycles, and other constraints, no assumptions can be made about the technological feasibility regarding a specific vessel in California without a thorough analysis of its design and operation to determine if and what conversion is possible. Furthermore, barriers that must be overcome include a current lack of charging/fueling infrastructure, burdensome regulatory processes, financial risks for early adopters, and a lack of commercial availability of ZEAT technologies.

Executive Summary

This report provides an update on the status of cleaner combustion and zero-emissions technology available for commercial harbor craft. The update emphasizes progress in these areas since 2020 with particular interest in feasibility and commercial status of these technologies. This is germane to adoption of Amendments to the Commercial Harbor Craft (CHC) Regulation adopted by CARB on December 30, 2022.

Trade journals, DNV, CARB, and IMO databases were used along with personal discussions with various organizations and individuals to gain awareness of recent projects involving these technologies.

Cleaner Combustion Technologies

The conclusion of the review is that progress has been made on evolving the technologies of interest. As of March 2024, there are 27 Tier 4 engines (most, but not all, incorporate after treatment) are currently commercially available. Notably, 4 commercial offerings are available since 2018 in the low power range (<600kW). Several manufacturers indicate that they are working on smaller output engines which holds promise for many of the operating missions associated with physically smaller commercial harbor craft vessels as well as for auxiliary engines. The available cleaner engine technologies generally (but not all) involve aftertreatment in the form of selective catalytic reduction (SCR) for NOx and diesel particulate filters (DPF) for fine particulate. These technologies are generally modular in nature, but generally require additional physical space to be incorporated onto the vessel which creates challenges for fitment and can play a factor in retrofit. The amended CARB Commercial Harbor Craft Regulation essentially necessitates a DPF as diesel fine particulate is deleterious to health. Incorporation of a DPF to further mitigate fine particulate involves further addition and/or modification of exhaust system modules. Ideally a DPF can be added after the SCR, but most manufactures tend to locate the DPF before the SCR as higher exhaust temperatures are beneficial for the operation of the DPF. There are exceptions to this positioning, and it appears technically feasible to simply add the DPF downstream of the SCR which current Tier 4 engines tend to utilize. A noteworthy exception is the Wabtec line of engines which utilize extensive exhaust gas recirculation (EGR) which allows them to avoid using SCR to meet NOx standards. Table ES-1 summarizes the commercially available marine engines that can meet CARB Tier 4 emissions regulations along with details regarding the engine characteristics and emission reduction technologies utilized.

Translating the individual engines into their availability for specific commercial harbor craft, a summary of the commercial status of Tier 4/Tier 4 equivalent main/auxiliary engine technology is provided in Table ES-2. Several factors were used to categorize each entry, including presence or absence of an example vessel, as well as results from a feasibility study to assess cases where an example vessel is absent. It is difficult to generalize the appropriateness of Tier 4 technology for a particular vessel class. Essentially each vessel layout and mission need to be individually considered when adopting a particular Tier 4 engine and it associated aftertreatment system.

Effort is underway for “add-on” or retrofit DPFs that can be added to Tier 4 engines. A handful of demonstrations of these retrofits have occurred, but more work is needed to bolster confidence in their operation and effectiveness in service. Engine OEM’s could also possibly develop DPFs that are specific to particular engines or range of same. CARB verification of one add on DPF (Rypos) is available, though others are planning to get verification for their marine products.

Table ES-1: Tier 4 Certified Engines and their Specifications as of March 2024

Manufacturer	Model	Cylinders	Stroke	DPF	SCR	Turbo	Emissions Compliance	Weight (kg)	EPA Category	Power Range (bkW)	Year Available
M&H Engines	M&H 4045MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	570	1	55-130	2023
M&H Engines	M&H 6068MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	785	1	169-224	2023
M&H Engines	M&H 6090MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	1097	1	205-317	2023
Baudouin	6M-26.3	6	4	No	Yes	Yes	Tier 4, IMO III	2185	1	441-599	2019
Yanmar	6AYEM-GTWS	6	4	No	Yes	Yes	Tier 4, IMO III	2418	1	670-749	2021
MAN Diesel	D2862 Series	12	4	Yes	Yes	Yes	Tier 4, IMO III	2270	1	749-1066	2020
Caterpillar	C32	12	4	No	Yes	Yes	Tier 4, IMO III	3248	1	746-1081	2018
Cummins	QSK38	12	4	No	Yes	Yes	Tier 4, IMO III	5270	1	746-1119	2022
Mitsubishi	S12-R	12	4	No	Yes	Yes	Tier 4, IMO III	5350	1	840-1270	2021
Baudouin	12M-26.3	12	4	No	Yes	Yes	Tier 4, IMO III	3615	1	883-1214	2019
Caterpillar	3512E	12	4	No	Yes	Yes	Tier 4, IMO III	8193	1	1000-1901	2015
MTU	12V-4000M 05	12	4	No	Yes	Yes	Tier 4, IMO III	8000	1	1119-1932	2021
EMD 710 Series	8E 23	8	2	No	Yes	Yes	Tier 4, IMO III	14742	2	1249-1864	2016
Cummins	QSK60	12	4	No	Yes	Yes	Tier 4, IMO III	10154	1	1491-2013	2022
EMD 710 Series	12E 23	12	2	No	Yes	Yes	Tier 4, IMO III	19414	2	1561-2237	2016
EMD 710 Series	12E 23B	12	2	No	Yes	Yes	Tier 4, IMO III	23133	2	1561-2237	2016
Wabtec	6L250 MDC	6	4	No	No	Yes	Tier 4, IMO III	19944	2	1700-1900	2017
MTU	16V-4000M 05	16	4	No	Yes	Yes	Tier 4, IMO III	9300	1	1840-2576	2021
Caterpillar	3516E	16	4	No	Yes	Yes	Tier 4, IMO III	9620	1	1865-2525	2014
Wabtec	8L250 MDC	8	4	No	No	Yes	Tier 4, IMO III	23356	2	2250-2500	2016
MTU	20V-4000M 05	20	4	No	Yes	Yes	Tier 4, IMO III	11600	1	2300-3220	2021
Caterpillar	C280-8	8	4	No	Yes	Yes	Tier 4, IMO III	19000	2	2460-2530	2017
EMD 710 Series	16E 23	16	2	No	Yes	Yes	Tier 4, IMO III	22589	2	2479-2983	2016
EMD 710 Series	20E 23	20	2	No	Yes	Yes	Tier 4, IMO III	25719	2	3098-3729	2016
Wabtec	12V250 MDC	12	4	No	No	Yes	Tier 4, IMO III	27080	2	3150-3500	2016
Caterpillar	C280-12	12	4	No	Yes	Yes	Tier 4, IMO III	26036	2	3700-4060	2017
Wabtec	16V250 MDC	16	4	No	No	Yes	Tier 4, IMO III	35788	2	4200-4700	2017

Table ES-2: Tier 4 Main and Auxiliary Engine Technology Commercial Status

Vessel Type	Tier 4 Main Engine	Tier 4 Auxiliary Engine
Barge-ATB	Commercially Available	Commercially Available
Barge-Bunker	Commercially Available	Commercially Available
Barge-Other	Commercially Available	Operational In California
Barge-Towed Petrochemical	Operational In California	Commercially Available
Commercial Fishing	Commercially Available	Operational In California
Commercial Passenger Fishing	Commercially Available	Commercially Available
Crew/Supply	Commercially Available	Operational In California
Dredge	Operational In California	Commercially Available
Excursion	Operational In California	Operational In California
Ferry-Catamaran	Operational In California	Commercially Available
Ferry-Monohull	Commercially Available	Commercially Available
Ferry-Short Run	Commercially Available	Operational In California
Pilot Vessel-Station	Commercially Available	Commercially Available
Pilot Vessel-Run	Operational In California	Commercially Available
Research Vessel	Commercially Available	Operational In California
Tugboat-Escort/Ship Assist	Operational In California	Commercially Available
Tugboat-ATB	Operational In California	Commercially Available
Tugboat-Push/Tow	Commercially Available	Operational In California
Workboat	Operational In California	Operational In California

N/A	Not Applicable
Not Commercially Available	Not Commercially Available
Commercially Available	Commercially Available
Operational In California	Commercially Available and Operational in California

Further, technology under development, but not yet commercial for marine operations, include a DPF that integrates SCR technology into it as well as other particulate removal strategies such as electrostatic precipitators.

Zero Emission and Advanced Technology (ZEAT)

Demonstrations of hybrid and zero emissions technologies are underway in the state, particularly for ferries and tugs. While these portend commercial status as duplicate vessels start to appear, the current projects feature a consortium of partners, and it is hard to consider these technologies as "off the shelf" at this point. The overall conclusion from the study is that there are potentially feasible options for converting CHC to ZEAT vessels in California, and these opportunities are likely to grow as technical advancements and enhanced commercialization of vessel and infrastructure technologies is achieved. Additionally, it is likely that applicable regulatory processes will be streamlined, and stakeholders will develop a better understanding and familiarity with ZEAT vessels and infrastructure. In particular, the successful demonstration of the current ZEAT projects in California and other regions will inspire confidence for owner/operators to pursue such vessels.

However, because vessels have unique designs, duty cycles, and other constraints, no assumptions can be made about the technological feasibility regarding a specific vessel in California without a thorough analysis of its design and operation to determine if and what conversion is possible. If significant alterations to vessel construction and design are required (which is likely for ZEAT), assessments by naval architects will be needed to ensure changes will not adversely affect the vessel's stability, seaworthiness etc. Critically, this includes the consideration and analysis of the feasibility of developing shoreside charging and/or hydrogen fueling infrastructure to support ZEAT vessels. The number of variables impacting the feasibility of ZEAT vessels must be carefully and comprehensively assessed on a case-by-case basis. In addition to meeting all the applicable vessel design and safety standards, ZEAT options must also be able to conduct the work required by each vessel vocation and must meet performance and operational requirement such as duty cycle, vessel speed, range, engine throttle response times and vessel maneuvering characteristics, vessel design and structural layout, and possible changes to vessel weight.

In general, battery electric propulsion systems are currently more commercially advanced than hydrogen fuel cell propulsion systems and are most viable for slower vessels with shorter routes, lengthier periods of downtime for charging, and vessels with low sensitivity to weight. If battery technology improves and reductions in energy density and weight are achieved additional CHC vocations and routes will become feasible. Nonetheless, several companies are working on hydrogen fuel cell vessels which are best suited for applications that require longer routes or higher power demands, and those that are sensitive to weight limitations. For example, smaller, faster vessels may require fuel cell propulsion due to the size and weight of the battery pack that would otherwise be required. Advancement in battery and fuel cell technologies including improved energy density, cost reductions, and improved reliability and durability are needed and will increase the flexibility and utility of ZEAT vessel design and operation.

In the near- to mid-term, it is likely that hybrid electric systems will be a more attractive option for many CHC vocations until full zero emission systems progress and are proven. Designing a hybrid propulsion system to maximize the efficiency and environmental benefits of ZEAT vessels will be based on the individual operating profile of the vessel under consideration, e.g., when shore-side charging is required, charging time and capacity are the most important factors for battery sizing relative to sailing considerations [90].

In summary, the following represent potentially feasible opportunities for converting some California CHC to ZEAT and further discussed in the following sections. However, it is essential that opportunities are considered on a case-by-case basis and thus the following list does NOT represent all vessels within those categories.

- **Short run ferries, passenger ferries with short- to medium- routes**
- **Excursion vessels with amenable routes and turnaround times**
- **Line tender tugs (or similar), select ship assist tugs**
- **Pilot, crew vessels, work boats with less rigorous routes and duty cycles**
- **Small harbor dredges operating close to shore and with access to appropriate infrastructure**
- **Some small or near-shore commercial fishing boats or commercial passenger fishing vessels that can handle vessel design and operational changes**

The current lack of available charging/fueling infrastructure represents one of the most important barriers for ZEAT vessel deployment and successful operation and the buildout of infrastructure will be critical to the commercial success of ZEAT.

Route length, power demands, service frequency, layover time, speed of travel, and passenger capacity/weight are all important to electrifying CHC as they impact vessel energy consumption and shore side charging needs. Appropriate design can help reduce the size of the battery systems and landside infrastructure, but efforts to reduce energy demands can also negatively impact the practicality, quality, and cost effectiveness of vessel service. Thus, a balanced approach is necessary to determine the parameters of each project.

The selection of shoreside infrastructure will be influenced both by vessel location and activity and planned construction and terminal upgrades are important because they represent a key opportunity to more cost effectively incorporate landside infrastructure as it is simpler to incorporate electrification improvements during the initial design and construction phases. Terminals that may be more amenable to infrastructure upgrades including those with local land availability (e.g., parking areas) or reduced shoreside infrastructure congestion. For example, the availability of land for developing solar photo voltaic (PV) and battery storage systems will be important to support the large power requirements for vessel charging.

Higher power (i.e., DC fast-charging) and/or charging systems with automation have higher costs but provide the benefits of minimal charging times. In contrast, lower power (i.e., AC charging) and/or manual charging systems are currently cheaper and offer the benefits of being more technologically advanced and available and can generally interface with existing infrastructure more smoothly. These charging strategies are not exclusive, e.g., a combination of fast-charging during operation and slow-charging during periods of inactivity may be optimal in some cases. Decisions will need to be made on a per-case basis to determine which approach will best serve ZEAT vessels.

Introduction

This document supports the requirements of California Air Resources Board (CARB) Resolution 22-6 which requires an assessment of commercial availability of ZE and lower emitting combustion technologies in the context of the California Commercial Harbor Craft applications. This document leveraged the Initial Statement of Reasons (ISOR) Appendix E which describes the status of available technology as of 2021 [1]. For perspective, Table 1 summarizes the vessel types associated with the commercial harbor craft (CHC) sector and the counts of each type as of 2021. The current report emphasizes what specific technologies are available, what technologies are nearing commercialization (within 3-5 years), and what ongoing research efforts are occurring that may lead to eventual commercialization of technologies in the future (> 5years). The report focuses on technology status and information from 2020 and onward.

The document also includes a brief discussion on the status of alternative fuels as well as associated infrastructure needed for ZE technologies. For marine applications a number of molecular energy sources are being considered to displace carbon from the use of traditional fossil fuels (i.e., diesel). Some of these alternative fuels can be used by multiple technologies (e.g., fuel cells and diesel engines).

Table 1: Vessel Types of Interest and Approximate California Count. [1]

Vessel Type	2021 Vessel Count [2]
Barge-ATB	13
Barge-Bunker	12
Barge-Towed Petrochemical	9
Crew/Supply	71
Dredge	20
Excursion – High Speed Excursion – Low Speed	177
Ferry-Catamaran/High Speed	32
Ferry-Monohull	19
Ferry-Short Run	16
Tugboat-ATB	11
Tugboat-Escort/Ship Assist	58
Tugboat-Push/Tow	108
Commercial Fishing	797
Commercial Passenger Fishing – Inspected Single Day Commercial Passenger Fishing – Inspected Multi-Day Commercial Passenger Fishing – 6-pack	274
Pilot Vessel - Station Pilot Vessel – Run Boat	9
Research Vessel	44
Workboat	204

1 As of September 2021

Brief Vessel Description

The vessels of interest cover most of the harbor craft in the State of California. It is noted that in most cases, each specific vessel has its own features and operational requirements and mission cycles. Many of the vessel categories include specific examples with varying characteristics, operational requirements, and feasibility concerns, e.g., pilot run boats operate very differently depending on which port or region they are servicing. These generally disparate requirements create challenges in generalizing what is or is not possible in terms of repowering, retrofitting and/or new build for both Tier 4 engines, after treatment technologies, and suitability for near-zero and zero-emission technologies. That said, to provide a context for discussion that follows on available and/or developing technology, this section provides brief descriptions of the CHC vessels of interest. The suitability for a specific technology adoption by a specific vessel will require further engineering and analysis.

Barges

A barge is a flat-bottomed boat or vessel used for transporting goods and materials on rivers and canals. Typically lacking a propulsion system, unmanned and towed or pushed by tugboats, barges are designed to carry bulk cargo, such as coal, grain, or containers, and are commonly used for shipping goods in inland waterways and coastal areas. They often have several auxillary engines.

1.1.1.1 ATB

An articulated tug barge (ATB) system consists of a tugboat and a barge that have a hinged or articulated connection which provides several advantages in terms of navigation, safety, and operational efficiency. Figure 1 shows an example of the ATB tug and its associated barge. An ATB tug and barge can be separated into two distinct vessels and the barge is considered a separate unmanned vessel even when connected to the ATB tug. The tugboat typically has the necessary propulsion systems and control mechanisms to effectively navigate and connect with the barge. ATB systems are used for numerous shipping applications including transporting bulk commodities, petroleum products, and other cargo. ATB systems are especially common in the shipping of refined petroleum products.

Figure 1: Crowley 550 Class ATB Tug and Barge [3]

ATB barges are double-hull petrochemical tank barges that vary in size to accommodate a range of cargo capacities and operational requirements. These capacities are generally measured in "registered tonnage," which ranges from 6,500 at the lower end, to more than 17,000 at the higher end. A registered ton corresponds to about 24 barrels or 100 cubic feet of volume. Additionally, the tugboat portion of the ATB vary in size and engine characteristic (fuel, power, etc.) and their characteristics are closely integrated with those of the barge they are designed to tow. In California, an example of a currently operating ATB tug includes the Crowley *Ocean Reliance* which is 130' long with a 6,500-ton registration, powered by two Caterpillar C-280 5096 hp main engines. The Crowley 550 class barge has nine auxiliary marine grade diesel engines to power transfer pumps, ballast water pumps, electric generators, gas generators, and hydraulic pumps for anchor and hose handling deck equipment. It should be noted that newer ATB barges often have different and more efficient arrangements than legacy vessels. For example, the Crowley 650 class barge has two large 1900 hp diesel-electric generators powering electrically driven pumps and deck equipment.

ATBs typically operate along the California coastline using shipping lanes 24/7 365 days a year. ATBs are restricted to rigorous arrival and departure schedules dictated by the companies whose products they are contracted to transport. ATB operators do not have any control over adjusting the schedule (including both where and when they operate). Most main propulsion engine operating time is spent transiting on the ocean at high engine loads over 80% at approximately 10-12 knots. Such mission information will often help determine the appropriateness of different advanced technology options.

One design challenge with ATB tugs is that, when not connected to its corresponding barge, vessel balance and stability become impacted. This is discussed in Section 1.1.2.1 below.

1.1.1.2 Bunker

Double-hull fuel-bunkering barges are used for fueling ocean going vessels either at berth or at anchor. Figure 2 illustrates an example alongside a container ship. Bunker barges are smaller than the ATB type barges and designed to be towed on a wire or hauled alongside by a tug in protected waters near the coast. The fuel capacity of a typical bunker barge in California is 20,000-50,000 barrels (~840 – 2100 ton reg). Most bunker barges have at least two fuel pumping engines in the 350 hp range as well as auxiliary engines in the 25-75 hp range for powering deck equipment and generating electricity. An example in California is the Olympic Tug and Barge's 239' *Bernie Briere* which has two Detroit Diesel Series 60 product pumping engines rated at 350 hp each and a third engine, a 25 hp Shibaura generator [4].

Figure 2: Bunker Barge operated by OW Bunker [5].

1.1.1.3 Towed Petrochemical

Common towed petrochemical barges are double-hulled and towed using a wire to move large quantities of fuel or petrochemicals. Apart from lacking ballast water pumps, towed double hull barges utilize a number of auxiliary engines to pump products, power generators, and power hydraulic pumps for deck equipment such as anchor winches or hose handling booms. Figure 3 shows an example which is the 349’ Sause Brothers Ocean Towing barge *Alsea Bay* that has four Detroit Diesel Series 60 product pump engines rated at 375hp, and two auxiliary pumps/generators one at 190hp and the other 220hp [6].

Figure 3: Sause Brothers Towed Petrochemical Barge [7]

Tugs

A tugboat is a powerful, compact, and highly maneuverable boat designed to assist larger vessels by towing or pushing them. Tugboats play a crucial role in guiding ships in and out of ports, navigating through narrow channels, and aiding in docking and undocking procedures. They are characterized by a sturdy build, powerful engines, and towing equipment, making them essential for providing control and assistance to larger ships in various maritime operations.

1.1.1.4 Articulated Tug Barges (ATB)

Articulated tug barge tugs, or ATB tugs are specifically designed to push their ATB barge counterparts. Because they are designed to work with specific barge counterparts, their sizes vary based on the associated barge counterparts. They typically have very tall pilot houses as mentioned in Section 1.1.1.1 above. When the tug is detached from its associated barge, this leads to stability/balance concerns as rolling on the longitudinal axis is amplified at the top of the pilot house. This presents challenges for installing/retrofitting with advanced technology as any added or reduced weight or even different configurations of weight from conversion to advanced technology options must be carefully considered to not exacerbate this issue.

1.1.1.5 Escort/Ship Assist

Ship assist tugs are highly maneuverable and powerful with a power range between 5000-6800hp. An example is shown in Figure 4. Additionally, they are designed to be multipurpose, with equipment to aid with ship assistance, escort duties, and ocean towing. Their high maneuverability allows them to guide ocean going vessels in docking, undocking, and navigating tight channels. It is common for several ship assist tugs to assist one vessel simultaneously. Escort tugs are similar in design to ship assist tugs;

however, they are larger and more powerful. These tugs are certified by the California Department of Fish and Wildlife Office of Spill Prevention and Response and must have the capability of producing 90 short tons of sustained bollard pull.

Figure 4: Glosten Ship Assist Tug [8]

1.1.1.6 Push/Tow

In California, near-shore push/tow tugs are often repurposed older ship assist tugboats. An example is shown in Figure 5. These vessels have winches and fenders, but typically have less bollard pull or maneuverability compared to modern escort/ship assist tugs. The main propulsion engines are often in the 750-1200 hp range. Some smaller near-shore push boats are of a shallow draft design and resemble a flat rectangular barge with two vertical beams on the bow for squaring up to a barge, and a tall pilot house high enough for visibility over the barge. Most of the smaller shallow draft push tugs have smaller 300-400 hp engines. Unlike escort and ship assist tugs, push tugs operate their engines at higher loads for extended time intervals typically performing barge moves related to maritime construction or aggregate production. The average load factors for these pushing and towing tugs are estimated to be 40-50% (similar to a larger ATB push tug).

Figure 5: Curtin Maritime Push/Tow Tug [9]

Ferries

Ferries are large vessels tasked with carrying passengers from one location to another, typically across bays, rivers, or between islands. Because of the variation in their routes, they are designed for either low speed or high-speed operation. So called short run ferries are typically designed for shorter routes (less than 3 nautical miles) and can be constructed from normal shipbuilding materials, while high speed ferries are typically designed for speed with lightweight construction.

1.1.1.7 High-Speed Catamaran

High-speed ferries are designed to be light and fast utilizing powerful diesel engines at high engine loads for extended time intervals while transiting. Relative to monohull designs, catamaran ferries generally have the benefits of faster speed and fuel efficiencies due to reduced water resistance, enhanced stability, larger space, and shallow drafts. Figure 6 shows an example of a catamaran style ferry. However, they are wider which can complicate docking, have less maneuverability, are not as able to handle rough seas, and can be more expensive. Additionally, monohull ferries are feasible in a wider range of sizes and configurations which improves the flexibility of meeting different routes.

Figure 6: Water Emergency Transportation Authority (WETA) Dorado, a High-Speed Catamaran [10]

1.1.1.8 High-Speed Monohull

Monohull ferries in California are like excursion vessels in that they operate with slower speeds (10-14 knots) operating with 500-1000 hp main propulsion engines typically over short to mid-distance routes up to 6 nm round trip, with some monohull ferries operating on longer routes. Additionally, there are high-speed mono-hull ferries in-use in California that operate at 20-24 knots. Several ferry operators using monohull vessels switch seasonally to excursion vessel work. An example is shown in Figure 7.

Figure 7: Global Marine Design Sea Flyte 1, a High-Speed Monohull Ferry [11]

1.1.1.9 Low-Speed Short Run

Short-run ferries are a subcategory of monohull ferries that operate at slower speeds (<10 knots) on short routes. They are typically older, and like monohull ferries, may switch to excursion vessel work on a seasonal basis during the off season. A California example is shown in Figure 8.

Figure 8: Angel Island Tiburon, a Low-Speed Short Run Ferry [12]

Pilot Vessels

Pilot vessels are used to transport maritime pilots between land and inbound/outbound ships and can range from 23’ to 104’. They are generally high powered and often constructed from lightweight materials (i.e., aluminum, fiberglass) to be fast and durable to withstand rough sea conditions and contact with other large vessels. Most current pilot vessels are monohull, other forms including catamarans also are used.

1.1.1.10 Pilot Run

In California, typical pilot run boats are 50-67’ with V-shaped monohull designs and are generally operated 24/7 365 delivering pilots to vessels at anchorage, terminals, and pilot station boats. They are powered by large twin main engines of 800-1000 hp each to reach speeds of 20+ knots while maintaining high maneuverability and stability. The frequency and duration of routes varies dramatically depending on location with some needing short trips and others requiring substantial time at sea. Figure 9 illustrates an example pilot run boat.

Figure 9: P/V Golden Gate, a Tier 4 Pilot Run Boat [13]

1.1.1.11 Pilot Station

Pilot station boats in CA are unique to the SF Bar Pilots Bay Area operation. An example is shown in Figure 10. Pilot station boats are similar in hull design to the run boats except they are larger at 104’ in length to accommodate six pilots living aboard for six-day shifts at their station point 11 nautical miles from San Francisco Bay. The vessels essentially function as floating hotels for SF Bar Pilots. SF Bar Pilots operate three station boats. One on-duty at the designated station point 24/7 365 days a year, and two spare vessels back in San Francisco.

Figure 10: P/V Drake, a Pilot Station Boat [14]

Crew/Supply

Crew/supply boats are used to transport offshore support personnel, deck cargo, and below-deck cargo to and from offshore installations including oil platforms, drilling rigs, wind farms dive ships, and others. An example is shown in Figure 11. Crew boats range significantly in size, including from 30’ to 200’ depending on purpose and location. They are often constructed of aluminum and can be used to transport between 50 and 100 passengers.

Figure 11: NRC Quest, an Offshore Crew/Supply Vessel [15]

Larger crew/supply boats are often over 150’ in length and typically have two or four powerful U.S. EPA category 1 main propulsion engines in the 2300-3300 hp range each. Utilizing twin-screw propulsion, they commonly operate with 10 knot transit speeds, although some faster vessels may operate with jet-drive propulsion for higher transit speeds up to 26 to 32 knots. In California such vessels are regularly used to service offshore drilling platforms and assist in towing and repositioning of drilling platforms. They are commonly available for charter and may perform a variety of specialized offshore maritime work, e.g., ocean towing, engineering project support, research project support, rocket recovery, offshore wind projects etc. The vessels often have a flat extended main deck, often with a large hydraulic crane for cargo or machinery handling.

Fishing

Fishing vessels consist of both commercial fishing and commercial passenger fishing vessels. Both vessels are designed for offshore fishing, and range in size from small commercial day fishing vessels to larger charter passenger fishing vessels that can accommodate dozens of people with overnight accommodations. Both vessels are still relatively small when compared to the typical high-speed ferries and are commonly constructed from wood or fiberglass.

1.1.1.12 Commercial Fishing

Figure 12 illustrates a commercial fishing vessel. These vessels may be under transit for several days while locating fish and the vessel will load with as much weight as safely as possible to operate profitably. Therefore, vessel stability and space constraints are an inherent design issue. Additionally, irregular operational patterns further complicate recharging or refueling infrastructure strategies, particularly for battery electric options. Most of the fuel consumption by fishing vessels is for vessel propulsion, but auxiliary loads requiring fuel also include onboard processing, freezing and refrigeration, and others.

Figure 12: Tarka II, A Commercial Fishing Vessel [16]

1.1.1.13 Commercial Passenger Fishing

Commercial passenger fishing vessels carry paying passengers out to sea to fish for durations ranging from half-day to full day trips to multi-day trips. An example if shown in Figure 13. Typically, single day and multi-day vessels carry dozens of passengers. Those referred to as “6-packs” are vessels that can carry up to six passengers in addition to two crew.

Figure 13: Western Pride, a Commercial Passenger Fishing Vessel [17]

Commercial passenger fishing vessels are subjected to the same constraints as commercial fishing vessels. Often, they will idle while warming up and loading passengers and equipment. Vessels then transit at high speed out to the open ocean to locate fishing grounds where they will troll at low speeds or maintain position.

Dredge

Dredge vessels are generally equipped with specialized machinery and tools for the purpose of excavating and removing sediment or other materials under bodies of water. An example is shown in Figure 14. Dredging is often used to maintain or deepen navigation channels, create new harbors, reclaim land, and address issues like erosion or environmental remediation. Common types of dredgers include cutter suction dredgers, trailing suction hopper dredgers, bucket dredgers, and suction dredgers. Larger dredgers are often used for long-term projects and may have crew accommodation including living quarters and dining facilities.

Figure 14: Conrad Industries Hopper Dredge [18]

Dredge vessels can be self-propelled or towed to work sites. Large dredgers may have multiple propulsion units for efficient operation and provide maneuverability in restricted spaces. Common equipment on dredge vessels includes large and powerful pumps, dragheads or dredge buckets, and cutterheads. Diesel engines are commonly used for both propulsion and to power dredging equipment including pumps. Additionally, some dredgers utilize electric propulsion systems that are powered by diesel generators due to increased fuel efficiency and equipment control benefits.

Excursion Vessel

Excursion vessels carry passengers and engage in recreational operations such as sightseeing, dinner cruises, ecotourism, diving, snorkel, etc. An example from Newport Harbor is shown in Figure 15. Excursion vessels can range in size from 20’ to 100’ and capacity depending on factors including design, purpose, and regulations imposed by maritime authorities. Most excursion trips are 60 or 90 minutes. Excursion vessels transit at ~10 knots and are typically powered by main propulsion engines in the 400-500hp range.

Figure 15: The Wild Goose, an Excursion Vessel [19]

Work Boat

Within the context of Commercial Harbor Craft, workboats are defined as a vessel that pushes, pulls, or hauls alongside within a worksite such as shipyards, owner's yards, or lay-down areas used by marine construction projects. The workboat sector encompasses a wide variety of CHC tasked with supporting various maritime construction or infrastructure development projects. Vessel hull designs vary from mono-hull to low draft vessels resembling self-propelled barges. An example of a small workboat is shown in Figure 16.

Figure 16: A Workboat Tasked with Oil Spill Response [20]

Multi-purpose workboats consist of vessels capable of doing light towing/pushing to move construction barges, transporting equipment and small numbers of passengers out to equipment working on barges, and waiting on standby to assist during construction projects. Lacking specialized vessel designs to accommodate deck equipment other than a material-handling boom, these vessels can switch between general use workboat vocations quickly and easily. However, some workboats are highly specialized such as fireboats that utilize additional pumps, valves, and water monitors with additional propulsion systems to counter thrust from the water monitors.

Research Vessel

Research vessels are designed to operate along the coast, or in the open ocean while carrying passengers, scientists, and scientific equipment. They greatly vary in size depending on their class with Ocean class vessels typically being larger (see Figure 17) and coastal class vessels being smaller. Both ocean and coastal class research vessels typically have an open deck in the rear of the vessel with an A-frame crane that is used to launch submersibles or deploy/recover buoys.

Figure 17: R/V Sally Ride, an Ocean Class Research Vessel

Introduction to Alternative Fuels

Alternative marine fuels for commercial harbor craft are gaining increased attention as the maritime industry seeks to reduce its environmental footprint and comply with stringent emissions regulations. This section provides a brief introduction to several potential alternative marine fuels, including liquefied natural gas (LNG), electricity, alcohols (e.g., ethanol, methanol, butanol), dimethyl ether (DME), ammonia, biodiesel, and hydrogen, highlighting their potential as cleaner options for powering vessels[1],[20],[21],[22],[23]. Electricity is really the focus of the ZEAT sections of this report, but it is briefly discussed here relative to comparison with the other options that have potential for use in combustion engines (or fuel cells). Other possible alternatives may evolve in time. In terms of options being looked at by vessel designers may not include all of these which may be germane to near term practicality of these fuels. For example, Elliot Bay Design Group discusses Hydrogen, methane, Ammonia, Methanol, Ethanol, and Biodiesel (or renewable diesel) [24] as possible alternative fuels for fishing vessels. It is noted that fuels like ethanol, methanol, ammonia, and other small molecule alternative fuels don't form appreciable soot, even when burned in a non-premixed manner (like diesel engines) which means such engine can potentially meet soot regulations without a diesel particulate filter [25]. Current engine OEMs that are working with these fuels often have a requirement that some diesel be injected ("pilot fuel") with the alternative fuel to facilitate combustion. In such cases, the particulate is associated with the amount of pilot fuel used. Other views have suggested methanol and methane are earlier leaders but that no fuel will dominate by 2030 [26]. In the following sections, a number of potential alternative fuels are described in an introductory manner. Brief reference is made to example vessels in some cases, but the results under the Tier 4 and Zero-emissions sections will go into more detail.

Renewable Diesel

An attractive low carbon option to diesel derived from fossil sources (i.e, DF-2) is renewable diesel [27]. Renewable diesel is a synthetic fuel derived from non-petroleum renewable feedstocks such as vegetable oils, fats, greases or algae. Renewable diesel is essentially a "drop-in replacement" for conventional fossil derived diesel and must meet the requirements of ASTM D975-21—Standard Specification for Diesel Fuel. The benefit of using "simple" fats from vegetables, animals, or plants is that the resulting renewable diesel is inherently low sulfur (vs conventional diesel where crude oil contains sulfur) and low in aromatic content (know soot precursors). Hence it has a lower carbon intensity compared to conventional fossil derived diesel and a lower propensity for producing fine particulate. However, it still produces NOx because of the combustion process and, while particulate and smoke are significantly reduced, they are still produced to some extent during combustion. These attractive features and interchangeability with regular diesel have resulted in California requiring use of renewable diesel for commercial harbor craft since January 1, 2023 [28]. Renewable diesel can also be blended with fossil derived diesel with the designation RXX, where XX indicates the percentage by volume of renewable diesel in the blend (e.g., R99 means the fuel contains 99% renewable diesel and 1% fossil derived diesel). A challenge with renewable diesel is cost of production, limited supply and, in some cases stock that meets US Coast Guard 140 deg F flashpoint regulations [27], [29].

Renewable diesel is *not to be confused* with "biodiesel". Biodiesel is chemically much different from renewable diesel. Biodiesel is essentially a collection of several long chain molecules (methyl esters) which are created from the transesterification of the feedstock fats which is often accomplished with an alcohol in the presence of a catalyst. Biodiesel needs to comply with ASTM-6751. While the fat feedstocks for synthesizing biodiesel can be the same as those used for renewable diesel, renewable diesel requires additional hydrotreating of the fuel to attain compliance with ASTM D975-21. Biodiesel can be blended with fossil derived diesel and uses the designation BXX, where XX is the percent by volume of the biodiesel in the blend (e.g., B20 indicates 20% biodiesel in the blend). Biodiesel poses several challenges for fuel and combustion systems due to significantly differing physical properties (e.g., viscosity and vapor pressure). Biodiesel may result in higher NOx emissions compared to renewable diesel.

Liquid Natural Gas (LNG)

LNG is essentially natural gas (which is mainly methane, CH_4, but includes some varying amounts of higher hydrocarbons like ethane, propane, and butane) that has been cryogenically condensed to below -260 deg F to reach a liquid state. By liquefying the gas, the volume required to store the fuel is reduced by a factor of 600. LNG is regularly transported by tankers across oceans and the increased energy content of the liquid state makes movement of the commodity more cost effective than that of pressurized gas owing to the higher energy density in liquid state. The original source of the natural gas could be derived from renewable means (e.g., biogas), but even as a fossil derived fuel, LNG has about a 30% reduction in CO_2 compared to oil derived diesel fuel. The cost of renewable LNG is roughly 3.5x that of fossil derived LNG.[24] LNG can be used in existing heat engine technologies and has been widely used in ground-based transportation fleets (e.g., buses, refuse collection, taxis, etc.). As a result, engine technology is readily available, but not necessarily Tier 4 compliant. According to DNV Alternative Fuel Insight platform [30], as of 2023, some 469 LNG fueled vessels are in operation worldwide since 2003. Less than 5% are in North America and none seem to operate in California. The majority of these are ocean going vessels, though examples of large ferries (e.g. *Francisco*, *F.A. Gauthier*,) are evident and tugs are also starting to appear (e.g., *Haisea Kermode*). The AFI platform also indicates that Norway has several fishing vessels in operation that operate on LNG. Engines are made by MAN, Wartsila and others. Some offer “dual fuel” engines which have been designed to operate on either diesel or LNG which provides flexibility. The space needed by two separate fuel tank systems does pose a challenge.

As with other hydrocarbon fuels, combustion of LNG results in pollutant emissions. However, sulfur and particulate emissions are lower than diesel (either fossil or renewably derived) due to the use of the chemically less complex methane (e.g., Section 3.1.2). That said, marine engines typically utilize compression ignition and often some diesel fuel is co-injected to ensure successful ignition of the mixture which offsets some of the PM emission benefits. Combustion of LNG may also result in methane slip (i.e., unburned methane) On-road vehicles have demonstrated the potential for ultra-low NOx emissions. At this point, no examples of Tier 4 compliant LNG maritime engines have been identified. Further, it seems existing US regulations do not specifically address the design and installation of natural gas fuel systems on commercial vessels[20].

Electricity

Electricity as a fuel can essentially be thought of as battery driven. This is one basis of zero emission technologies in that literally no emissions of pollutants or gases are emitted from a battery driven motor. General arguments against batteries include the space requirement on the vessel, the weight, limited energy density, and recharging times. None-the-less, batteries can make sense for certain duty cycle scenarios. Charging times do limit the utilization factor of such vessels. Infrastructure is also a limitation. Lithium-ion batteries are the primary battery type suitable for marine energy systems with various chemistries currently commercially available [31]. Of these, lithium nickel manganese cobalt oxide (NMC) appears to be the most feasible for ship design due to a balance of cost, lifetime, specific energy and power, safety, and thermal performance. Specifically, NMC batteries provide high specific energy and energy density, which is important given the limited space on vessels, while being able to satisfy high power application such as thruster power peaks during maneuvering. Several companies are working on containerized battery systems suitable for marine applications including Asea Brown Boveri, EST-Floattech, and Fleetzero.

Vessels traversing on shorter, fixed routes, such as ferries and tugboats are optimal for battery electric operation as battery packs can fully power vessels during shorter trips and simplify charging infrastructure needs and deployment. Conversely, vessels operating over long distances faces challenges with time under power and the ability to recharge due to battery energy limitations. A major barrier to battery electric vessels is the current lack of charging infrastructure at most locations and dockside charging facilities will be required to support commercial adoption of these vessels.

Many examples of electricity-based vessels are now available. DNV AFI estimates that 879 vessels are currently in operation [30]. But of these more than 94% are located outside of the United States. The results do indicate that in the harbor craft arena, several tugs, pleasure vessels, fishing vessels, and ferries are in operation and therefore the feasibility of the use of electricity (i.e., batteries) is viable. As discussed in the zero emissions section, demonstration projects are coming along. Crowley Maritime Corp recently delivered the 82' *eWolf* tugboat that will displace 30,000 gallons of diesel each year and is slated for service in Port of San Diego in spring of 2024. More discussion regarding electricity in context of ZEAT is included in Section 5 below.

Ethanol

Ethanol (C_2H_6O) is oxygenated ethane. Because of the presence of oxygen in the fuel, the air required to burn ethanol is less than it is for non-oxygenated (i.e., typical hydrocarbon) fuels. Generally, this means less air is moved through the device for a given fuel energy content which implies potential reduction in parasitic power load. However, the energy density is lower than diesel which increases on-board fuel storage volume or a reduction in range. Ethanol can be a renewable fuel if produced from organic materials such as crops (e.g., corn) and organic waste (e.g., corn stover) material. Organic material is carbon-neutral because its formation removes carbon from the atmosphere. Ethanol is readily stored in liquid form at ambient conditions which means typical tankage can be used. DNV AFI does not maintain a list of ethanol fueled vessels. It appears that no Tier 4 engines are certified for operation on ethanol. That said, numerous spark-ignited gasoline engine types have been adapted to operate using ethanol.

Methanol

Methanol is another alcohol-based fuel that can be readily synthesized from various sources. Methanol has a similar molecular structure as methane (CH_3OH for methanol vs CH_4 for methane). An advantage of methanol is that it is in the liquid state at ambient conditions which facilitates convenient tank storage (compared to high pressure gas storage or cryogenic storage for hydrogen or LNG). That said, methanol may have incompatibility with seals that are generally used in diesel or other hydrocarbon fuels [32]. Hence, gaskets and other soft materials (e.g., fuel lines, o-rings) may need to be evaluated for possible change out. Finally, methanol is toxic to aquatic life and humans. Inhalation of vapors, ingestion, and/or contact of the liquid with skin can cause blindness and death. It seems there are 29 methanol fueled vessels are in operation [30]. Of these, relevant to commercial harbor craft, single examples of a ferry and a tug are indicated, though neither is in the US. The IMO database suggests 10 projects are underway involving harbor craft with 3 tugboats and the rest as support vessels. It appears that no Tier 4 engines are certified for operation on methanol.

Hydrogen

Hydrogen can be used as a fuel both through combustion in reciprocating engines or turbines, and through electrochemical conversion in fuel cells. In either case, there are no CO2, CO, sulfur, or particulate emissions produced directly by use of hydrogen. Fuel cells are also ~zero NOx devices while hydrogen combustion requires NOx mitigation via fuel-air management and aftertreatment using techniques and technologies like those used in natural gas combustion systems. Currently hydrogen is made primarily from fossil fuel (reformation of methane which produces approximately 1 molecule of carbon dioxide for every 4 molecule of hydrogen), but can be produced renewably by using renewable electricity via electrolyzers and also from various conversion processes associated with renewable biological feedstocks [33]. There is no bunkering infrastructure currently available in California, but development of hydrogen fueling infrastructure for vehicle applications is ongoing and additional infrastructure, including at ports, is planned for the California DoE Hydrogen Hub. In the near term, it may be possible hydrogen blended into natural gas and delivered via existing natural gas networks may gain some utilization. OEMs have been working on engine technology to accommodate such blends[34] [35]

Hydrogen can also be produced on board from another alternative fuel to take advantage of the other fuel's potentially higher energy density. An example is the use of methanol as the stored fuel and then use of a hydrogen generator to produce hydrogen which can then be used to produce useful work (via an engine or fuel cell). RIX Industries [36] offers a system to convert methanol into hydrogen capable of fueling fuel cells in the 100 kW to multi megawatt (MW) range. The hydrogen produced could also be used to power ICE engines as well, though if these engines could handle methanol directly it would likely be preferred. This is also being planned for *M/V Hydrogen 1*, a hydrogen powered towboat, which is being developed by Elliott Bay Design Group and Maritime Partners and will use e1 marine methanol reformers. This vessel is expected to be IMO 2030 compliant regarding emissions (i.e., 40% reduction in GHG emissions in 2008 by 2030). Notable is the inclusion of a 150kW diesel engine and use of Lithium-Ion batteries in addition to the PowerCell Marine System 200 fuel cell which clearly increases capital cost and reduces space available on board. But the use of methanol instead of hydrogen allows much more convenient storage of the energy carrier.

Similarly, hydrogen can also be produced from ammonia which, like methanol, can be stored with high energy density and then cracked to produce hydrogen for use on board. One example in the R&D stage is the GenCell FOX hydrogen generator [37] which converts liquid ammonia into hydrogen.

It appears that no Tier 4 engines are certified for operation on hydrogen, though several OEMs are working on this technology as it may also serve other heavy duty transportation sectors. BeHydro offers hydrogen specific engines (1,360 to 3630 HP or 1-2.6MW) that are dual fuel and EU Stage V compliant. These engines use port fuel injection for hydrogen and diesel pilot injection for operation on 85% hydrogen using compression ignition (i.e., diesel cycle). Like LNG, the diesel pilot may offset some emission benefit. The monofuel option for 100% hydrogen (e.g., DZ H2) is spark ignited.

According to DNV AFI, 3 vessels are in operation that are using hydrogen reciprocating engines [30]. One is a tug (*Hydrotug1*) which operates using two 2MW V12 dual fuel (hydrogen or diesel) BeHydro medium speed engines with DU Stage V aftertreatment (SCR + DPF). Further, DNV indicates one ferry (*MF Hydra*) is operational using a fuel cell power train in Norway. Capable of operating on 4 tons of liquid hydrogen, the 80 car ferry also has a 1.45 MWh battery and two 440 kW diesel generators that allow fuel flexibility. Initial hydrogen supply is trucked from Leipzig, Germany. The IMO NextGen database indicates 44 projects are underway [38]. Of these, about 25 are germane to commercial harbor craft. Of these, nine (9) are using hydrogen reciprocating engines and the rest are fuel cells. Growth in this market appears to be increasing.

Ammonia

Ammonia (NH_3) is receiving increased interest as a fuel due to its energy density and potential for reducing carbon emissions. Current ammonia production, like hydrogen, is from fossil sources, although production from renewable feed stocks is possible. While it is a carbon free carrier, its features relative to combustion, like hydrogen, are dramatically different from natural gas or diesel requiring new engine designs as illustrated in Table 2. According to DNV AFI, no ammonia vessels are currently in operation though it is noted that 11 are on order. This includes at least one tugboat (Sakigake retrofit of a LNG platform, *A-Tug*) that is slated for delivery in 2024 and operation in Tokyo Bay. The IMO NextGen project database indicates 51 projects are underway (conceptual, feasibility, or demonstration) using internal combustion engines. Of these, 10 are relevant to harbor craft with 5 being tugboats. The majority of these are dual fuel engines implying the ability to use ammonia or diesel fuel, but 3 fuel cell projects are also listed. Ammonia is widely used in agriculture and in refrigeration systems. As a result, infrastructure for its handling and movement is widely in place, though not necessarily for bunkering at this point. The ability to store and utilize ammonia may be limited due to toxicity. The OSHA AEC Hazard Classification for acute toxicity for ammonia is the same as that for diesel [39]. And diesel is considered a greater hazard to aquatic life than ammonia is. Extensive safety guidelines are in place associated with storage and transportation of ammonia. California, in particular, has additional safety guidelines that must be adhered to relative to storage and use of ammonia [40] including specialized response requirements when more than 450 lbs. are stored in one control zone.

It appears that no Tier 4 engines are currently certified for operation on ammonia The dual fuel developments underway generally feature a pilot injection of diesel to facilitate ignition in reciprocating engines.

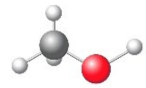
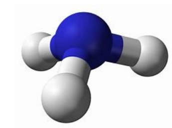
Summary

In summary, while numerous potential alternative fuels to fossil derived diesel exist, each has a combination of advantages and drawbacks as expected. Numerous examples of commercial harbor craft with some operation on these fuels are available. Some summary information is shown below.

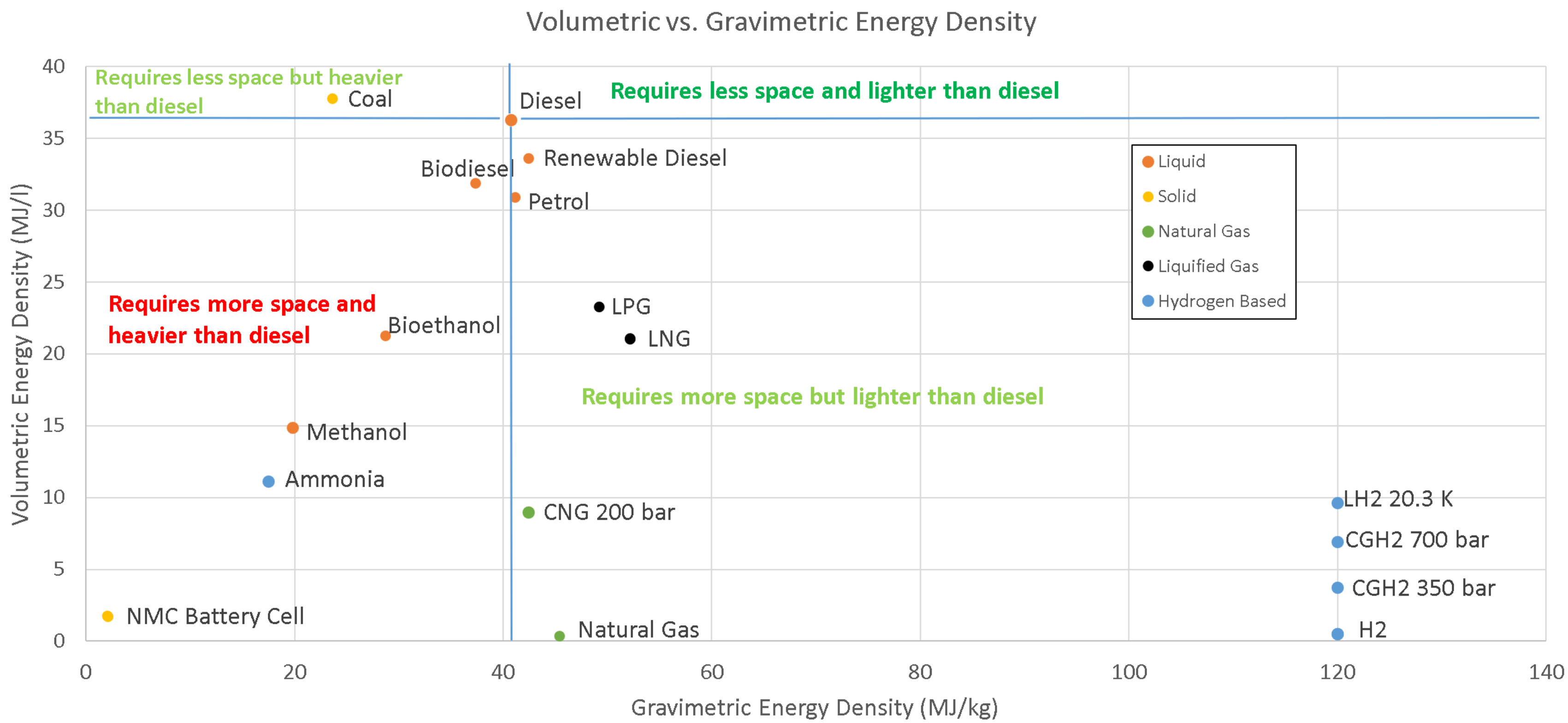
Table 2 compiles some key properties of diesel, methane, methanol (representing a typical alcohol including ethanol and n-butanol), hydrogen, and ammonia. As shown, the various properties vary over a significant range. For this reason, combustion systems employing the fuels must be designed for each specific fuel. The growing global interest in these fuels is driven by the potential to develop zero or low-carbon pathways for producing them. However, each of these fuels produces non-carbon pollutants when they are combusted, and their differing characteristics require different technical approaches to pollution control. Methane has properties that are most like diesel in terms of heating values and combustion properties while alcohols, hydrogen and ammonia have significantly different properties. As a result, if engines are being considered, tailoring of the fuel air mixture and accounting for differing amounts of air needed for complete combustion is required. The temperatures of combustion also vary, and so, for low NOx performance, further tailoring is needed. Generally, combustion of any of these fuels will result in some NOx formation. Ammonia, with the fuel bound nitrogen, will generally result in higher levels of NOx compared to the other fuels. This will be taken care of with after-treatment generally involving selective catalytic reduction (SCR). One attribute of the fuels besides diesel is that the propensity for soot formation is greatly reduced. While methane and methanol can potentially soot, the conditions are extreme. Hydrogen and ammonia do not have sooting tendencies.

Figure 18 summarizes the relative energy densities (both volumetric and gravimetric) of these fuels. As shown, diesel (and diesel like) fuels have a remarkably high energy density from both a volumetric and gravimetric view. Figure 18a illustrates these features based only the properties of the fuels themselves. Essentially, all the alternative options are less energy dense on both a mass and volume basis and require both more space and more weight budget than diesel. Gaseous fuels like natural gas and hydrogen can be liquified to gain substantial improvements in volumetric energy density but this comes at a cost and, even in liquefied form, these fuels are less energy dense than hydrocarbon fuels, alcohols, or ammonia. Figure 18b presents the same type of information but also includes the energy penalties associated with storing the fuels. For example, the net energy density of the cryogenically stored fuels drops significantly when the storage infrastructure is included in the volume budget. It is also worthy of note that adoption of gaseous fuel for vessel applications will require deployment of new bunkering infrastructure with very limited re-use of existing infrastructure. Some Infrastructure details are discussed in Section 5.

Table 2: Representative Properties of diesel, methane, methanol, hydrogen, and ammonia

		Diesel Fuel				
Formula		C8-C25	CH_4	C_3HOH	H_2	NH_3
Molar Mass	Gm/mol	~200	16	32	2	17
Boiling Point	Deg-C	210-235	-161	64.7	-253	-33
Heating Value	BTU/scf		915		275	365
Heating Value	MJ/kg	45.6	50	22.9	120	18.6
Flammability Limits (STD)	%	0.6-7.5	5-15	6-36	4-75	16-25
Flammability Limits	Equivalence Ratio		0.5-1.7	0.55-4.32	0.1-7.1	0.63-1.4
Adiabatic Flame Temperature AFT (STD conditions, stoic)	Kelvins	2366	2223	2143	2320	2073
Flame Speed, max	cm/s	80--85	30-40	50-60	200-300	6-7
Min Autoignition Temp	Deg K	483	903	738	844	924
Research Octane Number (RON)	Isooctane = 100	25-40	120	109	63	130
Flame Appearance		Orange/blue	Bluish	Blue/violet	Clear	Whiteish/yellow

a) Fuels Alone



b) Consideration for Storage/Compression

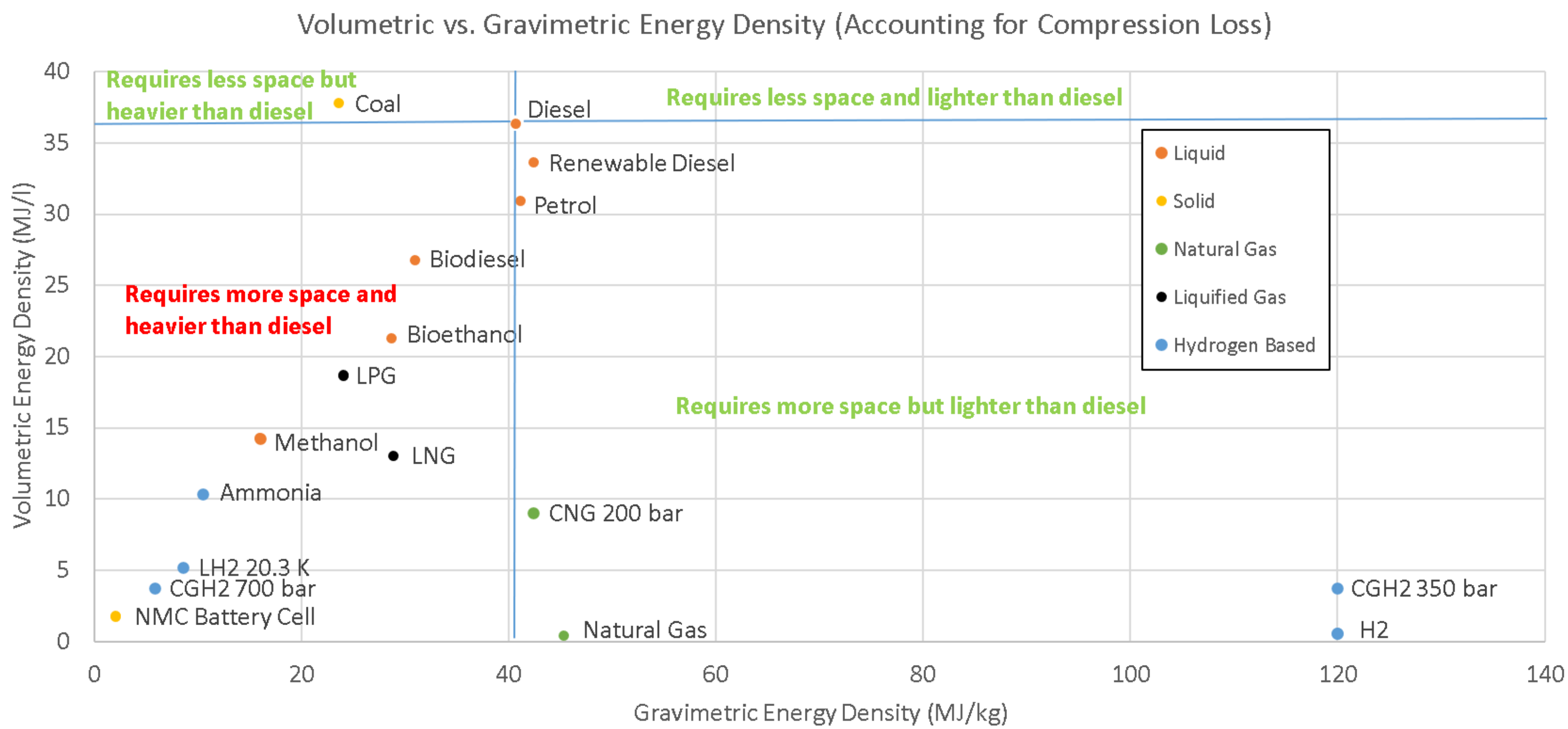


Figure 18: Energy Densities for various energy carriers. Arrows shown reflect accounting for storage systems. Adapted from [21].

Table 3 summarizes the relative merits of the possible alternative fuels in a color-coded manner compared to low sulfur diesel and HFO. From perspective of the California marketplace, stringent emissions requirements around greenhouse gases as well as pollutant emissions would seem to place focus on low carbon fuels and use of those in very low pollutant emissions technology (e.g., Tier 4 engines, zero-emissions). As a result, focus will continue to be on renewably derived fuels (vs fossil derived). As shown in Table 3, for the low carbon intensity options (bio/renewable diesel, ammonia, hydrogen, electricity), each option has several drawbacks compared to diesel. Common drawbacks include lack of bunkering for these alternatives which means infrastructure is needed for these options to succeed. Further, the technical maturity of the ammonia, hydrogen, and electricity is limited. This implies that bunkering choices may be technically and financially risky depending on which approach might be adopted since development of multiple bunkering infrastructure is not cost effective. In most cases, the cost is estimated to be high. Electricity seems to be gaining a foothold but involves considerations for local utility infrastructure and charging standards.

Table 3: Relative Merits of alternative fuels compared to baseline diesel. Adapted from [21].

Energy Source:	Fossil (without CCS)					Renewable				
Fuel:	HFO + Scrubber	Low Sulphur Fuels	LNG*	Methanol*	LPG*	Renewable Diesel**	Biodiesel***	Ammonia	Hydrogen	Fully-electric
High Priority Parameters	**Baseline**									
Energy Density										
Technological Maturity										
Local Emissions										
GHG Emissions										
Energy Cost										Varies Regionally
Capital Cost - Converter										
Capital Cost - Storage										
Bunkering availibility										
Commercial Readiness										Case by Case
Other Key parameters										
Flammability										
Toxicity										
Regulations and guidelines										
Global production capacity and locations										

Attributes Relative to Baseline Fuels

Positive		Neutral		Negative

*Potential to be produced renewably (only fossil included here)

**Meets ASTM D975-21: Standard Specification for Diesel Fuel

***Does not meet ASTM 975-21, but meets ASTM-6751

Materials and Methods

The current assessment relies on secondary research to provide the information base for the analysis. The primary research element is the compilation, interpretation, and extrapolation of information compiled through secondary research. The primary information sources were published reports and research papers, materials provided by CARB from prior efforts relevant to this topic area, and discussions with various organizations and individuals familiar with commercial harbor craft. Harbor craft are diverse in mission and general power requirements which makes generalization challenging. The main objective is to assess the feasibility of implementing advanced engine technology (e.g., Tier 4 engines and associated after treatment systems), near-zero emissions technology (e.g., engine-battery hybrid systems), and zero emissions systems (e.g., fuel cells, batteries).

Currently Available Engine Technology

In this section a discussion regarding what technology is currently available is provided. This section is primarily dedicated to combustion engine technologies including engines and aftertreatment. It is evident that a majority of zero emission technologies are not "commercial". These technologies are discussed in detail in Section 5 below.

Technology Description

Marine Engine Emission Standards

In comparison to Tier 3 emission standards, Tier 4 standards require significant reductions in particulate matter (PM), NOx, and hydrocarbon (HC) emissions for engines with a power output greater than 600kW. For PM emissions, Tier 4 standards require a 63% decrease in comparison to Tier 3 for engines typically used in harbor craft. (Category 1, kW/L<35, kW>600) [41]. Regarding NOx and HC emissions, Tier 4 standards require a 64% decrease in comparison to Tier 3 for engines typically used in harbor craft. These required decreases are illustrated in Figure 19 and Figure 20 [42].

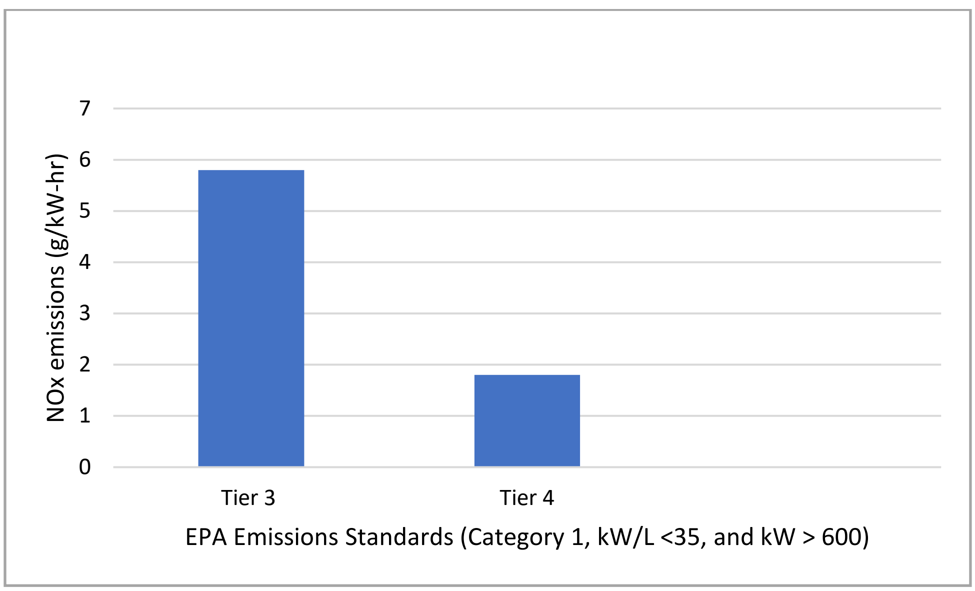


Figure 19: Comparison between Tier 3 and Tier 4 NOx Emissions Standards

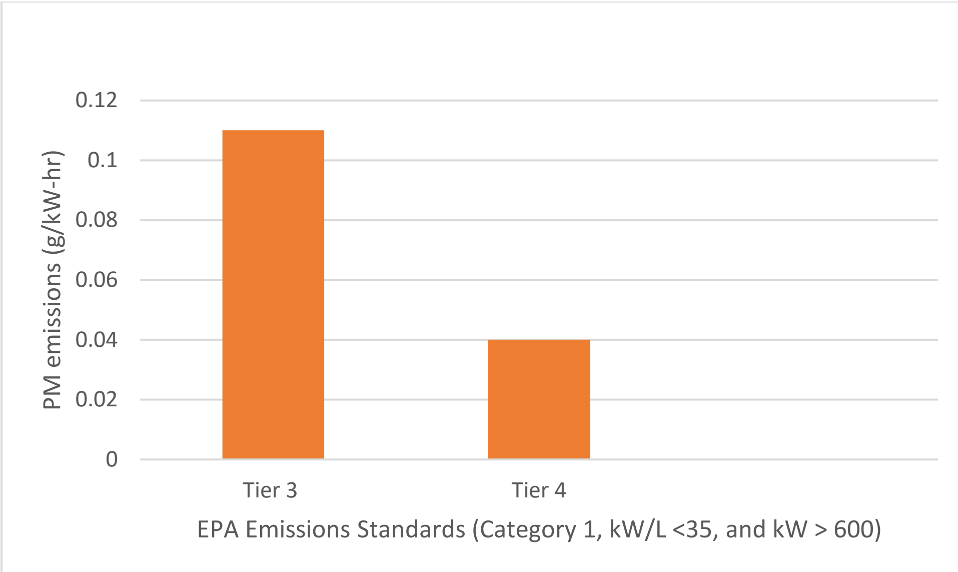
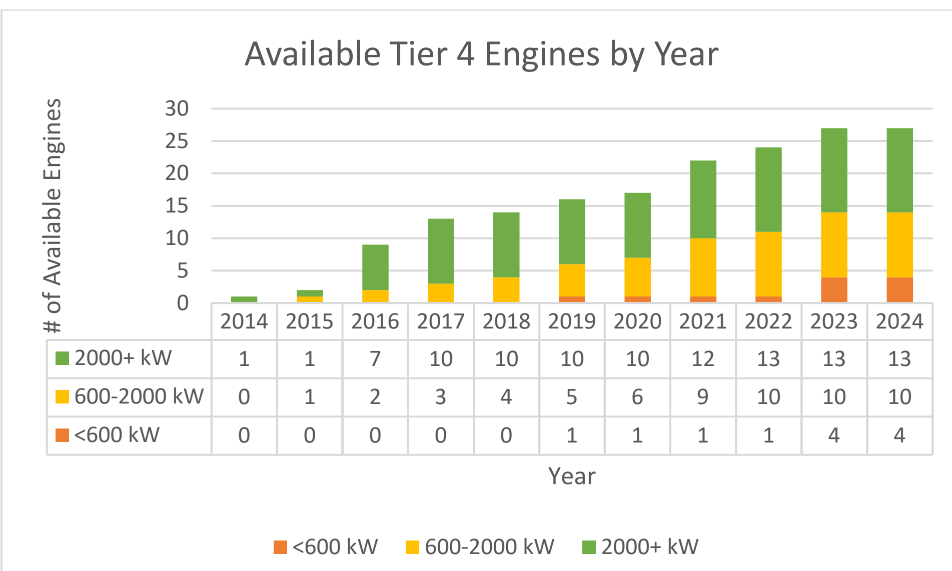


Figure 20: Comparison between Tier 3 and Tier 4 PM Emissions Standards

Tier 4 engines are produced by a variety of manufacturers, and their designs are roughly similar. All current Tier 4 marine diesel engines are forced induction compression-ignition 4-stroke engines (except for the 2-stroke EMD 710 Series). Tier 4 engines are available across a range of outputs. There are fewer engine options available at lower power outputs (<600 kW). This is important for the harbor craft sector, as the power required varies greatly between vessel types. Vessels such as fishing and workboats require less powerful engines, and are more space constrained when compared to, for example, a large escort tug. As a result, the ability to repower these less powerful vessels (<600 kW) with Tier 4 engines has been an ongoing concern. Figure 21 shows the number of commercially available Tier 4 engine models from 2014 through 2024 [43].



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
2000+ kW	1	1	7	10	10	10	10	12	13	13	13
600-2000 kW	0	1	2	3	4	5	6	9	10	10	10
<600 kW	0	0	0	0	0	1	1	1	1	4	4

Figure 21: Available Tier 4 Engines by Year.

Marine engines are divided into three size categories. Category 1 engines are derivatives of land-based engines with a displacement per cylinder of less than 7 liters. These engines represent the smallest engine-size group and are primarily used in small, fast, maneuverable vessels that operate at variable duty cycles. Category 2 engines are derivatives of locomotive engines with a displacement per cylinder between 7 L and 30 L. These engines are typically much larger and heavier than Category 1 engines and are used in larger vessels at near continuous duty cycles. Category 3 engines have unique marine designs and are primarily used aboard ocean-going vessels but are also found on some larger harbor craft vessels (e.g., ATBs and dredges). They have a displacement per cylinder greater than 30 L. Commercially available Tier 4 engines include both Category 1 and 2 engines, but no Category 3 engines.

In addition to Tier 4, several other emission standards are used across the world and include EU Stage V, and International Maritime Organization (IMO) III. EU Stage V emission standards share HC requirements with Tier 4, with additional reductions in NOx, CO and PM emissions. IMO III regulates NOx emissions only, with limits based on engine speed specified in RPM. For an engine operating at 1800 RPM, the IMO limit is slightly higher than EPA Tier 4 and EU Stage V. A comparisons of the three standards is shown in Table 4.

Table 4: Comparison between Emissions Standards

Pollutant	CARB Tier 4+DPF (Category 1/2 Engines) (<1400kW) [44]	EPA Tier 4 (Category 1/2 Engines) (600-1400 kW) [41]	IMO III (@1800 RPM) [45]	EU Stage V (IWP-v-5 IWP-c-4) (>1000 kW) [46]
NOx (g/kWh)	1.8	1.8	2.01	0.4
HC (g/kWh)	0.19	0.19	N/A	0.19
PM (g/kWh)	0.0067	0.04	N/A	0.01
PN (#/kWh)	N/A	N/A	N/A	$1x10^{12}$
CO (g/kWh)	5	5	N/A	3.5

It should be noted that although the measurement levels between different emissions standards use the same units, they may be obtained through different means of measurement. This means that there is the possibility of differences in measurements that may arise due to the testing methodology for the certifications of different standards. One example of different measurement methods between Tier 4 and Stage V is that Tier 4 uses PM measurements on a mass basis, while Stage V uses both PM mass and particle number measurements.

CARB's Commercial Harbor Craft rule utilizes the Tier 4 NOx, HC, and CO emission levels, however, it imposes additional Performance Standards that require further reduction in PM levels compared to EPA Tier 4. Required PM reductions are from 0.03 g/bhp-hr (0.04 g/kWh) to 0.005 g/bhp-hr (0.0067 g/kWh) or 0.03 g/bhp-hr (0.04 g/kWh) depending on the engine's displacement, Category,category, and power output [44]. Additionally, these standards must be met with a CARD verified DPF or and engine OEM-integrated U.S. EPA certified engine, unless an exception is granted by the E.O.

The rule is applicable for both main and auxiliary engines, and the compliance dates are based on engine model year and vessel type. This information is shown in Table 5.

Table 5: CARB's Commercial Harbor Craft Rule Compliance Dates [44]

Compliance Dates for Any Pre-Tier 1 and Tier 1 Certified Engines on All Regulated In-Use Vessels		Compliance Dates for Tier 2, Tier 3, or Tier 4 Engines on Ferries (Except Short-Run Ferries), Pilot Vessels, All Tug/Towboats, and Push Boats		Compliance Dates for Tier 2, Tier 3, or Tier 4 Engines on Research Vessels, Commercial Passenger Fishing Vessels, and In-Use Excursion Vessels		Compliance Dates for Tier 2, Tier 3, or Tier 4 Engines on Research Vessels, Commercial Passenger Fishing Vessels, and In-Use Excursion Vessels	
Engine Model Year	**Compliance Date**	**Engine Model Year and Vessel Category**	**Compliance Date**	**Engine Model Year**	**Compliance Date**	**Engine Model Year**	**Compliance Date**
1993 and earlier	December 31, 2023	2009 and earlier (Except Pilot Vessels)	December 31, 2024	2010 and earlier	December 31, 2026	2010 and earlier	December 31, 2026
1994-2001	December 31, 2024	2012 and Earlier Pilot Vessels	December 31, 2025	2011 - 2012	December 31, 2027	2011 - 2012	December 31, 2027
2002 and later	December 31, 2025	2010 - 2012 All Other Vessels	December 31, 2025	2013 - 2014	December 31, 2028	2013 - 2014	December 31, 2028
		2013 - 2015	December 31, 2026	2015 - 2017	December 31, 2029	2015 - 2017	December 31, 2029
		2016 - 2019	December 31, 2027	2018 and later	December 31, 2030	2018 and later	December 31, 2030
		2020 - 2021	December 31, 2028				
		2022 and later	December 31, 2029				

To achieve these levels of emissions required by CARB, and other emissions standards, engine manufacturers use several engineering strategies to reduce NOx, HC, CO, and PM emissions. These strategies fall into two categories: In-Engine, and “after treatment”.

In-Engine Strategies

In-Engine emissions control strategies employ physical engine design elements, such as fuel-air systems and engine control devices, to reduce emissions before any after treatment processes. In-Engine strategies are advantageous in the marine sector, as the modifications generally involve minimal changes in engine envelope envelop and weight compared to most after treatment strategies. Envelope is important, as large scale after treatment strategies may require several modifications to the vessel due to limited space in engine rooms. The In-Engine emission strategies can be incorporated in a new engine model with little change in size.

EGR, or Exhaust Gas Recirculation reduces NOx emissions by increasing the specific heat of the charge air in the cylinder which reduces the peak in-cylinder combustion temperatures [47]. This reduces the thermal NOx formation, allowing for lower total NOx emissions [48]. EGR is used worldwide in both gasoline and diesel engines, including marine diesel engines. Notably, engines by Wabtec, derived from GE locomotive diesel engines, use high levels of EGR to attain U.S. EPA Tier 4 marine NOx emissions levels without typical urea based selective catalytic reduction (SCR) after treatment systems [49][49].

High-Pressure Common Rail, or HPCR is an In-Engine emissions control system that allows for high pressure fuel injection, reduced droplet sizes, and improved fuel-air mixing at all engine speeds [50]. This also provides greater flexibility in fuel injection timing with multiple injections per stroke possible. This increased flexibility in fuel injection means that it can be precisely controlled in order to minimize NOx and PM emissions [51]. HPCR is used worldwide in passenger road vehicles and light trucks and is commonly used in marine engines to meet Tier 3 and Tier 4 emissions standards.

To decrease the PM emissions of diesel marine engines, special modifications to the geometry of the combustion cylinders can be made to improve efficiency and reduce emissions. Some modifications include increased displacement, multi bowl piston design, and raised injection pressures through improved piston designs. Together, these modifications can improve the mixing of the fuel air mixture in the cylinder, decreasing NOx and PM emissions [52]. These modifications can be found on both spark ignition as well as compression ignition engines, including Tier 4 marine engines.

Retarded Injection Timing is used to decrease the NOx emissions produced through combustion inside the cylinders. This is done by injecting fuel into the cylinders later in the compression stroke which results in lower peak temperatures and pressures [53]. This process decreases thermal NOx production, which lowers total NOx emissions [54]. A side effect of this process is an increase in PM emissions; however Retarded Injection Timing is used in conjunction with PM emission control methods such as geometric changes to the cylinders.

Turbocharging is a method of forced induction that utilizes the kinetic energy from hot exhaust gases to force cooled air into the intake of an engine. Turbochargers are used in a variety of applications from spark ignition to compression ignition engines, including marine engines [55]. The increased cooled air that enters the intake allows for increased power and efficiency. Turbochargers can be used in several configurations that include either a single turbocharger, or a sequential turbocharger. Sequential turbochargers are commonly used as they use a smaller turbocharger at lower engine speeds and a larger turbocharger at higher speeds in order to reduce turbo lag, or the lag in power that results from a turbo spooling up from rest [56]. Turbocharging is present on all Tier 4 certified engines.

When considering potential alternative fuels such as renewable diesel and biodiesel, engine modifications need to be made to circumvent extra wear on the engine components. This may include stronger metals as well as changes to the engine control unit (ECU). Engine modifications that allow for different fuels are used in both spark ignition as well as compression ignition engines, including those in the marine sector.

A summary of how these strategies help “navigate” engine operation around the pollutant formation regions is illustrated in Figure 22. As shown, by tailoring the combustion process using fuel air ratios to control temperature and stoichiometry, injection timing to tailor temperature rise, and exhaust gas recirculation, fuel rich medium temperature and stoichiometric high temperatures can be avoided avoiding during the combustion process. While this can help reduce emissions, engine controls generally cannot attain the most stringent emission regulations and are thus complemented with after treatment.

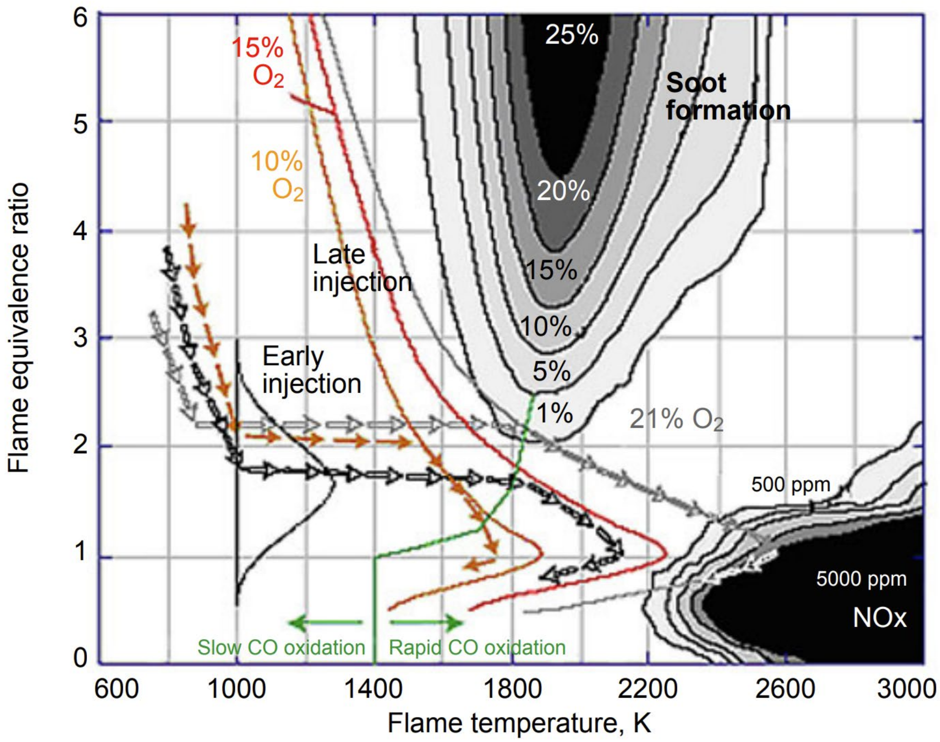


Figure 22: Summary of Combustion processes during diesel combustion using different EGR, injection timing, and fuel air ratio in context of critical soot and NOx formation regions [57].

Exhaust After Treatment Strategies

Exhaust after treatment emissions control strategies are processes that are used to treat the exhaust of engines to reduce certain kinds of emissions. This allows them to be retrofitted on older models of engines that may not pass modern emissions standards without them. They are used in marine engines, as well as passenger/commercial vehicles. Unlike in-engine emission reduction strategies, after treatment systems may have substantial impact on vessel layout, as they are often large in physical size.

Figure 23 presents a detailed schematic of possible exhaust aftertreatment components. The system is generally comprised of a system to reduce NOx which typically uses SCR and a separate system to reduce particulate (diesel particulate filter—DPF). For diesel engines, SCR systems involve the addition of ammonia to the exhaust gasses, such that NOx reacts with NH3 to produce N2 and water as it passes through a catalyst bed [58]. The products from this reaction may then pass through an ASC/AOC, or ammonia slip catalyst (ammonia oxidation catalyst) that oxidizes any excess ammonia that did not react with NOx. SCR technology results in a decrease in NOx emissions up to 90%.

Because ammonia is toxic, it is usually introduced via a urea solution which is also known as diesel exhaust fluid or DEF. DEF consists of approximately 32 percent urea and 68 percent deionized water. SCR systems thus require additional infrastructure to store DEF. The amount of DEF used per gallon of fuel varies between systems, however it is typically used at a rate of 3-5% % of fuel consumption. To be effective, the amount of urea used must match well with the amount of NOx present. SCR technology has been well established in stationary power generation applications [59], however due to increasingly strict emissions regulations such as Tier 4 marine, on-road heavy duty, and off-road standards, it has seen increased use in vehicles, such as heavy duty trucks, off-road equipment, and ships. Most Tier 4 certified engines meet the NOx levels required for Tier 4 by utilizing a form of SCR.

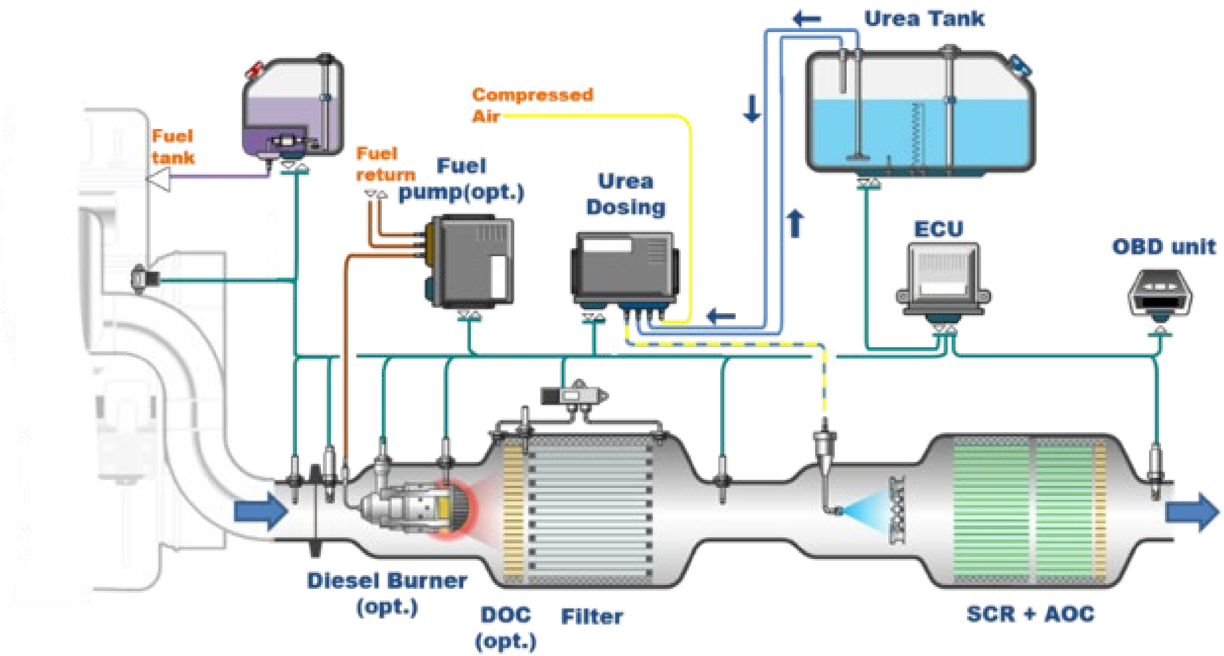


Figure 23: Illustration of possible exhaust aftertreatment components to reduce NOx and particulate from diesel engine combustion [60]. .

Due to the combustion characteristics of diesel fuels, they produce significantly higher concentrations of soot particles than gasoline engines and soot formation can be elevated in some duty cycles. Soot particles are pollutants that have been linked to several health problems. Because of this, diesel engines utilize Diesel Particulate Filters, or DPF's to minimize soot [61]. The performance of DPFs vary, however they typically remove over 85% of soot emissions. There are several different kinds of DPFs but they all work by forcing exhaust gases through a filter that physically traps large soot particles. The process is shown in Figure 24 [62]. The most common kinds of materials used in DPFs are Cordierite, Silicon carbide, and ceramic carbide. Over time, the DPF will require "regeneration," where the collected soot is burned off, therefore cleaning the filter. This can be done actively or passively. Passive regeneration occurs when the engine's exhaust temperatures reach the temperature required to oxidize the soot particles (above approximately 570 deg F). This is usually done with a catalyst which lowers the activation energy needed for oxidation. Active regeneration occurs when the temperatures required to burn the trapped soot are reached through outside assistance, including electric heaters, injection of fuel to combust ahead of the DPF, or other engine management methods. Active regeneration typically occurs at temperatures above 1000 deg F. Regeneration temperatures are typically limited to conserve power (in case of electrically heated) or fuel (in case of fuel combustion heated). That said, the amount of fuel needed to regenerate is about 1-3% of the fuel consumed for the engines. Because DPFs are used to treat exhaust, they can, in principle, be retrofitted onto older engines. DPFs are used in nearly all on-road diesel engines including those in trucking and construction. DPFs have been utilized in off-road engines since 1980 and in on-road trucks since 1987 and can now be found on recently marinized non-road Tier 4 engines. For the marine engine sector, DPFs are not widely used, and only appear on a few Tier 4 certified marine engines CARB's Commercial Harbor Craft Regulation requires vessels (except commercial fishing vessels) to meet performance standards using U.S. EPA-certified Tier 4 or Tier 3 engines with CARB-Verified Level 3 DPFs capable of removing 85% or more of diesel PM.. Because many engines in the harbor craft sector are typically larger and operate at lower engine speeds than their on-road counterparts they may require different regeneration cycles. As mentioned above, if the temperatures entering the DPF DPR are high enough (~570 deg F), passive regeneration will occur. When active regeneration does occur via combustion of injected fuel, higher exhaust temperatures will result for short periods of time which been anecdotally mentioned by some end users [63]. A US Department of Agriculture study from 2008 demonstrated that exhaust out temperatures of about 400 deg F during normal operation increased to about 700 deg F during regeneration [64].

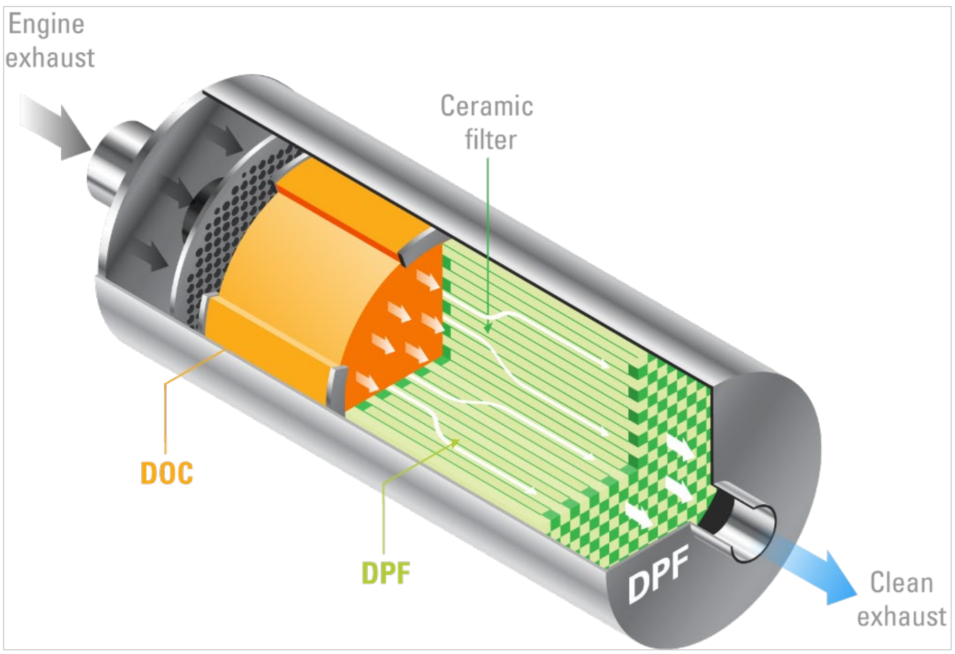


Figure 24: Diesel Particulate Filter (DPF) Schematic [62]

One challenge with advancement of after treatment technologies is the required step of joining the SCR system with a DPF. One option is to place the DPF upstream from the SCR, as shown in Figure 23. This is attractive (and typical) as the temperatures will be higher, leading to more passive regeneration time. However, since many installed Tier 4 systems currently only have an SCR, a need to separate the engine from the SCR is required to place the DPF upstream of the SCR. This may lead to retrofit challenges. Another option is to simply place the DPF after the SCR system, like the methods used in the Ford Powerstroke diesel engines [65]. The amended CHC regulation essentially requires installation of a DPF, which means that these positioning challenges must be overcome for a vessel with SCR to achieve compliance. Placement of the DPR downstream of the SCR is likely preferred in general for retrofit.

DPFs and CARB Certification

As of July 2024, there is one commercially available "stand alone" DPF verified by CARB for use in marine harbor craft. This DPF is created by Rypos Inc. and was certified as Level 2 Plus compliant, meaning that it reduces PM by 50% percent or more [66]. The DPF is indicated to be appropriate for engines in the 50-

900 bkW range. This DPF utilizes active regeneration, meaning that it requires heat input to regenerate [67]. The energy that is used to regenerate the Rypos DPF is provided electrically and is sourced from auxiliary engines. These DPFs consist of an electrically conductive sintered metal fiber medium that when powered electrically, burns built up soot, regenerating the DPF. Rypos' marine DPFs are designed for use in marine engines between 50 kW and 900kW. In addition to their certified DPF solution, Rypos offers custom DPF solutions that can be used for specialty applications where an off the shelf design wouldn't fit. Space constraints are very common issues that need to be addressed when installing marine DPFs.

Other companies (e.g., Nett Technologies) are pursuing certification (see Section 4.2.2), but DPFs are generally manufacturer certified to work with a particular engine. In this case the end user can rely upon the manufacturer to ensure the DPF performs reliably.

In Use Marine Engines that meet Tier 4 Standards <600 kW

M&H Engines in the UK has developed a line of marinized John Deere engines under 600 kW that meet Tier 4 emissions standards, as well as the stricter EU Stage V emissions standards [68]. These engines are smaller than most recent commercially available Tier 4 certified engines, meaning they may fit inside vessels with small engine rooms such as fishing vessels and workboats. Their lower power outputs would also allow them to replace the engines in these less powerful vessels. Additionally, these engines utilize DPF's, allowing them to comply with CARB's Commercial Harbor Craft rule.

An additional engine with Tier 4 certification under 600KW is the Baudouin 6M-26.3, with engines rated for full load power at 441-599 kW[69].[69].

Recently Certified Tier 4 Engines

Since 2021 new Tier 4 engines have been introduced by several OEM manufacturers and are described in this section. This does not necessarily mean that they comply with the CARB CHC performance standards as the additional reduction in PM emissions must be attained. In some cases, manufacturers have added an integrated DPF with the goal of attaining certification for meeting the performance standard.

1.1.1.14 Mitsubishi S12R-Y4

The Mitsubishi S12R-Y4 is a 49-liter, V12 marine propulsion engine that is Tier 4 certified. The engine generates 1260 horsepower at a speed of 1600 rpm. It is the first Tier 4 marine engine to be produced by Mitsubishi and achieves this standard with an SCR system. It is a Category 1 engine which makes it optimal for variable duty cycle applications. This engine is commercially available and has been incorporated into vessels. The first vessel to incorporate this engine was the *M/V Michael J. Kennelly*, a towboat operated by American Commercial Barge Line (ACBL) in the waterways of Houston, Texas [70]. It appears that no California Commercial Harbor Craft utilizes this engine as of March 2024.

1.1.1.15 Yanmar 6AYEM-GTWS

The Yanmar 6AYEM-GTWS is a compact 20-liter, 6 cylinder marine propulsion engine that is Tier 4 certified. It can output between 670 kW and 749 kW at speeds from 1938 rpm to 2000 rpm and is coupled with an SCR system. It appears that no California Commercial Harbor Craft utilizes this engine as of March 2024.

1.1.1.16 MAN D2862 Series

The MAN D2862LE428 and D2862LE489 are 24-liter, 12-cylinder marine propulsion engines that are Tier 4 certified. The 428 outputs 749 kW at 2100 rpm, and the 489 outputs 1066 kW at 2100 rpm. Both engines are fitted with SCR after treatment systems but do not have the additional DPFs required to attain the CHC performance standard. The D2862LE489 model was chosen to repower the WETA Gemini fleet of high-speed catamaran ferries [72]. As a step to reach CARB performance compliance, MAN has recently outfitted these engines with DPFs, which should allow them to comply with CARB's Commercial Harbor Craft rule [71]. New D2862 family models that are certified with full DOC/DPF/SCR after treatment with three power and duty cycle ratings: LE44A (735 kW), LE43B (882 kW), and LE48B (1,066kW) [73].[73] are available in 2024.

Tier 4 Engine Potential and Implementation

It has already been mentioned that even though advanced technology may be available, the ability to implement the technology is heavily dependent on the *specific vessel*. This section summarizes examples of specific vessels from a vessel Cal Maritime Academy (CMA) conducted study in 2019 that assessed the feasibility of a Tier 4 repower, and retrofit of existing commercial harbor craft of several categories [74]. Feasibility was determined for a repower with a commercially available Tier 4 engine, a retrofit SCR+DPF after treatment system, and a DPF only after treatment system. The feasibility was determined using vessel drawings and 3D scans and were also reviewed by a 3rd party naval architect. The vessels chosen for study were representative of the typical vessel of its category with respect to age, engine size, and architecture.

Table 6 summarizes the feasibility assessment of implementing commercial Tier 4 technology (available in 2019) into vessels as determined by the CMA feasibility study. A commonality among many harbor craft with small engine and engine room sizes, particularly those employing non-steel structural materials such as aluminum and wood, is that repowering or retrofitting Tier 4 equipment is challenging and expensive. Because of the challenges associated with repowering/retrofitting existing vessels with Tier 4 technology, many companies have elected to achieve Tier 4 compliance through new builds.

Table 6: Summary of Feasibility Findings from CMA 2019 Tier 4 Feasibility Study (these are vessel specific findings and should not be considered to apply generally to the vessel categories listed).

Vessel Category		Repower: Tier 4 Marine Engines	Retrofit: DPF + SCR	Retrofit: DPF	Evaluation Input
Tank Barge	Cargo Pump	N/A	Feasible Fitment	Feasible Fitment	3D Scan and Vessel Drawings
	Ballast Pump	N/A	Feasible Fitment	Feasible Fitment	
	Generator	N/A	Feasible Fitment	Feasible Fitment	
Dredge	Pump Engine	Feasible Fitment	Moderate Reconfiguration	Moderate Reconfiguration	3D Scan
	Thruster	N/A	Feasible Fitment	Feasible Fitment	
	Generator	N/A	Feasible Fitment	Feasible Fitment	
Commercial Fishing		N/A	No Fitment Identified	No Fitment Identified	3D Scan
Charter Fishing		N/A	No Fitment Identified	No Fitment Identified	3D Scan and Vessel Drawings
Excursion		Feasible Fitment	Feasible Fitment	Feasible Fitment	3D Scan and Vessel Drawings
Slow Speed Ferry		Feasible Fitment	Moderate Reconfiguration	Moderate Reconfiguration	3D Scan and Vessel Drawings
High Speed Ferry		Substantial Reconfiguration	Substantial Reconfiguration	Substantial Reconfiguration	Vessel Drawings
Ship Assist Tug		Feasible Fitment	No Fitment Identified	Moderate Reconfiguration	Vessel Drawings
Push Tug		Feasible Fitment	Substantial Reconfiguration	Moderate Reconfiguration	3D Scan
Crew and Supply		Moderate Reconfiguration	Substantial Reconfiguration	Substantial Reconfiguration	3D Scan
Pilot Boat		Substantial Reconfiguration	Substantial Reconfiguration	Substantial Reconfiguration	3D Scan and Vessel Drawings
Work Boat		N/A	Substantial Reconfiguration	Substantial Reconfiguration	3D Scan
Special Use		Feasible Fitment	Moderate Reconfiguration	Moderate Reconfiguration	3D Scan and Vessel Drawings

Since the CMA study in 2019, several additional engines have been Tier 4 certified (recall Figure 21 in Section 3.1.1). Three of these engines operate at power outputs <600 kW, putting them in line with the demands of smaller vessels such as fishing and work vessels. In summary , Table 7 and Table 8 provides a list of the commercially available Tier 4 engines for both main and auxillary engines as of March 2024.

Table 7: Tier 4 Certified Engines and their Specifications as of March 2024

Manufacturer	Model	Cylinders	Stroke	DPF	SCR	Turbo	Emissions Compliance	Weight (kg)	EPA Category	Power Range (bkW)	Year Available
M&H Engines	M&H 4045MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	570	1	55-130	2023
M&H Engines	M&H 6068MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	785	1	169-224	2023
M&H Engines	M&H 6090MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	1097	1	205-317	2023
Baudouin	6M-26.3	6	4	No	Yes	Yes	Tier 4, IMO III	2185	1	441-599	2019
Yanmar	6AYEM-GTWS	6	4	No	Yes	Yes	Tier 4, IMO III	2418	1	670-749	2021
MAN Diesel	D2862 Series	12	4	Yes	Yes	Yes	Tier 4, IMO III	2270	1	749-1066	2020
Caterpillar	C32	12	4	No	Yes	Yes	Tier 4, IMO III	3248	1	746-1081	2018
Cummins	QSK38	12	4	No	Yes	Yes	Tier 4, IMO III	5270	1	746-1119	2022
Mitsubishi	S12-R	12	4	No	Yes	Yes	Tier 4, IMO III	5350	1	840-1270	2021
Baudouin	12M-26.3	12	4	No	Yes	Yes	Tier 4, IMO III	3615	1	883-1214	2019
Caterpillar	3512E	12	4	No	Yes	Yes	Tier 4, IMO III	8193	1	1000-1901	2015
MTU	12V-4000M 05	12	4	No	Yes	Yes	Tier 4, IMO III	8000	1	1119-1932	2021
EMD 710 Series	8E 23	8	2	No	Yes	Yes	Tier 4, IMO III	14742	2	1249-1864	2016
Cummins	QSK60	12	4	No	Yes	Yes	Tier 4, IMO III	10154	1	1491-2013	2022
EMD 710 Series	12E 23	12	2	No	Yes	Yes	Tier 4, IMO III	19414	2	1561-2237	2016
EMD 710 Series	12E 23B	12	2	No	Yes	Yes	Tier 4, IMO III	23133	2	1561-2237	2016
Wabtec	6L250 MDC	6	4	No	No	Yes	Tier 4, IMO III	19944	2	1700-1900	2017
MTU	16V-4000M 05	16	4	No	Yes	Yes	Tier 4, IMO III	9300	1	1840-2576	2021
Caterpillar	3516E	16	4	No	Yes	Yes	Tier 4, IMO III	9620	1	1865-2525	2014
Wabtec	8L250 MDC	8	4	No	No	Yes	Tier 4, IMO III	23356	2	2250-2500	2016
MTU	20V-4000M 05	20	4	No	Yes	Yes	Tier 4, IMO III	11600	1	2300-3220	2021
Caterpillar	C280-8	8	4	No	Yes	Yes	Tier 4, IMO III	19000	2	2460-2530	2017
EMD 710 Series	16E 23	16	2	No	Yes	Yes	Tier 4, IMO III	22589	2	2479-2983	2016
EMD 710 Series	20E 23	20	2	No	Yes	Yes	Tier 4, IMO III	25719	2	3098-3729	2016
Wabtec	12V250 MDC	12	4	No	No	Yes	Tier 4, IMO III	27080	2	3150-3500	2016
Caterpillar	C280-12	12	4	No	Yes	Yes	Tier 4, IMO III	26036	2	3700-4060	2017
Wabtec	16V250 MDC	16	4	No	No	Yes	Tier 4, IMO III	35788	2	4200-4700	2017

Table 8: CHC Main/Auxiliary Engine Count and Power by Vessel Type [2]

Vessel Type	Vessel Count	Auxiliary Engine Count	Auxiliary Engine Average kW	Auxiliary Engine Average MY	Main Engine Count	Main Engine Average kW	Main Engine Average MY
Barge-ATB	13	81	511	2006	-	-	-
Barge-Bunker	12	33	228	2009	-	-	-
Barge-Other	46	102	300	2002	-	-	-
Barge-Towed Petrochemical	9	26	444	2005	-	-	-
Commercial Fishing	797	377	115	1999	888	409	1996
Commercial Passenger Fishing	274	196	90	2003	488	558	2005
Crew/Supply	71	77	143	2003	156	764	2006
Dredge	20	28	523	2009	16	591	2007
Excursion	177	170	146	2001	311	553	2000
Ferry-Catamaran	32	52	162	2010	78	2427	2010
Ferry-Monohull	19	26	107	2003	38	1601	2000
Ferry-Short Run	16	14	59	2002	26	536	2010
Pilot Vessel	9	9	99	2004	17	1047	2007
Research Vessel	44	45	229	1998	86	852	1996
Tugboat-ATB	11	34	397	2005	22	5894	2006
Tugboat-Escort/Ship Assist	58	122	240	2009	117	3286	2008
Tugboat-Push/Tow	108	162	125	2003	211	980	2002
Workboat	204	149	331	1998	327	632	2000

The following sections discuss more details regarding end use implementation of Tier 4 Engines for each vessel type. Again, it is emphasized that, even within individual vessel categories, large variation between every individual vessel exists, and feasibility cannot be assumed to be the same for every vessel with one engine technology on specific vessel types.

1.1.1.17 Barges

1.1.1.17.1 Articulated Tow Barge (ATB)

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

No ATB barges were found to operating in California with Tier 4 main engines as of March 2024 [75].

1.1.1.17.2 Bunker

Commercially available Categories 1 and 2 Tier 4 engine options exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

Golding Barge has chosen to power their upcoming new build with three Tier 4 certified CAT 3512E marine engines [76]. Scheduled for delivery in 2024, this vessel will serve the waterways of the Midwest between Texas and Kentucky and is projected to be in service for 40-50 years.

No Bunker barges operate with Tier 4 main engines in California as of March 2024 [75].

1.1.1.17.3 Other

Commercially available Categories 1 and 2 Tier 4 engine options exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

As of March 2024, no barges categorized as "other" operate with Tier 4 main engines in California [75].

1.1.1.17.4 Towed Petrochemical

Commercially available Categories 1 and 2 Tier 4 engine options for this vessel category exist. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

The *Jake J* is a petrochemical barge that is operated by the Jankovich Company that is powered by dual Tier 4 marine engines. It operates in the port of Long Beach [75].

1.1.1.18 Tugs

1.1.1.18.1 ATB Tug

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

Harley Marine has taken delivery of 2 Tier 4 ATB tugs designed by Entech Tec built by Conrad Shipyard that operate out of Seattle. The *OneCURE/Todd E. Prophet* ATB tugs have a length of 116' and a beam of 36' [77]. The vessels are powered by dual GE 6L250 Tier 4 engines which each produce 2280 HP. Each tug is paired with an ATB barge and is tasked with transporting fuels and petroleum products along the West Coast.

The *Cape Ann* is a 109' ATB Tug built in 2018 by Master Boat Builders Incorporated. It is powered by dual Tier 4 compliant CAT 3516E engines, and 3 Tier 4 off-road compliant John Deere 6068AMF85 auxiliary engines [78]. It operates out of the port of Long Beach [79].

1.1.1.18.2 Escort/Ship Assist

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

The *M/V Valor* is a 100' tug built in 2006. It was repowered by Crowley Maritime with dual Tier 4 CAT 3516E engines in 2020. The tug is tasked with assisting ships in the San Francisco Bay [80].

Crowley Maritime has developed a fleet of 4 ship assist/escort tug, all powered by dual Tier 4 certified CAT 3516E marine engines producing nearly 6800 HP [81]. They range in size from 77' to 82' and are chartered across the West Coast in Washington, San Francisco, and Long Beach.

Foss Maritime has taken delivery of 4 100' 90 ton tugs [82]. Each tug is tasked with aiding tanker and cargo ships along the West Coast, as well as Alaska and Hawaii. They are powered by dual Tier 4 MTU 16V 4000 engines that produce a maximum total power output of 6866 HP.

Foss Maritime repowered the *Alta June* tug from Tier 2 to Tier 4 in July 2022 [83]. The repower project replaced the dual Tier 2 CAT 3512B with dual Tier 4 CAT 3512E engines. The old and new engines have roughly the same power output.

1.1.1.18.3 Push/Tow

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

Pacific Marine Group installed a SCR+DPF system developed by Nett Technologies on one of its San Diego tugs [84]. The retrofit allowed the tug to reach Tier 4 emission standards. According to the manufacturer, the BlueMax Nova 320 after treatment system reduces NOx, PM, CO, and HC emissions by 95%, 95%-99%, 98%, and 82% respectively. Per the manufacturer, the BlueMAX NOVA Series system was designed for existing tugs, as well as other commercial harbor craft with medium and heavy-duty engines. It is indicated to have application for engines certified to Tier 1-3 emissions with more than 56 bkW power.

American Commercial Barge Line (ACBL) has announced a partnership with Steiner Construction, tasked with building a towboat [85]. The new towboat will be powered by dual Mitsubishi S12R Tier 4 engines, producing 2600 horsepower. The vessel will be 82 feet long, with a width of 34 feet. Once completed, the vessel will be tasked with operating in the waterways of Houston.

Blakeley BoatWorks has completed a new 110’ linehaul towing vessel powered by dual CAT C3512E Tier 4 engines producing a net output of 3400 horsepower. The vessel is named the *M/V Gretchen V. Cooper*, and will serve the Tennessee-Tombigbee Waterway [86].

As of March 2024, no tugs categorized as “push/tow” operate with Tier 4 main engines in California [75].

1.1.1.19 Ferries

1.1.1.19.1 High-Speed Catamaran

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

The San Francisco Bay Area Water Emergency Transportation Authority (WETA) has recently completed repowers for its 4 Gemini class high speed catamaran ferries [87]. The repowers featured dual Tier 4 MAN D2862 LE489 engines replacing older Tier 2 MTU 16V 2000 engines, and this led to a reduction in NOx and PM emissions by 73% and 80% respectively.

The San Francisco Bay Area Water Emergency Transportation Authority (WETA) is operating a new aluminum catamaran ferry in the San Francisco Bay [88]. The vessel, called the *Dorado*, is 100’ with a service speed of 32 knots. It is powered by dual Tier 4 certified MTU 16V 4000 M65 engines that produce 2575hp each. There is also a sister vessel, called the *Delphinus*, which entered operation in February of 2024. as well as two unnamed sister vessels planned.

WETA also built 4 Pyxis class Tier 4 ferries between 2019 and 2020. Each vessel has a length of 143’ with a service speed of 34 knots and a maximum capacity of 445 passengers. The ferries are powered by dual Tier 4 certified MTU 16V 4000 M65 engines producing 3,433hp each [89].

NYC Ferry has taken delivery of 2 97’ ferries powered by dual Tier 4 Baudouin 12M26.3 engines [90]. Each vessel has a capacity for 354 passengers, and a service speed of 26.5 knots. These two vessels will join NYC Ferry’s fleet for a total of 38 vessels, and 25 landings across New York City.

1.1.1.19.2 High-Speed Monohull

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

As of March 2024, no ferries categorized as "monohull" operate with Tier 4 main engines in California [75].

1.1.1.19.3 Short Run

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation. However, it is important to note that CARB's ZEAT requirement in the CHC regulation will apply to these vessels after Dec 31, 2025.

As of March 2024, no ferries categorized as "short run" operate with Tier 4 main engines in California [75].[75]. Further, these vessels will need to adopt ZEAT for use after Dec 31,2025.

1.1.1.20 Pilot Vessels

1.1.1.20.1 Pilot Run

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

San Francisco Bar Pilots Association (SFBP) has taken delivery of a 73' pilot vessel named *P/V Golden Gate* [91]. It was designed by UK based naval architecture firm, Camarc Design, and constructed by Seattle based boat builder Snow and Company. It is powered by dual MAN D2862 Tier 4 engines producing a combined 2400 horsepower. It is tasked with providing pilot services for the San Francisco Bay and has space for 2 crew and 12 pilots. It can also plug into a shore power facility when it is docked at its pier to reduce generator emissions.

1.1.1.20.2 Pilot Station

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

As of March 2024, no pilot station vessels operate with Tier 4 main engines in California. [75].

1.1.1.21 Crew/Supply

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

Atlantic Wind Transfers (AWT) has ordered 6 Tier 4 powered Crew Transfer Vessels (CTV) [92]. The first two vessels were planned for delivery in summer 2023, and January 2024. The *Atlantic Resolute* was delivered in July 2024. Each vessel will have a length of 63' and a beam of 24.' They are being built at St. Johns Shipbuilding, located in Florida and are powered by dual MAN Tier 4 engines. Once completed, the vessels will be tasked with providing service to various offshore wind farms off the coast of New England.

As of March 2024, no crew/supply vessels operate with Tier 4 main engines in California [75].

1.1.1.22 Fishing

1.1.1.22.1 Commercial Fishing

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

As of March 2024, no commercial fishing vessels operate with Tier 4 main engines in California [75].

1.1.1.22.2 Commercial Passenger Fishing

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

As of March 2024, no commercial passenger fishing vessels operate with Tier 4 main engines in California [75].

1.1.1.23 Dredges

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

DSC Dredge produces its Shark class dredges, which contain a Tier 4 CAT C32 engine used to power their winch. The dredge has a depth capacity of 56.' This class of dredge is the first to include a tier 4 engine [93].

The *Galveston Island* is the first of two new hopper dredges constructed by Conrad Industries for Great Lakes Dredge & Dock (GLDD) [18]. It is powered by 4 Tier 4 certified Wabtec engines (2x 12V250MDC, 2x 6L250MDC) that produce 16,500 total horsepower. Its length measures 364' and its beam measures 69.' It can dredge at depths up to 100' [94].

1.1.1.24 Excursion Vessels

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

American Cruiselines has a fleet of 6 American Riverboat class excursion vessels that are river cruise ships tasked with taking guests on cruises around U.S waterways [95]. The vessels are powered by dual CAT 3512E Tier 4 certified engines, each producing 1810 horsepower. The vessels have a capacity for 180 guests, as well as several guest amenities such as sun decks, cafes, and lounges. The vessels are 345' long, and 60' wide [96].

1.1.1.25 Workboats

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

As of March 2024, no work boats operate with Tier 4 main engines in California [75].

1.1.1.26 Research Vessel

Commercial Category 1 and 2 Tier 4 engines exist for this vessel category. Their use of diesel fuel means that new infrastructure is not required for commercial operation.

As of March 2024, no research vessels operate with Tier 4 main engines in California [75].

Auxiliary Engines

Auxiliary engines are secondary engines that are used to provide extra power for onboard systems and equipment that cannot utilize power from the propulsion engine. For most vessels, these engines are used to power generators, pumps, compressors, refrigeration systems, or cranes. They typically operate at lower power outputs than the main engines.

For vessels such as barges and dredges, these auxiliary engines can be larger with power outputs greater than 1MW, meaning there are available Tier 4 engines. Unlike with main engines, auxiliary engines are not always marine engines, and may instead be from the off-road category of engines [75]. Unlike Tier 4 marine main engines which typically have a power output greater than 600 bkW, Tier 4 off-road engines can have power outputs as low as 50kW. Because of this, auxiliary repowers using Tier 4 off-road engines typically do not face as many challenges with size and stability as main engine repowers often face. Tier 4 marine and off-road engines have been implemented as auxiliary engines in a variety of vessels in California.

Table 9 a summary of the commercial and operational status of Tier 4 main and auxiliary engines for use in California [75] for various vessel types. Again, it is pointed out that individual vessels need careful evaluation of specific engine makes and models for fitment and appropriateness for a given application.

Table 9: Tier 4 Engine California Operational Commercial Readiness

Vessel Type	Tier 4 Main Engine	Tier 4 Auxiliary Engine
Barge-ATB	**Commercially Available**	**Commercially Available**
Barge-Bunker	**Commercially Available**	**Commercially Available**
Barge-Other	**Commercially Available**	**Operational In California**
Barge-Towed Petrochemical	**Operational In California**	**Commercially Available**
Commercial Fishing	**Commercially Available**	**Operational In California**
Commercial Passenger Fishing	**Commercially Available**	**Commercially Available**
Crew/Supply	**Commercially Available**	**Operational In California**
Dredge	**Operational In California**	**Commercially Available**
Excursion	**Operational In California**	**Operational In California**
Ferry-Catamaran	**Operational In California**	**Commercially Available**
Ferry-Monohull	**Commercially Available**	**Commercially Available**
Ferry-Short Run	**Commercially Available**	**Operational In California**
Pilot Vessel-Station	**Commercially Available**	**Commercially Available**
Pilot Vessel-Run	**Operational In California**	**Commercially Available**
Research Vessel	**Commercially Available**	**Operational In California**
Tugboat-Escort/Ship Assist	**Operational In California**	**Commercially Available**
Tugboat-ATB	**Operational In California**	**Commercially Available**
Tugboat-Push/Tow	**Commercially Available**	**Operational In California**
Workboat	**Operational In California**	**Operational In California**

N/A	Not Applicable
Not Commercially Available	**Not Commercially Available**
Commercially Available	**Commercially Available**
Operational In California	**Commercially Available and Operational in California**

Barriers to market penetration for Tier 4 Technology

Several barriers hamper the ability for Tier 4 engines and technology to quickly integrate into the commercial harbor craft sector [97]. One barrier is the compatibility differences between Tier 4 engines and other engines. The Tier 4 engines are generally larger due to extensive after treatment systems and urea tanks. This increase in size can be visualized in Figure 25 [98]. This additional size means that many harbor craft will need to be substantially modified for proper fitment. Additionally, some commercial harbor craft such as fishing vessels have wood or fiberglass hulls, which makes vessel reconfiguration difficult as these materials are harder to work with. The aftertreatment add-ons of Tier 4 engines can increase parasitic losses. These barriers combine to make Tier 4 more expensive to install when compared to previous tiers. The Wabtec engines are able attain NOx reductions using solely EGR without SCR. This feature could be important in terms of facilitating retrofit. However, the heavy use of EGR may result in somewhat higher temperatures in the engine ducting.

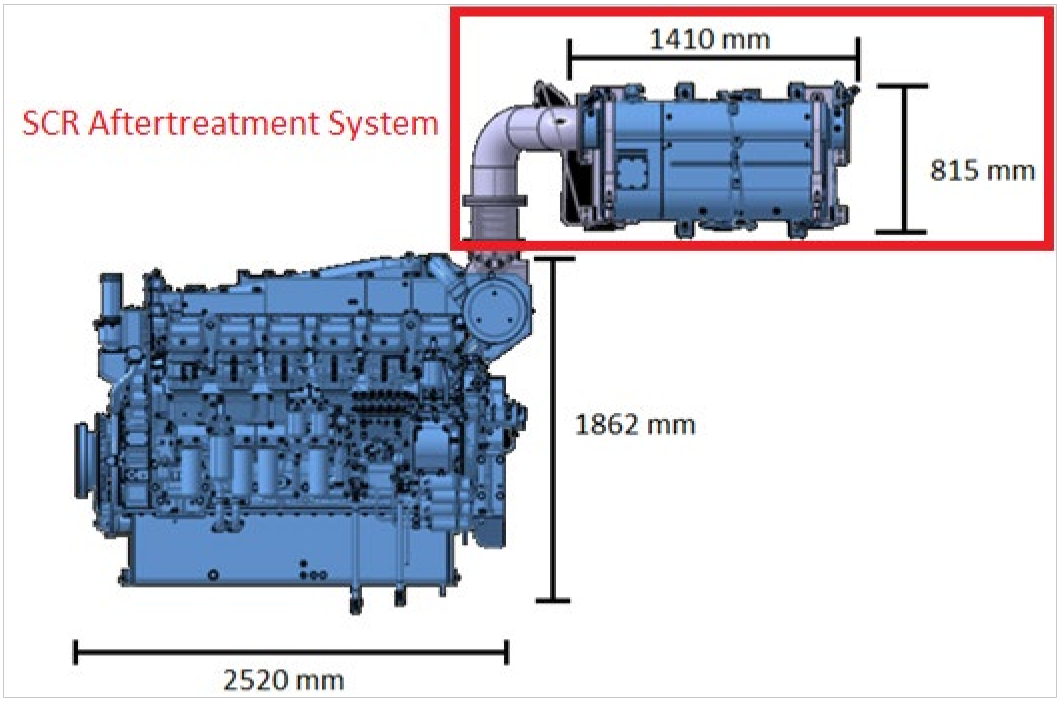


Figure 25: The Tier 4 certified Mitsubishi S12R and its SCR System

Specific to fishing vessels, a small sample polling of 135 fishing vessel owners (including 36 in California) [99] identified the primary barriers to adoption was the expense of the new capital which is not unexpected, along with concerns regarding downtime for the upgrade. Beyond that, concerns about reliability and repairability were noted in the survey. The same survey noted that potential for improved engine efficiency was a positive consideration although several use side measures (e.g., reduced hull drag, LED lighting) were more likely to be adopted. However, while these strategies may save on fuel, they are not compliance methods outlined in the CHC regulation. It would seem incentives (e.g., Carl Moyer) and demonstration and documentation of operational track record with the advanced technologies would be helpful in convincing the fishing sector to make upgrades.

The lack of options available for lower power Tier 4 engines has been another barrier, as engines less than 600 kW (804.61 HP) make up a bulk of the engines used in the CHC sector as shown in Table 8 [2]. As seen in Figure 21 above, there were, and continue to be fewer options available in this low power subcategory.

In addition to the barriers that hamper vessel owners to implement Tier 4 technology such as size, cost, and availability, more barriers exist for OEMs. Because of expensive fees associated with the testing and certification of Tier 4 engines, many OEMs are hesitant to use the required resources to develop and certify Tier 4 compliant engines, especially considering the small market for these engines that arises from the implementation challenges for their consumers. This problem is recognized by the EPA, and a provision was created to allow OEM's to use carryover test data from deterioration factor testing to certify engines across several years of an engine's production if versions have been previously certified as Tier 4 in other sectors such as on or off road [100].

It is noted that specific support for technology adoption has been put forth via Carl Moyer and also by the $50M in advanced technology demonstration and pilot projects announced by California Energy Commission and California Air Resources Board in March 2024. While much of the support is directed at zero emission technologies, some support for Tier 4 and Hybrid adoption was offered to the Port of Los Angeles [101].

High Readiness (but Pre-Commercial) Tier 4 Technology

Tier 4 Marine Engines

Because marine emission standards vary across the world, engine manufacturers may decide to only market their products locally, and design them to perform to their local emission standards. This can be seen between Europe and the United States where engine manufacturers may only sell to their home region, and therefore only test their compliance with their respective emissions standard. This may result in some engines that demonstrate measured emissions levels that would meet U.S. EPA's Tier 4 not being marketed for the U.S.

Volvo-Penta has a line of engines under 300 kW (D8 MH series) that are compliant with EU Stage V emissions standard [102]. Like the offerings by M&H Engines, these engines are likely able to fit into vessels with small engine rooms such as fishing vessels and workboats. Their availability in the lower power output range positions them to potentially replace engines that are found in smaller vessels or those requiring less power. However, even if these are EU Stage V certified, they cannot be considered without the U.S. EPA Tier 4 certification.

AGCO Power has a line of auxiliary and propulsion engines that meet EU Stage V standards. These engines have a power output of 179kW-221kW [103]. These engines are smaller than current commercially available Tier 4 engines and could potentially be used for repowering smaller vessels. Additionally, their line of auxiliary engines could be used to replace older, more polluting auxiliary engines.

Cummins has developed a Stage V configuration of its QSK38 engine that contains both an SCR and DPF after treatment system. There is a commercially available Tier 4 variant of the QSK38 that contains only an SCR after treatment system. The addition of a DPF to this Tier 4 variant is likely able to meet the CARB Tier 4+DPF standard.

MAN Diesel is in the process of developing a new line of 30-liter V12 Tier 4 engines that are planned to be commercially available by the end of 2024 [104]. These engines are from an entirely new family of engines and are not spinoffs of the current Tier 4 certified line of D2862LE engines. The new line of engines will be called the D3872LE, and 3 engines will be available ranging from 932 kW to 1213 kW. The engines are currently undergoing field testing [105]. In the future, this line of engines will be able to be combined with MAN's modular exhaust gas after treatment system, consisting of an SCR and DPF [106]. As mentioned in Section 3.1.6.3, MAN has already integrated DPF technology into their D2862 family of engines and have demonstrated certified emissions levels below the CARB in-use performance standard (certified at 0.006 g/kWh vs 0.0067 g/kWh standard).

Engine Technology

Dual fuel engines are categorized as such by having the ability to run on a mixture of different fuel sources. Typically, dual fuel marine engines can run on a combination of gaseous natural gas, and liquid diesel fuels. The advantages of dual fuel engines are a lower consumption of liquid fuels, as some dual fuel engines can operate at only 5% diesel and 95% natural gas. Dual fuel engines that operate on a mixture of hydrogen gas instead of natural gas are also being developed. Other potential advantages are lower emissions of HC, and SOx, as these are typically a consequence of the combustion of diesel fuel. Further, these engines still produce NOx. Dual fuel marine engines exist, however none are currently Tier 4 certified, instead typically being IMO II and IMO III certified. Examples of LNG/diesel dual fuel marine engines are produced by Wärtsilä (1700-3400 kW), Yanmar (auxiliary engine 1100-4080 kW; propulsion engines from 1533-4240 kW), MAN (1500 to 82,500kW), Hyundai (2,700 to 13,250kW), and Yuchai (600-3600kW). It is evident that these engines tend towards the large end of the size range.

Another type of dual fuel engine that is being considered for use in the maritime industry are methanol engines. These engines are designed to operate with both diesel and methanol. Green methanol, which is produced using green hydrogen and captured CO2, has the advantage of producing zero SOx, PM, and 80% less NOx than diesel, all while being carbon neutral [107] [108]. Methanol engines at harbor craft scales are currently being developed by companies such as Wärtsilä and MAN. Some of these engines require diesel piloting which would offset benefits gained by use of methanol in terms of particulate emissions reduction.

Ammonia dual fuel engines are also being developed by MAN and Wärtsilä.

After Treatment Strategies

It is evident that advanced after-treatment is a key factor to attaining Tier 4 emissions standards While commercial strategies are available, alternative after treatment strategies are under development with hopes for commercialization.

Engine OEM DPF Systems

It is likely that engine OEMs will develop DPFs specific to their marinized Tier 4 engines.

Other DPF Systems

Nett Technologies (Canada) has developed a line of standalone marine DPFs (GreenTRAP™ NOVA 320 Series) that they are currently seeking CARB verification for. These products are derived from their medium and heavy-duty vehicle line of DPFs and that are CARB verified for stationary power generation emission control system, thus has an established track record for non-marine applications. . This marine line contains both passive and active DPF designs for use in marine engines between 50kW and 450kW [109]. The Nett Technologies DPFs regenerate using hydrocarbon injection (HCI) which injects and reacts fuel over the DOC catalyst to raise the system’s temperature to a level which supports oxidation of the captured particulate. The need for regeneration is triggered by sufficient pressure loss across the DPF due to particulate build up. This injection of diesel for regeneration accounts for less than 1% of total fuel consumption. When exhaust temperatures are high enough under regular operation conditions (generally above 570 F), the carbon buildup will oxidize passively (i.e., without additional heat energy added to the system). As a result, the need to actively regenerate will depend on the engine duty cycle and the vessels vocation with higher power operation generally sufficient for passive regeneration, but low power conditions may warrant active regeneration. The Port of Long Beach is targeting a retrofit project (Pacific Tugboat Service's *S.Bass* tug) supported by San Pedro Bay Ports Technology Advancement Program [110]. Nett Technologies also makes a line of electrically regenerated DPFs (GreenTRAP™ VOLT 320) which could presumably be marinized. Nett Technolologies also offers combined DPF, SCR, and DOC systems (BlueMAX™ NOVA-Series) which have been retrofitted onto marine vessels (see Section 3.1.7.2.3).

DCL International is another manufacturer that is offering a marinized DPF (Marine-X® Diesel Particulate Filter) targeting ferries, pleasure yachts, and tugs. [111] They are headquartered in Ontario, but have a regional office in Walnut Creek, CA. SeaClean© is another developer of marine DPF systems that uses electrical active regeneration [112]. Target applications include private yachts. It is not clear if these manufacturers are or will be seeking CARB verification.

Additional DPFs that have undergone CARB verification procedures for vehicles may have the potential to be marinized. A number of manufacturers and devices are available with different effectiveness levels verified (Level 1 20% reduction, Level 2: 50% reduction, Level 3: 85% reduction). A large number of these products are offered by a variety of manufacturers for various engine sizes. [113] These vendors should be closely watched relative to their plans regarding marine markets. Examples of manufacturers on this list that have or are pursuing marine markets include Rypos, Nett Technologies, and DCL International.

Integrated SCR/DPF System

Johnson Matthey has developed an exhaust after treatment system that combines a DPF and an SCR into a single after treatment module. The technology, which they refer to as SCRF, doses the exhaust stream with urea just before the stream passes through a DPF-like filter to remove particulate matter [114]. Because of its compact package, an SCRF system would be well suited for space constrained vessels. This technology has not been marinized as of June 2024.

Electrostatic Precipitators

Electrostatic precipitators are an example of a technology that has a high level of readiness but is not yet commercial for the scale required for use in harbor craft. Electrostatic precipitators, or ESP systems operate by electrically charging the incoming exhaust air, which causes them to be attracted to collection tubes. The cleaned exhaust air is then released, and the collection tubes are then sprayed with chemicals, or water to be cleaned. This technology is used in several industries including mining and metallurgy; however, it is not used in the marine sector. Because exhaust gas conditions that contain high moisture, a wet electrostatic precipitator can also be used to remove liquid droplets. WESP systems may be used alongside SCR systems to retrofit existing engines to Tier 4 levels. The process of electrostatic precipitation is shown in Figure 26 [115].

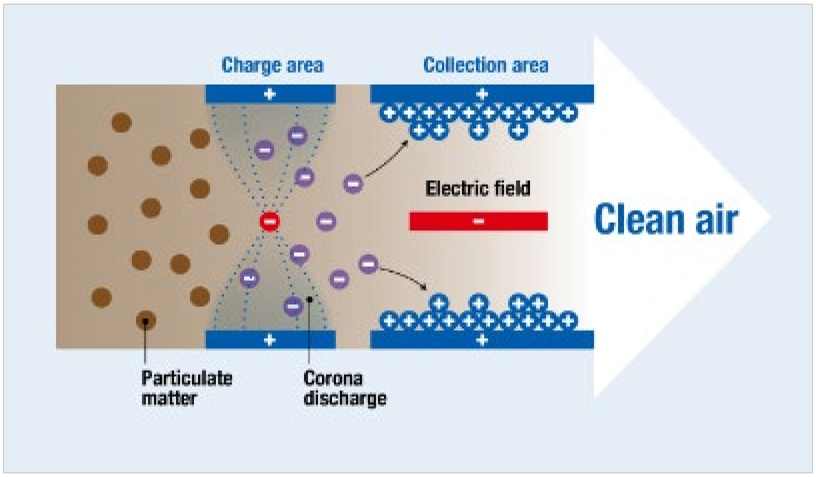


Figure 26: ESP System Schematic

Researchers from Tampere University have demonstrated in a lab environment that WESP, combined with a scrubber, is able to remove PM, SO2, and black carbon emissions by up to 99% [116]. The engine used in this experiment was a 1.6MW marine diesel engine, which is within the same power range desired by many harbor craft. While temperature of the corona discharge is likely an important factor, no information on the actual temperatures was identified in the current effort. Information regarding possible direct formation of ozone as well as NOx from this process also needs to be considered but was not researched in the current effort.

Ecospray, an exhaust gas cleaning company, has developed a WESP system that is used in their after treatment systems that removes up to 90% of PM2.5 and PM10 at engine loads between 55% and 65% [117]. It is unclear whether these reductions are mass or number based. Due to its size, which is between 2.2 to 3.5 meters wide and 3.6 to 4 meters tall, it is too large to be used in a vast majority of harbor craft. It is instead suited for oceangoing vessels which operate at power outputs between approximately 8MW and 24MW. The Ecospray module requires approximately 0.5% of the rated engine power for operation. Valmet offers a similar product for oceangoing vessels, however it also faces the same size issues that restrict its uses in harbor craft [118].

Fuji Electric is developing an ESP suited for marine diesel engines that is more compact in size than the offerings from Ecospray and Valmet [115]. This smaller scale means that it may be better suited for harbor craft. The PM collection performance of the Fuji Electric ESP is lower in comparison to the offerings from Ecospray and Valmet as seen in Figure 27. Because of its low performance, this unit would not meet CARB's Level 3 Verification requirements to remove 85% or better of diesel PM in its current state.

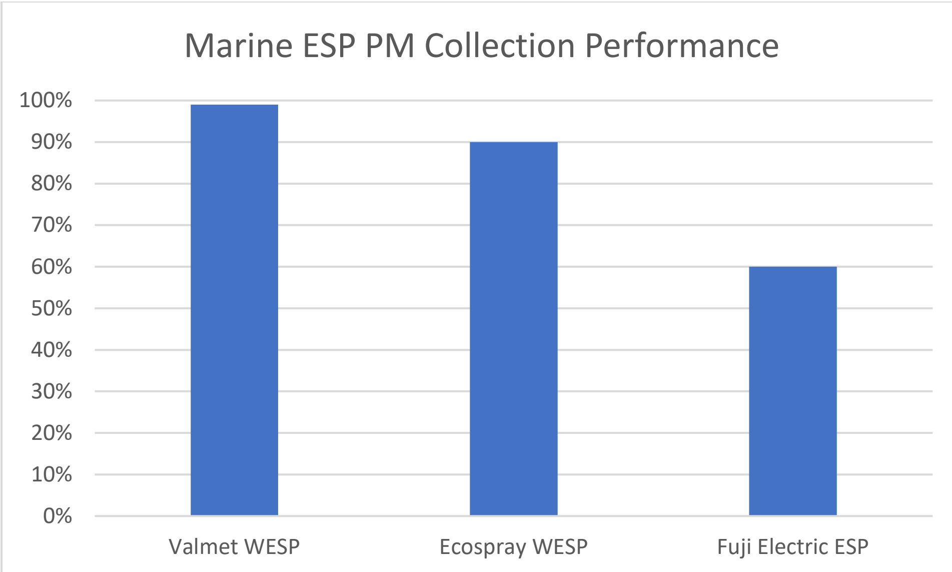


Figure 27: PM collection performance comparison between marine ESP systems as stated by manufacturer.

Zero-Emission and Advanced Technology Vessels

Commercial Harbor Craft Zero-Emission and Advanced Technologies (ZEAT) requirements include new or newly acquired excursion vessels by December 31, 2024 and all short run ferries (those traveling 3 nautical miles (nm) or less on a single run) by December 31, 2025 [119].2025 [119]. **It should be noted that most of the vessel types considered in this report are not required by the CHC regulation to repower or convert to near-zero emission or zero emission (ZE) propulsion at this time.** In addition, the Proposed Amendments include an Alternative Control of Emissions (ACE) compliance pathway allowing vessel owners and operators to propose an alternative plan to achieve equivalent emission reductions compared to directly complying with the requirements, and a credit for deploying ZEAT where not required.

Important definitions for this section are taken from CARB [119] and shown below:

- **ZEAT** – Zero-Emission and Advanced Technology including zero-emission capable hybrid, and zero-emission vessels.
- **Zero-Emission** – CHC with a propulsion system, auxiliary power system, and/or vessel utilizing a propulsion and auxiliary power system that has no tailpipe exhaust emissions and includes battery-electric and hydrogen fuel cell electric systems.
- **Zero-Emission Capable Hybrid Vessel or Hybrid System** – CHC utilizing a power system with two or more onboard power sources, one or more of which is approved by CARB to be capable of providing a minimum of 30% of vessel power required for main propulsion and auxiliary power operation with zero tailpipe emissions averaged over a calendar year.
- **Zero-Emission Infrastructure** – Infrastructure to support ZEAT vessel charging and refueling, e.g., charging equipment for batteries, and hydrogen storage and dispensing equipment.

An overview of the vessel configurations considered in this report are provided in Table 10. Battery-electric vessels operate using battery systems only, which are recharged using power from shore power.

All-electric CHC utilize a battery system comprised of large amount of rechargeable batteries to store electrical energy with common battery types including lithium-ion, lithium iron phosphate, and other advanced chemistries. An electric motor converts electrical energy from the battery into mechanical energy to drive propulsion and auxiliary systems. Vessels utilize a charging system that allows the battery system to be recharged from shore power.

Hydrogen fuel cell vessels operate using fuel cell propulsion systems operating on gaseous or liquid hydrogen. Hydrogen fuel cell electric vessels use hydrogen as a fuel to generate electricity through a chemical reaction. Fuel cell vessels use hydrogen storage tanks to store hydrogen at high pressure or in liquid form using cryogenic refrigeration. The hydrogen is fed to a fuel cell stack where hydrogen reacts with oxygen to produce electricity and water, with the electricity being used to power an electric motor to drive the propulsion or auxiliary systems of vessels. Additionally, fuel cell vessels incorporate a battery system that is used as an energy buffer for peak power demands or when the fuel cell is not operating, although the battery system is significantly smaller than those used for electric vessels.

It should be noted that both battery electric and hydrogen fuel cell electric vessels are ZE, however current versions often include a small diesel genset on-board as a backup in case of a failure of the primary systems. CARB allows up to 20 annual hours for backup engines unless they require operation during a documentable emergency scenario.

Table 10: Overview of ZEAT CHC vessel configurations considered in this assessment.

Vessel Configuration	Description
Battery-Electric Hybrid	Utilize batteries as an additional or primary power source in combination with an engine or fuel cell. Can operate in hybrid mode using both parallel and only battery power. ZEAT vessels charge using shore power for all or some of their battery energy.
Battery-Electric	Utilize batteries as the sole power source. Batteries are charged using shore power.
Hydrogen Fuel Cell	Utilize hydrogen fuel cells as the sole power source in combination with a battery system. Fueling is provided through gaseous or liquid hydrogen.

Zero-emission capable hybrid vessels (near-ZE) are generally described as hybrid vessels that use two power sources, usually a conventional combustion engine and a ZE engine including battery electric and hydrogen fuel cell electric systems. Hybrid systems allow the vessel to switch between ZE and conventional engines, or use them simultaneously, based on operational needs, power requirements, and environmental considerations. Engine types that are being considered for hybrid platforms are typically conventional combustion engines utilizing diesel fuel, although it should be noted that alternative fuels such as hydrogen, methanol, and ammonia may also be considered. Generally, hybrid vessels utilize integrated battery systems to 1) optimize the overall vessel propulsion system through functions including spinning reserve, peak shaving, block out prevention and/or load ramp-up support, and 2) to provide zero-emission propulsion during which the conventional engine is shut down and only the zero-emission engine is utilized. Utilizing hybrid propulsion systems can provide fuel savings leading to reductions in cost and emissions relative to a conventional diesel-powered vessel. Also, when operating at low speeds electric propulsion helps protect the diesel engines from unnecessary wear from operation outside ideal working loads. Additional benefits include reduced noise and vibration when operating in zero-emission mode, which can be beneficial both to the crew and the surrounding environment.

It should be noted that hybrid vessels that ***do not*** receive electricity from shore power (i.e., not plug-in hybrid vessels) have been in service for many years, including operation in California since 2009 with the delivery of the Foss Maritime's diesel-electric *Carolyn Dorothy*. The *Carolyn Dorothy* is powered by two Tier 2 Cummins diesel engines and two Siemens generators driven by two Cummins QSM11 diesel generators in tandem with 126 lead acid batteries [98]. In the U.S., the Robert Allan produced 98' Seabulk tug Spartan operates in Port Arthur, Texas. In hybrid mode, power is balanced between diesel and electric motors to optimize fuel consumption and bollard pull [120]. While these examples do achieve efficiency benefits which reduce fuel consumption and emissions due to the inclusion of a battery system, they do not meet the criteria for ZEAT and near-ZEAT established by CARB regulations and are therefore not considered in this assessment.

ZEAT Vessels in California

The following section discusses current and planned ZEAT vessels and infrastructure in California including short run and passenger ferries, tugboats, excursion vessels, dredges, commercial fishing vessels, research vessels, and smaller CHC including workboats, patrol boats, pilot boats, etc.

Short Run Ferries

The following section discusses the planned conversions of California short run ferry fleets to ZEAT technologies. Short run ferries operate on shorter, fixed routes, which are favorable for battery electric operation as battery packs can fully power vessels during shorter trips and simplify charging infrastructure needs and deployment. As noted previously, short run ferries with a single voyage of less than three nm will be required to be fully-zero-emission by the end of 2025.

Angel Island Ferries

Angel Island Tiburon Ferry operates three commercial vessels including two short run ferries that travel between Tiburon and Angel Island State Park, and one excursion vessel. All three vessels which will be retrofitted to or replaced by ZEAT technologies in a collaboration with Pacific Gas and Electric and Green Yachts [121]. First, the 59' 400-passanger short-run *Angel Island* Ferry will be retrofitted to an all-electric propulsion system comprised of two 170 kW electric motors and 686 kWh semi-solid state batteries [122]. The *Bonita* ferry will be retrofitted with a ZEAT system comprised of two 170 kW motors, 660 kWh of NMC lithium-ion batteries and a test-sized wing sail. The *Tamalpais* excursion vessel will be replaced with a new vessel called the *Watts Up* which will be an EV Maritime 200 ultra efficient semi-foiling composite hull with twin Hamilton LTX jets, four 370 kW motors, 1029 kW of batteries and two 305 kW EPA Tier IV DPC generators. According to Green Yachts, the *Angel Island* Ferry will require approximately 30 kWh to travel one mile, which is approximately 15 times that of an electric semi-truck [123].

In addition, shoreside charging infrastructure will include upgrades to the electrical grid and the electrical system on-site including a corded charging system and an inductive charging system. Modifications will also be made to the floating dock to support the weight of the fast-charging system. In addition, a 95 kW solar array will be included. Pacific Gas and Electric (PG&E) will assist in providing charging infrastructure to support vessel operation. PG&E will extend its Electric Vehicle Fleet Program, which assists customers electrify large- and medium-sized vehicles through construction support and financial incentives, to the marine sector for the first time.

Balboa Island Ferries

Balboa Island Ferry owns and operates three vintage wooden ferries that carry passengers between Balboa Island and the Balboa Peninsula in Newport Beach, California. The vessels are 64' by 20' and capable of carrying 75 passengers and three cars or 100 passengers if no cars are carried. The three vessels may be converted from 135 HP Tier 2 diesel engines to ZEAT all-electric propulsion systems and the corresponding infrastructure to facilitate charging. To support the conversion, Balboa Island Ferry was recently awarded approximately $8 million in grant funding through CARB's Advanced Technology Demonstration and Pilot Projects program.

Figure 28: Balboa Island Ferry, Newport Beach, California. From Reference [124].

Passenger Ferries

Water Emergency Transportation Authority Fleet

The Water Emergency Transportation Authority (WETA) currently operates six ferry routes in the S.F. Bay area. WETA worked with partners to develop a Zero Emission Vessel Feasibility Blueprint outlining the transition of their fleet of high-speed ferries to full zero emission vessels [125]. The blueprint considered available vessel technologies, current and future vessel routes, terminal infrastructure requirements, key stakeholders, timelines, and costs. WETA's existing operational routes are not considered short run ferries, but planned Treasure Island and Mission Bay routes will service shorter routes and will be required to be zero-emission by 2025. The first three phases of the conversion will involve WETA's short and medium routes, with the fourth phase involving longer routes and requiring further technological advancement due to large power requirements.

From the analysis, WETA determined that charging requirements for the first three phases will require DC fast charging at ferry terminals ranging from 1 MW to 5 MW. Additionally, battery energy storage will be required, with a possible solution being the storage of battery systems within floating docks used at ferry terminals.

For the first phase targeting commercial operation by 2025, WETA has partnered with Elliot Bay Design Group and Wärtsilä to develop 5 battery electric high speed ferries including three 150 passenger and two 300 passenger vessels [126]. To support the efforts, WETA has been awarded significant grant funding including $16 million grant from the Federal Transit Administration (FTA) for its Rapid Electric Emission-Free (REEF) Ferry Program, which will fund the electrification of four ferry floats at the Alameda Seaplane, Downtown San Francisco and Main Street Alameda ferry terminals [127]. The electrification project will include structural modification to the passenger floats, attaining and installing battery energy storage systems, grid connections and installation of charging equipment.

Switch Maritime Sea Change Hydrogen Ferry

The first-of-its-kind hydrogen fuel cell passenger ferry was developed under the management of SWITCH Maritime. The *Sea Change* is a 70' aluminum catamaran, designed by Incat Crowther, with a top speed of 15-knots and 75 passenger capacity. The vessel started construction in Alameda, CA at the Bay Ship & Yacht shipyard, and was completed at All American Marine shipyard in Bellingham, WA. Zero Emission Industries provided technical management and expertise for the hydrogen systems, and Sandia National Laboratories will analyze data collected from the initial demonstration operations.

The *Sea Change* s powered by a fuel cell system provided by BAE Systems comprised of three independent Cummins 120 kW fuel cells fed by 10 compressed gaseous hydrogen storage tanks with a capacity of 242 kgs at 250 bar [128]. The *Sea Change* has enough on-board hydrogen storage capacity for up to two days of normal operation. The *Sea Change* has a 600 kW electric propulsion system comprised of electric traction motors. This allows the *Sea Change* to operate for approximately 150 nautical miles at a cruising speed of 12 knots in between refueling.

Figure 29: Sea Change fuel cell electric catamaran ferry. From Reference [129].

The *Sea Change* must comply with rigorous USCG captain of the port, Port of SF, fire marshal, and S.F. city manager-approved fueling plan requirements. Switch Maritime has been bunkering the *Sea Change* from a pick-up truck and trailer at Pier 60 in SF according to their approved fueling plan. The engineered fueling plan was approved by all authorities having jurisdiction in SF. The *Sea Change* has a Short Run Ferry operating plan for WETA with Blue and Gold Fleet as operator with service beginning July 2024 and running for six months between Pier 41 and the S.F. Ferry Building [130]. The current regulatory process was a major challenge and led to significant project timeline delays due to the USCG design review and approval process which is performed on a per-vessel basis with retrofit or new-build ZE projects.

Tugboats

Crowley Marine *eWolf* Ship-assist Tug

Crowley Engineering Services (formerly Jensen Maritime Consultants) oversaw the construction of the recently delivered 82'×40' *eWolf*, which is the first fully electric ship-assist tug in the U.S. with a 70-ton bollard pull at the Port of San Diego [81]. The operational profile of the tug for the Port of SD demonstrated a good fit for battery electric vessel in that the tug was operated with the highest power during morning and evening maneuvers which left opportunities for charging during mid-day. The *eWolf* will operate principally on batteries that are recharged nightly at berth, although small onboard diesel gensets may be used if needed. Additionally, Crowley is focusing on improving the living and working conditions for crew through design features including improved safety. The *eWolf* will serve as a testing platform for future generations of electric tugs, which are targeting a 90-ton bollard pull. According to Crowley, the *eWolf* will be "approximately twice the cost of a conventional diesel tug, and that does not necessarily include the cost of the charging infrastructure.", which could be a barrier to adoption [131].

Figure 30: Crowley eWolf ship assist tug. From Reference [132].

One of the foremost challenges associated with *eWolf* was the development of the shoreside charging infrastructure. Currently, work is under way to develop a MW-scale charging station to support operation. In the meantime, a 480-amp AC connection is being used to recharge the batteries. The slower charging rate makes it more likely that the *eWolf* will need to use its onboard backup diesel genset, although this is being actively avoided when possible. As an example of the infrastructure challenges, an existing switch gear needed to be turned off to allow for the re-energizing of the new infrastructure. This step resulted in a month's delay as every impacted entity downstream of the switch gear had to be notified and provide approval. It was noted that the challenges with installing infrastructure across approximately 300 feet of a parking lot owned by one of the project partners was difficult, which highlights the significant challenge that will be associated with the installation of infrastructure in more challenging situations or locations.

Hybrid Electric Ship-assist Tug at the Port of Los Angeles

Funding is in place to support the design, construction, and demonstration of a battery electric hybrid ship-assist tug at the Port of Los Angeles and Long Beach with a total project cost of approximately $32 million [122], [133]. The initial design for the tug is an 82' vessel with 70-ton bollard pull and a 5.2 MWhr battery system capable of speeds up to 12 knots. A shared trial of the vessel has been approved by both the L.A. harbor commission and the Port of Long Beach [134]. According to one of the initial project partners, with 3 strategic charging stations throughout both Ports the tug could potentially operate in all-electric mode up to 90% of the time. However, it may be challenging to jointly deploy shoreside infrastructure throughout the two different jurisdictions, e.g., both have different power utilities, municipalities, etc. Currently, infrastructure is being developed at two berths at the Port of L.A. [134].

Hydrogen Zero-Emission Tugboat Project

A team led by CALSTART worked on the HyZET initiative to design a fully hydrogen-powered tug operating on liquid hydrogen for operation at the San Pedro Bay Port Complex [135]. Additional partners included Ballard Fuel Cell Systems, ABB, DNV, Chart Industries and the Port of Los Angeles. The tug was designed to be 90' with 90-ton bollard pull and powered by around 2,400 kW of fuel cell power and 1,740 kWh of battery energy storage. The project team conducted detailed modeling and concluded that, with the selected design, the tug would be able to meet the duty cycle for tugboat operations in the Port of Los Angeles. The tug is expected to operate for a minimum of one week in between refueling of an estimated 4,000 kg of liquid hydrogen stored onboard. The project team also found that there are feasible pathways for refueling using a liquid hydrogen bunkering system that connects the vessel to a tanker truck. The results of the project demonstrate the technological feasibility of such a design. However, the estimated cost of approximately $42 million is significantly higher than a conventional tug ($17 million), although estimations of economies of scale demonstrated a reduction in cost to approximately $30-33 million.

Bay Area Zero-Emissions Tug (BAZE ElectRA Tug)

The Port of Oakland with AMNAV received funding to support the design and build of a ZEAT electric tug that will operate in S.F. Bay [108]. The project will be supported by a turnkey microgrid system comprised of Caterpillar ESS and associated switchgear which will receive power from the Port which can be used to charge shoreside batteries while the tug is in operation to support fast charging and allow for charging at a lower power when docked. A tenant of the project will be developing a replicable prototype for zero-emissions vessel commercialization and identify and address safety, technical, and regulatory challenges.

Excursion vessels

***Enhydra* Excursion Vessel**

Operated by the Red and White Fleet, the *Enhydra* is a 128' plug-in diesel electric hybrid aluminum 600-passenger battery/diesel-electric excursion vessel capable of 12 knots providing harbor tours in the San Francisco Bay [136]. The *Enhydra* utilizes Corvus ESS with a capacity of 158 kWh, but was purpose built to support upgrades in the future to accommodate new technologies. BAE Systems supplied its HybriDrive propulsion system that includes a variable speed generator, propulsion power converter, house load power supply and control system. Additionally, two variable speed Cummins QSL9 305 kW diesel engines are included. The Enhydra was designed to require no more than 300 to 350 kWhr to do the one hour long route comprising a tour of the Golden Gate Bridge. The Enhydra could run 100% zero-emission excursion trips but is currently operating as a diesel/battery hybrid due to challenges associated with access to sufficient shore power to facilitate battery recharging between trips.

Figure 31: Plug-in hybrid diesel electric excursion vessel the Enhydra. From Reference [137].

Port of LA Harbor Breeze Excursion Vessels

The Port of LA recently was awarded funding for a project which includes the design, construction, and demonstration of two zero-emission capable battery electric hybrid excursion vessels [122]. The vessels will have Tier 4 compliant diesel engines operating on renewable diesel but will be able to operate in all-electric mode 30% to 100% of the time depending on duty cycle and route length. The vessels will be operated by Harbor Breeze, who will install shore power at a public wharf to provide charging.

Whale Watching Boat

A project led by the Monterey Air Resources Board with partners Monterey Bay Eco Tours and Left Coast Composites will build the first ZEAT plug-in electric hybrid whale watching vessel [122]. The vessel will be a 57’ catamaran with an Elco EP-70 electric propulsion system, twin 22 kW Polar Power DC Gensets, a lithium iron phosphate battery system, and Sunpower Maxeon 3 DC 420-watt solar panels. The vessel will be based out of Moss Landing and built to carry 49 passengers for year-round excursions.

Dredges

***Sandpiper* All-electric Dredge**

The *Sandpiper* is a 74’ x 26’ all-electric cutterhead suction dredge operated by Pacific Dredge and Construction that is used to maintain Santa Barbara Harbor and channels year-round [138]. The dredge has a 14,000-foot dredge discharge pipeline with 65’ SPUD length and a production of up to 28,000 cubic yards per 24 hours. The *Sandpiper* is powered by a 13,800 volt trailing electrical cable that is shore powered. The dredge is used in the harbor entrance to keep that channel at the desired depth and configurations for safe navigation.

Figure 32: Sandpiper 18' Cutter Suction Dredge used to maintain Santa Barbara Harbor. Image taken from Reference [138].

Curtin Maritime *DB Avalon*

Curtin Maritime has designed and built the *DB Avalon* which is the first hybrid-powered clamshell dredge in North America [139]. The 250' x 77' *DB Avalon* has a gross tonnage of 2412 and is powered by 2 Cummins QSK60 Tier 4 diesel generators and a large battery system comprising 4 banks of 20 lithium ion battery modules designed by Sumimoto Heavy Industries. The *DB Avalon* is designed with fully automated dredging technology, two fixed spuds and two walking spuds, and all hydraulic mooring winches. The *DB Avalon* is configured to optimize charge and discharge balance through regenerative power while lowering or decelerating the bucket and power from the batteries and generators to hoist. Additionally, the *DB Avalon* has the capability to connect to shore-power which could allow the dredge to operate as a ZEAT if the vessel was able to comply with CARB regulatory definitions for ZEAT.

Although not as ZEAT, the *DB Avalon* is being utilized in the Project 11 Houston Ship Channel Expansion to widen and deepen the important waterway for deep-draft ship and barge visits [140, p.]. Towing tugs accompany the dredge, bringing an empty scow alongside. The dredge excavates material and loads it onto the scows with the loading process taking anywhere from 4 to 10 hours. Once loaded, the scows are transported to offshore disposal areas, where the material is deposited. The *DB Avalon* can accommodate 18 crew members ensuring continuous operation.

Additionally, Curtin is planning the construction of an even larger hybrid clamshell dredger, the *DB Catalina*, which will utilize supercapacitors instead of a battery system. Two Wabtec 12V250MDC Tier 4 certified marine engines will power the dredge and will be prepared for conversion to operate on low-carbon or zero-carbon fuels when feasible.

Commercial Fishing Vessels

Due to power/endurance requirements and vessel design challenges, commercial fishing vessels represent a major challenge for transitioning to fully zero emission operations. Fishing vessels may be under transit for several days while locating fish and the vessel will load with as much weight as possible in order to operate profitably. Therefore, vessel stability and space constraints are an inherent design issue. Additionally, irregular operational patterns further complicate recharging or refueling infrastructure strategies, particularly for battery electric options. The majority of fuel consumption by fishing vessels is used for vessel propulsion, but auxiliary loads requiring fuel also include onboard processing, freezing and refrigeration, and others.

Reflecting these challenges, there are currently minimal ZEAT fishing vessel projects planned in California. The first is a recently funded project led by Clean Coalition and including SF Fishing Charters, Green Yachts, and EPTechnologies will include the conversion and electrification of the *Gold Rush* Commercial Fishing vessel to a battery electric hybrid [122]. The *Gold Rush* is based out of Fisherman's Wharf in San Francisco. The vessel is a retired Fish and Wildlife patrol craft and has a larger size which will assist in supporting the addition of batteries.

Small Hydrogen Harbor Craft

Zero Emission Industries is developing and demonstrating a 27' fast hydrogen fuel cell vessel that may be appropriate for various harbor craft vocations including work boats, pilot vessels, crew transfer vessels, harbor patrol boats, small fishing boats, etc. [141]. The vessel is currently undergoing initial sea trials and has been able to achieve 40 knots. Although the the highly diverse sizes, applications, duty cycles, etc. for the vocations mentioned may not all represent feasible options, the vessel may be appropriate for some applications. Smaller boats and/or those with shorter routes will likely represent more favorable, near-term opportunities for the deployment of ZEAT. Conversely, larger vessels, those operating for significant distances offshore, or those with heavy operational profiles will likely require additional technology advancement and proof of concept demonstration prior to commercialization.

Research Vessels

Research vessels in California are used for a diverse range of purposes including oceanographic, environmental, and marine biology research. There are several notable research vessels being used by different research institutes in California.

Currently, $35 million has been provided by the State of California to support the design and construction of a new ZEAT coastal research vessel with a hydrogen-hybrid propulsion system to replace the current R/V *Robert Gordon Sproul* being used for research at Scripps Institution of Oceanography [142]. Glosten will serve as the naval architect for the proposed 125' vessel that will integrate a hydrogen fuel cell power plant with a conventional diesel-electric power plant scaled to target 75% zero emission operation [143]. The ship will be outfitted with numerous laboratories, equipment, instruments, and sensing systems to support multidisciplinary research dedicated to understanding climate impacts on coastal ecosystems.

ZEAT Vessels in the U.S. and Globally

The following sections provides an overview of ZEAT CHC projects in the U.S. Additionally, examples of global ZEAT vessels are provided although it should be noted that these examples are not meant to be exhaustive, but rather provide a general understanding of current trends and focus on projects of interest for applicability to California.

Short Run Ferries

The 95', 15-vehicle/132-passenger *Gee's Bend* Ferry was retrofitted to battery electric powered by two lithium ion 135 kWh Corvus Energy battery systems and has been in service since 2019 [144]. The vessel was built by Horizon Shipbuilding, Inc. located in Bayou La Batre, Alabama. The *Gee's Bend* Ferry operates on the Alabama River connecting the small community of *Gee's Bend* with Camden. The route serviced is conducive to battery electric as it is a short (1.4 miles), involves a slow speed (5-8 knots), and includes a 30 minute loading/unloading time for charging. The ferry significantly reduces travel time for Gee's Bend residents. Charging stations are installed at both ferry terminals on either side of the route which allow for battery charging during docking. The ferry makes five round trips daily and can recharge in 20-25 minutes. The success of the Gee's Bend Ferry demonstrates the viability of battery electric propulsion for short run ferries with similar routes.

Passenger Ferries

In the U.S., Washington State Ferries (WSF) has set a goal of an emission-free ferry fleet by 2050. To achieve this goal, WSF plans to convert six existing vessels to hybrid-electric power and build 16 hybrid electric vessels with plug-in capabilities to operate primarily on shore power [145]. As a first step, the three largest Jumbo Mark II ferries the *Tacoma*, *Wenatchee*, and *Puyallup* will be converted with the contract awarded to Vigor Marine with work starting on the *Wenatchee* in September 2023. To support the hybrid ferry fleet, shoreside charging infrastructure will also be added to 16 WSF ferry terminals. In May 2023 WSF entered a partnership with a local utility to add ferry charging capabilities to eight additional terminals. WSF estimates that the Ferry System Electrification program will cost $3.98 billion [116].

There are several countries that have been actively investing in and deploying ZEAT ferries including in several in Europe, South America, and Asia, e.g., in Norway roughly 70 ferries have been converted to hybrid electric or all-electric since 2015 [146]. Plug-in hybrid electric ferries have been in operation for several years in Europe. For example, a 350' Ro-Pax ferry with a vehicle capacity of 827 tons powered by two 772 kWh battery systems that can be fast charged in 10 minutes has been operating in Norway since 2021 [147]. In Canada, BC ferries currently has six Damen Island-class 265' hybrid-electric car ferries capable of carrying 47 vehicles and 450 passengers, and was recently approved to purchase an additional seven more hybrid vessels [148], [149]. The vessels are powered by diesel-electric hybrid systems with the plan to transition to full electric operation when shore-side charging infrastructure becomes available. Currently, BC ferries has plans to fully electrify four of the vessels [150].

Similarly, several examples of ZE ferries exist worldwide. The first battery electric aluminum catamaran ferry has been in service since 2015 by Norled [151]. The 262' *Ampere* completes 34 3.5-mile-long crossings daily with a capacity of 120 cars and 360 passengers. The vessel is powered by a 1,000 kWh Li-ion battery system developed by Corvus and integrated by Siemens. The vessel can recharge during the 10-minute loading and unloading times from dockside charging stations that utilize 260 kWh stationary battery systems at both sides of the crossing to provide charging power and assist in minimizing challenges to the local electrical infrastructure. Similarly, the 195' battery electric ferry E-ferry *Ellen* has been operating on a 22 nm route in Denmark since 2019 [152]. *Ellen* can transport 198 passengers and 31 cars. The 100' *MS Medstraum* is the world's first fully electric fast ferry that will operate on a multi-stop commuter route in Norway [153]. The *MS Medstraum* can carry 147 passengers at a typical cruising speed of 23 knots, which is required to be classified as a high-speed craft. The vessel is powered by two Corvus Dolphin Power Lithium battery systems with a capacity of 1.5 MWh that can charge at over 2 MW. To support charging, Wartsila led the development of a novel lightweight shore-charging concept that uses standard CCS2 chargers which are the same as those used to fast charge electric vehicles in Europe. Candela developed the *Candela P-12*, an 40' catamaran all electric ferry with a 30 passenger capacity capable of average speeds of 20-30 knots, which will be trialed serving a passenger route in Sweden [154]. The vessel can cover more than 50 miles on a single charge and fully recharge the 180 kWh battery in one hour using DC fast charging. The vessel has a hydrofoil design that lifts it from the water during transit which reduces energy consumption and increases vessel speed. A 426’ Incat Hull 096 aluminum catamaran ferry will be the largest ship ever built using a fully battery electric propulsion system and waterjets and is scheduled for delivery in 2025 [155]. Wartsila will supply the energy management system, the power conversion system, DC shore charging system, 40-MWh battery system, eight electric motors, and eight axial flow waterjets. The Incat Hull 096 will operate between Argentina and Uruguay and will be capable of carrying over 2000 passengers and 225 vehicles.

There are also global examples of ferries powered by hydrogen fuel cell systems. Norled’s *MF Hydra* is a 270’ liquid hydrogen fuel cell electric ferry with a capacity of 300 passengers and 80 vehicles and has been in service since early 2023 [156]. The MF Hydra has 80 m^3 liquid hydrogen storage tank that feeds 2 200 kW fuel cells, two 440 kW generators, two Shottel thrusters, and can reach a speed of 9 knots. The fuel cells were supplied by Ballard Power Systems and the batteries were provided by Corvus Energy. The liquid hydrogen is supplied by Linde, who also developed, built and installed the fuel containment system, the associated onshore truck-to-ship bunkering facility, onboard storage tank and fuel processing equipment. Additional hydrogen fuel cell ferries include plans to build two new 390’ 120 car/599 passenger RoPax ferries which will operate on a 75 mile open ocean route in Norway [157]. The vessels are expected to consume approximately 5 to 6 tons of hydrogen daily and will be able to utilize other fuels as an additional safety measure.

Tugboats

In the U.S., a ZEAT Push/Tow tug in service in the U.S. is the Kirby Inland Marine’s 74’ plug-in hybrid electric inland towing vessel, the *Green Diamond* [158]. The *Green Diamond* utilizes two 575 KW Danfoss electric motors for 1,542 hp powered by a 1,243 kWh Corvus Orca-series battery system or onboard Caterpillar C18 generators. A Shell New Energies charging system will be used for dockside charging, allowing the vessel to complete trips on battery power approximately 80% of the time. Design changes were required to facilitate the plug-in hybrid technology, including reduced fuel capacity and the size and configuration of the ballast and potable water tanks to compensate for the weight of the batteries and associated control cabinets [159]. Maritime Partners is leading the design and construction of a hydrogen fuel cell-powered inland towboat for operation in the U.S. called the *Hydrogen One* [160]. Hydrogen fuel will be provided to the fuel cell power plant via on-board reformation of methanol fuel. The *Hydrogen One* will be able to embark on trips up to 550 miles at standard operational speeds between refueling.

Worldwide, KOTUG International currently has a line of all electric pusher tugs available for inland shipping ranging from 18’ to 72’, with the largest size (type M) capable of pushing barges with up to 4,000 tons of cargo [161]. To support vessel operation, KOTUG has developed a modular battery swap system ranging from 70 kWh to 6 MWh. The smaller vessel size is currently being used for various projects in the Netherlands. Additionally, the E-Pusher type M and E-Barges are being used by Cargill to transport cocoa beans from the Port of Amsterdam to a factory inland [162]. Zeeboat is developing all-electric towboats for the transportation of cargo on barges between ports and terminals with a targeted operation date of 2025 [163]. The design will be based on The Shearer Group’s proven hull design for a 95’ towboat and will be fitted with a battery energy storage system supplied by Shift Clean Energy.

Worldwide, there are several examples of existing ZEAT ship assist/escort tugboats. Robert Allan Ltd. is developing a series of electric tugs with the first completing the delivery voyage to its port of operation in Canada in 2023 [74]. The ElectRA 2800 battery electric harbor tugs will be 93’ in length with 75 tons bollard pull and 5,288 kWh of installed battery capacity. The tugs are designed to perform their regular ship-berthing and unberthing missions on battery power and recharge from dedicated shore charging facilities between jobs. The tug also employs backup generators to provide flexibility and redundancy of power systems. Damen Shipyards Group has constructed and delivered a full-sized harbor tug with 70-ton bollard pull, the RSD-E Tug 2513 *Sparky*, which is now in service at the Port of Auckland [75]. *Sparky's* battery system is 2,800 kWh which requires 1.4 MW of charging power and can sustain operation for two or more assignments prior to recharging. Damen is also developing an all-electric compact tug, the Azimuth Stern Drive Electric 2111 (ASD-E 2111), which is 68' by 35' with a 50-ton bollard pull. The compact tug is designed to operate in ports and harbors where there is little space to maneuver. NAVTEK Naval Technologies produces a range of all-electric tugs under the ZEETUG name which can be built from 5 ton to 80 ton bollard pull [76]. The 61' *Gisas Power* has 30-ton bollard pull was delivered in 2020 to service Gisas Port and is powered by 1.45 MW Corvus battery packs that can be recharged in one hour via a dedicated 1.2 MW fast charging station. Additionally, two sister tugs have been launched as well as a larger all-electric tug.

Research Vessels

In the U.S., the 50' *RV Resilience* will be the first plug-in hybrid research vessel in the Department of Energy's fleet [164]. The *RV Resilience* will have laboratory space with multiple science stations, a large deck, an A-frame, and knuckle crane to help move research equipment. The vessel will be powered by an advanced parallel hybrid-electric propulsion system, consisting of two Volvo Penta D8 diesel engines, capable of producing 374 kW each, supplemented by two Danfoss Editron electric motors. Power will be stored using a 113 kWh Spear Power Systems trident battery system, allowing the vessel to operate with zero-emissions during various operational modes for over 4 hours. The RV Resilience will operate on battery power at lower speeds and up to 20 knots using diesel power.

Operating in the U.K., the Transship II project is a retrofit of hydrogen fuel cell technology alongside existing diesel engines to enable zero emission for short trips and reduced diesel engine operation on longer trips [165]. The converted vessel is the 114' *Prince Madog*, a multi-purpose research vessel used to conduct marine research along the British coastline and in the Irish and Celtic seas. Currently, the vessel is powered by a 1400 hp Wartsila 20c diesel motor to achieve speeds up to 10 knots. The new hydrogen propulsion system will work in tandem with a diesel-fueled main engine to enable zero-emission operation at slow speeds or over short distances.

Excursion Vessels

Maid of the Mist is currently operating a fleet of all-electric battery catamaran passenger vessels featuring twin hulls made of 5086 H116 marine-grade aluminum alloy that serve as tour boats in Niagara Falls, New York. The transition to battery-electric vessels began in 2020 and were the first all-electric passenger vessels in the U.S. The vessels have a capacity of 600 passengers which is equivalent to the diesel-powered vessels they replaced. ABB provided integrated power and propulsion systems for the newbuild vessels, including an onshore charging system. The ferries are powered by two 316kWh lithium-ion battery packs supply power to a 400 kW electric propulsion motor controlled by ABB's power and energy management system. Each trip lasts about 20-30 minutes and consumes approximately 38 kWh and the batteries of the vessels can be recharged in seven minutes during the embarking and disembarking of passengers. However, the battery capacity is sufficient to provide multiple trips without the need for frequent recharging during operating hours. Reflecting the challenge of permitting novel technologies, the rigorous approval process required by the U.S. Coast Guard was a barrier to deployment and the use of the first Maid of the Mist vessels was delayed by approximately nine months due to the regulatory review including ensuring that the battery systems could be operated without safety issues.

Global examples of ZEAT excursion vessels include a plug-in diesel-electric hybrid sightseeing vessel in operation since 2022 [166], [167]. Designed and built by Marell Boats Sweden AB, the 49' vessel has a capacity for 12 people. The vessel is powered by a Volvo Penta twin D4-320 DPI Aquamatic hybrid solution and is capable of a top speed of 32 knots and a cruising speed of 25 knots. In addition, Volvo Penta technology is also being used to power an 82' hybrid-electric aluminum catamaran excursion vessel called the *MS Bard* in Norway [168]. The *MS Bard* has a capacity of 146 passengers and is capable of sailing at 10 knots for 10 hours using only battery electric power. In hybrid mode the vessel is capable of a 22 knot maximum speed.

Commercial Fishing Vessels

Zero-emission battery electric vessels are being pursued in Canada to support inshore lobster fishing operations as the usage pattern is conducive to deployment [169]. Most of the inshore lobster fleet travels about 12 miles from shore and maintains a consistent pattern of operation including leaving and returning to the same docking location on the same schedule daily. The conversion of a 22 foot fishing catamaran vessel for close-range lobster potting comprised two 6 kW motors powered by a 40 kWh battery pack was estimated to cost three times more than the cost of replacing the original diesel engine with a new diesel engine [170].

However, for offshore fishing vessels using mobile gear (e.g., trawlers, dredgers) all-electric systems are unsuitable due to the weight and volume of batteries required for higher power or longer routes between docking and technological advancements in battery technologies will be required. Hydrogen fuel cell powered vessels may represent a future possibility. A study of zero emission systems to power a commercial crab fishing vessel in Alaska on a one-way 1707 nm trip demonstrated the only feasible option was the use of hydrogen fuel cells in combination with liquid hydrogen fuel [171]. The long trip in combination with the small size of the vessel limits the available onboard mass and volume. However, it should be noted that the assessment only considered the one-way transit between port destinations and did not account for energy and endurance requirements when engaged in fishing activity which could affect the feasibility overall. A similar assessment was conducted for a fishing trawler following an actual voyage of 484 nm with four days of fishing [171]. Given the similar challenge of low power, long distance trips, hydrogen fuel cells were determined to be the only feasible option. A system utilizing gaseous hydrogen could accomplish one trip and a system with liquid hydrogen could be sized to achieve six trips.

Alaska-based Longline Fishermen's Association, NREL, and Sandia National Laboratories will convert a small 46' commercial salmon troller, the *I Gotta*, to a parallel plug-in hybrid battery-diesel system with support from the U.S. DOE's Energy Transitions Initiative Partnership Project [172]. Targeting operation by spring 2024, the *I Gotta* will be able to travel at full speed using its diesel engine and switch to a battery-electric motor when needed, which can reduce diesel fuel consumption by 80%. In the design phase, Sandia considered next-generation fuels including hydrogen, ammonia, biofuels and fully battery-electric scenarios, as well as the charging and filling infrastructure that would be required. Analysis of the data, including detailed modeling, indicated that a plug-in hybrid vessel was technologically feasible and would not cause the vessel to sacrifice speed or range. A Transfluid hybrid propulsion was selected that will allow the *I Gotta* to switch between a diesel engine for top speeds and a battery-electric motor during other periods, such as when the vessel is actively fishing. The hybrid system will also be capable of optimizing the use of both the engine and motor and equipped with data loggers to measure the achieved fuel efficiencies. In addition, the funding is expected to support the testing of two additional alternative propulsion systems including a series hybrid system that will allow flexibility for vessels traveling short or long distances while minimizing diesel use. The series hybrid will use an electric motor to power the propeller at all boat speeds and a battery to power the motor, allowing vessels to travel 10- to 20-mile routes under battery-electric power. Batteries can be charged at dockside. In the cases where vessels need to travel hundreds of miles batteries can be charged with an onboard diesel generator. There are also plans to build and test a fully battery-electric vessel for vessels which cultivate fish, shellfish, and aquatic plants. Such vessels operate within 10 miles of shore and follow regular transit schedules which makes them potentially good candidates for full electrification.

There are examples of ZEAT commercial fishing vessels worldwide. One of the first plug-in hybrid-electric fishing vessels is the *Karoline*, which has been in operation since 2015 in Norway. The *Karoline* is equipped with two Corvus 195 kWh battery packs and a Siemens BlueDrive PlusC marine propulsion system, as well as a 500-litre diesel engine. The battery bank can be fully charged overnight using a 63 Amp 220 V dockside charging system. The *Karoline* utilizes diesel propulsion during transit to and from fishing grounds and electricity for fishing, loading and unloading (generally around three hours per day). Skipsteknisk is designing the *Loran*, a 229’ plug-in hydrogen fuel cell diesel-electric hybrid fishing vessel for longlining [173]. In addition to conventional diesel engines, the *Loran* will also have two 185-kW hydrogen fuel cells and a 2,000-kWh battery bank which can be charged by the on-board diesel engines and fuel cells or by shore charging.

Pilot Boats

In the U.S., the Canaveral Pilots Association is partnering with Glosten and Ray Hunt Design on a demonstration project for the design, construction, and operation of an electric pilot boat at Port Canaveral [174]. Required performance criteria for the vessel includes a cruising speed of 18 knots and an operating range on battery propulsion only of 24 nautical miles.

Examples of global ZEAT pilot vessels include a 46’ plug-in hybrid diesel-electric pilot vessel developed by Goodchild marine at the Port of London Authority in 2019 [175]. The parallel hybrid system is supplied by Transfluid and is coupled with a 400 HP Yanmar engine and a lithium-ion battery system. The battery system can provide enough power for 40 nm at speeds up to 15 knots on a full charge, with speeds of 19 knots attainable when the diesel engines are used in tandem. Transfluid developed 78’ pilot boats equipped with two MAN V6 diesel engines, producing 600hp at 2,100 rpm. For each shaft line, the hybrid system consists of Transfluid’s HM3350 module, with two 75kW electric motors powered by a 288V battery pack [176].

For examples of all-electric operation, in France the historic pilot boat *Maguelonne* was retrofitted battery electric operation and is now operational at the commercial port of Sète-Frontignan [177]. The 39’ *e-Maguelonne* can reach a top speed of 19 knots. Charging is provided by a 120 kW shore power facility and takes approximately 90 minutes to recharge after three consecutive pilot transfer trips. Robert Allan announced plans for a 53’ aluminum all-electric pilot boat called the *RAlly 1600-E* that can reach a top speed of 20 knots in 2018 [178]. However, the vessel will be limited to jobs where route is 5 nm or less which guarantees approximately 30% remaining battery capacity. It should be noted that the plans for the *RAlly 1600-E* were released in 2018 but it is unclear if the vessel was constructed.

1.1.1.26.1.1 Workboats/Crew/Supply Vessels

There are several examples of ZEAT workboats or crew transfer vessels worldwide with many associated with the offshore wind industry. A Japanese start-up company called PowerX is developing an all-electric automated vessel concept called the *Power ARK 100*, a specially designed 330' trimaran for transporting fully charged batteries from offshore windfarms to the mainland to support the electrical grid [179]. AMC is developing a 50' all-electric Faraday-class electric personnel transfer vessel to transport wind turbine technicians from ports to windfarms. Plans include the use of battery swap strategies and the use of offshore charging at windfarm locations to provide around 4 to 5 hours of vessel operation [180]. Similarly, Artemis Technologies has developed a design for a 39' all-electric high-speed crew transfer vessel for the offshore wind industry. The *Artemis EF-24* CTV has a max speed of 36 knots and a range of 87 nautical miles. Two hybrid crew transfer vessels from Volvo Penta and Danfoss Editron are operating in Denmark [181]. The 115' catamaran vessels have a max speed of 25 knots and a capacity for 24 passengers and are used to support the offshore energy and wind industry. The vessels can operate in zero-emission electric mode for up to 8 hours. Hybrid-electric crew transfer vessels are also operating in the UK, including two 82' vessels with 19.6 T bollard push and the capacity to accommodate 12 to 24 passengers [182]. A project to develop an offshore charging station for hybrid and electric crew transfer vessels has also secured funding in the UK [183]. The project will involve using battery and intelligent energy management technologies to charge a vessel via an Oasis power buoy while at sea. The buoy will be supplied by AC power generated by existing wind farms.

Considering full zero emission vessels, Ulstein is developing the *SX 190 DP2* construction support vessel using a 2 MW Nedstack fuel cell power plant coupled with 5.5 MW of conventional diesel-electric engines [184], [185]. According to Ulstein, the design will be capable of operating for 4 days in zero-emission mode with a future target of up to two weeks if improvements in hydrogen storage and fuel cell technologies are achieved. It was scheduled for sea trials potentially as soon as 2022, but no additional information is available at this time. Damen Shipyards Group will commence construction of the *Multi Cat 1908 Electric*, a fully electric vessel that can be used for a range of workboat activities including general port maintenance, buoy handling and salvage work [186]. The *MuC 1908 E* is 62' by 27', with a deck area of 377 square feet. The vessel has 7.7 tons of bollard pull and can travel at speeds of up to 7 knots. The batteries used for propulsion can operate for up to twelve hours on a single charge and have a lifetime of ten years.

Battery Charging and Hydrogen Fueling Infrastructure

To support the enhanced operation and successful operation of ZEAT vessels, the buildout and availability of infrastructure will be required to provide 1) electrical charging of on-board batteries for battery electric and plug-in hybrid electric vessels and/or 2) hydrogen refueling of fuel cell electric vessels. The current lack of infrastructure represents one of the most significant barriers to the adoption of ZEAT in California. The following section discusses requirements, considerations, and potential barriers related to the design, development, and utilization of charging/fueling infrastructure.

Battery Electric Charging

1.1.1.27 Charging Strategies

There are many potential charging strategies for battery electric and hybrid CHC. First, methods for charging CHC include either alternating current (AC) or direct current (DC) high power charging. AC chargers are commonly used for slower or overnight charging. They provide a reliable and cost-effective solution for charging electric boats at marinas or docking locations equipped with AC outlets. In contrast, DC chargers can provide large amounts of power quickly which can support CHC that require faster charging during periods of operation. Although less prevalent for electric CHC compared to electric cars, DC fast charging is gaining traction, enabling boaters to charge their vessels swiftly and get back on the water. Several companies currently offer DC charging systems for CHC including ABB and Siemens. In Europe ferry chargers have been demonstrated that can provide 15 MW AC medium voltage power to a ship, or over 23 MW in DC [187], [188].

Factors that will determine the most effective charging solutions include vessel routes and schedules, available charging points, vessel battery size, charging power and voltage, crew handling and manipulation, docking methods and mooring strategies, sea and weather conditions, and space availability both for vessels and dockside. The feasibility of different charging strategies may be influenced by battery charging rates (C-rate), grid capacity, size and weight of the connection equipment, and the time available for charging based on operational profiles.

It should be noted that, for DC fast charging, current dockside infrastructure usually requires a shore side battery system that serves as a buffer and recharges with AC charging. This is due to the constraints that available grid capacity can place on charging power in the absence of grid upgrades. Charging for battery electric vessels is characterized by short-term and high-power demands which can cause large peaks that may challenge the resiliency of electric service providers and stress local electrical grids and power generation facilities [131]. Strategies to alleviate these peaks may include battery storage systems or local, distributed power generation assets which can provide on-site electrical power and potentially waste heat for other uses [24]. Additionally, mobile battery energy storage systems that can be deployed on marine barges and tractor-trailers may represent a strategy to solve the near-term challenges of available power supply and electrical equipment shortages [131]. Additionally, the large power demands can also incur high demand charges due to existing utility rate structures and the use of a battery system can help avoid charging costs.

Hybrid ships typically have an engine with a connected generator that produces electricity at AC and a battery that produces DC. Generally, electricity has been distributed in AC where needed. However, electricity distribution that provides DC for battery charging eliminates a conversion step and is more efficient. Indeed, many hybrid ships are being designed with only a DC connection, which may make sense for smaller hybrid vessels with small high-speed engines. In contrast, this may not be ideal for high-powered vessels with many engines or larger hybrid vessels as these vessels generally have diesel generators as the main power source which produces AC, and the main consumer of power is an electric motor or auxiliary load which both require AC.

In addition, there are many different configurations for vessel chargers including how the vessel connects to the system. Standard plug-in chargers are often used, which requires manual connection using strategies like those used for electric vehicles, with existing examples including ferries in Norway. This requires crew members to manage the connection and disconnection of the vessel to the charger. An example of this type of system includes ABB's 1.65 MW chargers, consisting of a transformer, ACS880 converters, MCS plugs and cable management for electric ferries which must be connected by the vessel crew [189]. While this approach is simpler, cheaper to install and the most common approach currently, it may also increase the cost for vessel crew, limit the size and weight of the charger, and increase the charging time of the vessel. In contrast, there are several charging strategies that use various levels of automation to achieve the connection. These include automated plug-in systems that use robotic arms or other technology to connect to the vessel's charging port and inductive charging systems whereby charging pads are installed on the vessel and dock to transfer electricity wirelessly. For example, Stemmann-Technik offers ferry charging systems that can provide up to 23 MW and the ability to connect/disconnect automatically [188]. Other potential vessel charging strategies include battery swapping systems or mobile charging units, although these are currently less common due to cost and other barriers.

Power and voltage levels will in part determine the characteristics of chargers such as size and weight of the supply cables and selection of the plugs. High currents above 400 amps present additional challenges as they will either require larger, heavier cables or cooling if thinner cables are used. Contact resistance in the plug leads to more heat dissipation and will require a higher force between contact surfaces to avoid heating. Available space at the dockside and weight and forces from equipment can also prevent some systems from being utilized. Furthermore, the charging system, including the cable management and connections must account for environmental variables including tidal fluctuations and wave activity.

1.1.1.28 Grid Upgrades

In many cases the large power requirements for CHC charging will necessitate the upgrading of the current electrical infrastructure at ports, marinas, docks, etc. Electrical service and distribution requirements are based on type and number of vessels, overall usage profiles, proximity to existing infrastructure, peak demands, overall usage profiles, etc. Upgrades can include increasing electrical capacities through upgrades to transformers, substations, and distribution lines. The reinforcement of existing or the installation of new high-voltage lines may be needed to ensure a strong grid connection to maintain stability and reliability. As previously mentioned, the integration of battery storage systems to manage peak loads and storage during off-peak times will be necessary in many situations and planning for integration of these resources into the larger grid is needed. It will also be critical to upgrade or install appropriate safety systems to ensure compliance with codes and standards. To accomplish many of these steps, site modifications will be necessary including trenching, upgrading electrical panels, installing new wiring and conduits, and achieving proper grounding.

The international standard for utility connections in port (IEC/IEE 80005) for high-voltage shore connection (HVSC) systems allows vessels to access shore power and eliminates the use of auxiliary engines while docked. Potentially, HVSC systems could be used to charge battery systems of hybrid and all-electric CHC, and some larger vessels (RoPax, RoRo, and PCTC) currently being built with hybrid propulsion in Europe are equipped with IEC 80005 shore power connections allowing access to shore power at any compliant port, which is expected to include the majority of prominent ports by 2030 including those in California [190]. One benefit of HVSC provided shore power is that it can allow for the charging of batteries while meeting any auxiliary loads in parallel. However, it is expected that HVSC systems will have practicable applications only for ships requiring 1 MVA or higher and/or ships with HV main supply. The lower voltage shore connection systems that will be applicable to most CHC in California are not covered by the standard. Additionally, connecting to HVSC systems can take a few minutes and faster and simpler connections featuring standard plugs that can be connected or disconnected easily or even automatically may be required for applications where fast charging times are required, such as ferries.

1.1.1.29 Current and Planned Projects in California

Given the advancement of battery electric CHC, there are numerous examples of existing battery electric charging infrastructure in Europe. Generally, these systems are designed to meet a specific vessels requirement and therefore represent a private installation only accessed by that vessel or a fleet of vessels under the same owner/operator. As an example of a public charging network, Kempower is developing a network of publicly available fast charging stations for smaller vessels in Norway including the deployment of multiple dockside installations ranging in total charging power from 200 kw to 600 kw (each charger can deliver 200-220 kw) [191]. According to Kempower, the small footprint for their charging systems makes them suitable for deployment on floating pontoon piers and docks. Although chargers at this size are generally restricted in feasibility to smaller vessels including private recreational boats, smaller CHC may be applicable including some work boat types depending on duty cycle. Additionally, the concept could potentially be scaled up to meet the feasibility requirements of larger vessels or vessels with more demanding duty cycles.

In California, Crowley and the Port of San Diego are cooperating in the construction of a microgrid shoreside charging station at the Port of San Diego to support the fully electric *eWolf* ship assist harbor tugboat [192]. The charging station will be a microgrid facility to support fast charging while reducing peak loads on the local electrical grid. The station will be equipped with two containerized battery energy storage systems provided by Corvus Energy with each capable of providing nearly 1.5 MWh for a total capacity of 2.99 MWh. The station also incorporates a solar power array to provide renewable energy. In addition, the station will be equipped with a battery monitoring system, HVAC, and firefighting and detection technology for safety. Notable challenges with *eWolf* are alignment of charging schedules with local utility rates which may include time of use pricing as well as demand charges that can greatly affect the price of electricity paid for charging. To address this, the station is designed to operate during off-peak hours from the local utility grid when electricity prices are lower.

A recently funded effort led by the Center for Transportation and the Environment with project partners including ABB, American Bureau of Shipping, Cal Maritime, the Ports of Long Beach, LA, and San Diego, and others will establish an industry standard for megawatt-scale charging systems for marine electrification [122]. The project will seek to establish a design standard and deploy charging systems to service the two Crowley tugboats, the existing *eWolf* and the planned plug-in battery electric tug at the Port of LA. The charging systems will be supported by microgrids at two locations at the Port of LA and upgrades to existing infrastructure at the Port of San Diego.

Hydrogen Fueling

1.1.1.30 Hydrogen Fueling Strategies

Currently there is a lack of hydrogen bunkering infrastructure in California and the proliferation of hydrogen-fueled CHC will require standardized, reliable hydrogen fueling that is fast, safe, and secure. Potential hydrogen fueling strategies for CHC include hydrogen both in gaseous and liquid form. Currently, most of the hydrogen used for transportation is gaseous. Typically, storage and dispensing of gaseous hydrogen is typically done at high pressure ranging from 350 to 700 bar. In contrast, liquid hydrogen is stored in an insulated tank at approximately -253 degrees Celsius and then converted into compressed gas and dispensed in the same manner as gaseous hydrogen. Benefits of liquid hydrogen include a higher energy density allowing for larger amounts of hydrogen to be transported and stored in smaller volumes. In California, liquid hydrogen pathways are being pursued including the first public station to support heavy duty vehicle fueling that recently opened near the Port of Oakland [193].

The aim for a marine hydrogen fueling network will be to maintain high reliability while minimizing cost (e.g., due to redundancy measures and maintenance) [194]. In particular, high reliability will be critical to achieving early market success for hydrogen CHC [195]. The current on-road vehicle hydrogen station network in California has experienced low reliability due to a variety of issues including component failures and low hydrogen supply [194]. Given the similarity of the technologies currently used in current vehicle stations and those that will be used for CHC fueling, it is possible that efforts to address these existing issues can serve to benefit the development of CHC fueling strategies [196].

Safe and secure fueling will require the adoption of standards and best practices that minimize hazards from hydrogen storage and dispensing systems and minimize risk for fueling session disruption, tampering, and data insecurity. As marine hydrogen fueling strategies grow in both size and number, safety and security standards will need to be developed and re-evaluated to reduce risk.

1.1.1.31 Hydrogen Supply

Currently, the bulk of hydrogen (i.e., ~95%) is produced from natural gas using steam methane reformation (SMR) and in the near-term is the likely production pathway that will provide hydrogen for vessel fueling. However, SMR of natural gas does not represent an optimal outcome from an environmental perspective, particularly as it results in air emissions of GHG and pollutants including NO_x and $PM_{2.5}$. Given California's focus on reducing GHG emissions which includes achieving carbon neutrality by 2045, there is momentum in California for the production of cleaner hydrogen from renewable pathways that can provide fueling for hydrogen CHC [33]. Despite the current reliance on fossil fuel hydrogen, it is expected that renewable hydrogen, including production from electrolysis using renewable electricity, will 1) become more widely available and 2) will experience reductions in cost [197], [198]. One major step towards developing a renewable hydrogen ecosystem in California is the award of a DOE funded hydrogen hub in California under the Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) [199]. Under the ARCHES initiative, projects are planned at the Ports of LA/LB and Oakland.

1.1.1.32 Current and Planned Projects

Currently, the only example of hydrogen fueling of CHC in California is the *Sea Change* which involves the use of a mobile tanker truck supplying gaseous hydrogen directly to the vessel. Each refueling provides approximately 70-80 kg of hydrogen, which is less than the 240 kg on-board storage capability due to the use of smaller tanker trucks. To facilitate this, ZEI has developed a unique fueling system that allows direct fueling from the tanker truck and offers the system as a commercial product [200]. Given the safety concerns around hydrogen, the current refueling process must comply with stringent regulatory and safety requirements. This is significantly more stringent than those required for diesel refueling and it is likely that regulations will be relaxed as more experience with hydrogen is gained for maritime use.

Reflecting the energy density benefits, liquid hydrogen is being used to power the *MF Hydra* ferry in Norway. The *MF Hydra* is refueled using renewable liquid hydrogen trucked from a Linde electrolyzer plan in Germany [201]. Linde also designed and built the fuel containment system, the associated onshore truck-to-ship bunkering facility, onboard storage tank and fuel processing equipment. The *MF Hydra* has been designed to utilize three tons of liquid hydrogen provided every three weeks.

As an example of a novel strategy for CHC refueling, Hornblower Group is the leading the design and construction of the first floating hydrogen fueling station for commercial harbor craft refueling expected to be operation in 2024 [202]. The station is expected to be comprised of a first-of-its-kind hydrogen production, storage, and fueling capabilities of up to 530 kg of hydrogen per day. Glosten is leading the design and integration of the hydrogen production, storage, and bunkering equipment and working with the U.S. Coast Guard to establish the regulatory framework and design approvals. The goals of the project include demonstrating the feasibility and viability of hydrogen production, storage, and fueling on the water, establishing robust science-based protocols, procedures, operating parameters, and attendant training materials for the safe and routine generation and storage of electrolyzed hydrogen and handling of water-to-water and water-to-land hydrogen and fuel-cell power transfer [203].

Considerations for Infrastructure Development and Deployment

Establishing effective infrastructure for ZEAT CHC will require thorough planning including many different factors to ensure reliable, safe, and appropriate charging and fueling. The analysis conducted by WETA of required infrastructure to support their future electric ferry fleet serves as a good example of the type of analysis that must be considered initially [125].

Key considerations for charging and hydrogen fueling infrastructure for CHC includes:

- **Location:** Identify strategic locations for infrastructure based on the patterns of CHC travel, docking areas, operator needs, and others including marinas, ports, marinas, and destination sites.
- **Power Capacity:** Confirm that existing electrical grid and infrastructure at infrastructure sites can support required power demands. Evaluate power capacities of infrastructure to potentially accommodate both single charging and simultaneous charging of multiple vessels.
- **Charging Rate:** Select infrastructure that meets the requirements of CHC operators including suitable charging speeds for various battery electric CHC use cases. This will require assessing the battery sizes of the electric CHC and anticipated charging times.
- **Compatibility and Standards:** Meet industry standards CHC infrastructure to ensure feasibility across different CHC vessel types including using widely accepted standards such as those established by the International Electrotechnical Commission (IEC) or other regional standards.
- **Connectivity and Communication:** Implement smart infrastructure solutions that enable communication between charging/fueling stations, vessels, and central management systems, e.g., providing real-time information on charging/fueling status and availability.
- **User Experience:** Ensure user-friendly charging/fueling for CHC operators including clear signage and instructions, simple and easy to use interfaces, etc. Additionally, ensure secure and convenient payment systems including various methods, e.g., credit cards, mobile payments, subscription-based models.
- **Safety and Compliance:** Adhere to safety regulations and standards for electrical installations in maritime environments. Implement safety features, such as proper grounding, protective enclosures, and emergency shut-off systems.

- **Scalability:** Design charging infrastructure with scalability in mind to accommodate the increasing adoption of electric boats. Plan for potential expansion and upgrades as the demand for electric boating grows.
- **Environmental Impact:** Consider the environmental impact of the charging infrastructure. Opt for energy-efficient systems and explore the use of renewable energy sources, such as solar or wind power.
- **Maintenance and Support:** Establish a maintenance plan for regular inspections and repairs of charging stations. Provide customer support services to address issues and ensure the reliability of the charging infrastructure.
- **Regulatory Compliance:** Comply with local regulations and permitting requirements for the installation of charging infrastructure in maritime environments.

Key Steps for Infrastructure Development

Planning and developing marine charging and fueling strategies will require a multifaceted approach including considerations of infrastructure upgrades, stakeholder collaborations, and streamlining regulatory approval processes, among others. Major aspects towards achieving successful infrastructure for CHC includes:

- **Power Demand Assessment:** The power requirements of CHC utilizing specific infrastructure will need to be determined for both current and future demands to determine specifications including the number of charging plugs, charger power ratings, overall power capacities, and if any grid upgrades will be needed.
- **Grid Connection Analysis:** The capacity and reliability of local grid power supply will need to be assessed in tandem with charging infrastructure including available onsite or connections to offsite utility substations. Options that will need to be evaluated include direct medium or high voltage utilities connections versus developing on-port substations. The establishment of microgrids (such as that being pursued by Crowley at the Port of San Diego) can help alleviate pressure on existing grid infrastructure. This step should be coordinated with utility power providers early and on-going throughout the project.
- **Optimal Design of Charging Architecture:** The design of charging infrastructure must consider the layout of dock or port berths for CHC, vessel power demands, grid supplies and others. Key design points will include centralized vs distributed charging points, charging power levels and redundancy, load balancing capabilities, and smart charging technologies. Standardization of connections will be important for maximizing interoperability across a wide range of CHC and the avoidance of stranded assets.
- **Utilize Existing Infrastructure:** Where and when possible, leveraging existing infrastructure is a cost-effective approach to expand charging facilities. Retrofitting current structures with charging locations can help overcome challenges and provide suitable charging opportunities.
- **Portable Charging Solutions:** Consider portable charging solutions (e.g., portable battery banks, charging trailers) to provide flexibility and accessibility for CHC charging. Portable units can be positioned at different docking locations and provide short-term charging availability while more permanent infrastructure is established. Examples of these include the Zero Emission Industries Fuel Interface Box for hydrogen and Power Box for electrical charging.
- **Collaborative Initiatives:** Encouraging early and ongoing partnerships between port authorities, CHC operators, utilities, regulatory bodies, and local communities can streamline the development of charging infrastructure as combining resources and expertise allows stakeholders to work collaboratively to establish charging in strategic locations. Forming

working groups can assist in overcoming technical challenges and regulatory requirements. Community outreach will also be valuable in permitting approvals.

- **Funding and Financing:** The high upfront capital expenditures required will necessitate funding through financing, government incentives, public-private partnerships, and external grants. Business models and rate structures will further need to be developed for cost recovery for charging and fueling providers.

1.1.1.33 Need for Standardization

The issue of standardization of equipment, policies, and standards related to is also of major importance, particularly if publicly available or otherwise shared infrastructure becomes a reality e.g., some charging solution providers are pushing to set a standard for all marine-capable charging stations to include CCS2 connectors, the fast-charging plug standard in Europe that supports both AC and DC charging [191].

Infrastructure standardization will be important in providing market confidence, protecting State investments, and accelerating and streamlining ZEAT vessel deployment. A holistic approach of all standards and policies related to vessel charging and hydrogen fueling will be important for effective and efficient broad infrastructure deployment.

The benefits of adopting a standardized approach to vessel charging and hydrogen fueling include:

- **Improved performance:** Allows for sharing of knowledge and data across industry, academic, government, and non-governmental organizations. This coordination can support optimal design of equipment and protocols that maximize technical performance including reliability, accuracy, and efficiency.
- **Improved safety:** Standardizing safety protocols ensures all infrastructure equipment meets minimum safety requirements, protecting users from known safety hazards of charging and hydrogen fueling, such as electric shock and fire.
- **Improved reliability:** Standards establish technical specifications for manufacturers to follow, improving the consistency between individual stations and between different equipment providers.
- **Reduced cost:** Standardizing parts can reduce costs for manufacturing station components and reduce costs for maintenance by increasing ease of repair.
- **Reduced risk of stranded assets:** Standardization results in stations being interoperable across multiple OEMs, increasing access and reducing the risk of stations becoming obsolete in the face of an evolving market.
- **Improved ease of maintenance:** Standardized stations can leverage established test methods for troubleshooting errors and utilize standardized replacement parts.
- **More effective workforce training:** Standardized design and operation of charging and hydrogen fueling infrastructure means that the workforce trained to construct and maintain the infrastructure are well-equipped to work for a variety of station providers on diverse projects.
- **Improved user experience:** Standardized labeling, payment steps, as well as charging and hydrogen fueling protocols mean that customers can expect a similar user experience across stations.

Potential Barriers to Infrastructure Development

Seaports, harbors, and marinas are faced with distinct challenges to deploy zero-emissions vehicles and equipment including CHC and associated charging/fueling infrastructure due to factors including high energy demands, restrictive duty cycle conditions, and varied tenant and operational interests.

Historically, electricity demand at these locations has been low and therefore existing grid capacity and other features is often insufficient to support the power demands of vessel charging.

At most California seaports the port authorities do not own or operate the CHC targeted for zero emission conversion and must work with private operators to deploy vessels and install required infrastructure [204]. As an example of the unique challenges faced by ports, a blueprint for the electrification of cargo handling equipment at the Port of Long Beach reported that two gearmen[2] are onsite per shift for battery charging which complicates staffing procedures [205]. [205]. Though the assessment was for cargo handling equipment, it is possible that CHC charging and hydrogen fueling will require similar staffing requirements. Another barrier is the required workforce and training for the zero-emission CHC and the associated charging and hydrogen fueling infrastructure.

Additionally, marine environments can entail difficult conditions and installed infrastructure must be able to withstand such conditions requiring an emphasis on the durability and reliability of the equipment.

Lack of charging infrastructure may not only prevent new ZEAT from being deployed but also prevent the optimal use of existing ZEAT with an example including the Enhydra ferry operating in San Francisco. Though the vessel is equipped to potentially operate in 100% zero emissions mode for excursion trips, it is currently unable to do so due to the lack of dockside charging infrastructure. Similarly, examples of CHC able to operate on battery power but limited by lack of charging infrastructure include the Penguin Tenaga pilot vessel in Singapore [206].

Current challenges for hydrogen fueling and electric charging of ZEAT vessels include:

- **Limited Availability:** Infrastructure specifically designed for CHC is essentially non-existent in California and will require the buildout of a network of novel technologies and strategies.
- **Challenging Installation Requirements:** Installing charging infrastructure faces distinctive challenges requiring reliable equipment capable of withstanding marine environments.
- **Distribution Network:** Establishing a network of charging locations will be required to support widespread zero emission CHC deployment. Cooperative efforts between port/harbor authorities, municipalities, CHC operators, utility providers, and other stakeholders will be necessary to ensure development and access to charging infrastructure.
- **High Cost:** The cost of deploying infrastructure is potentially high and the responsibility for deployment currently falls on the vessel owner and operator. Additionally, the cost of vessel charging requires the consideration of utility rate structures in the region of deployment.
- **Space Constraints:** The space required to accommodate the footprint of charging and fueling infrastructure can be a major challenge at CHC docking locations including marinas, harbors, and seaports.
- **Policy and Regulatory Issues:** Regulatory requirements associated with multiple agencies can significantly complicate project permitting and approval. In many cases existing regulatory requirements are outdated and inflexible which can constrain project timelines.

[2] A longshoremen job classification for a person who fuels vehicles.

Barriers to ZEAT Vessels

In addition to the challenges posed by developing appropriate supporting infrastructure, there are other issues that may serve as barriers to the enhanced adoption of ZEAT CHC in California. The following section discusses some of the more prominent issues. As a result of many of the factors described in this section, current ZEAT vessel projects have faced costly and unexpected delays in project timelines. Two examples of this include the *Sea Change* hydrogen fuel cell ferry and the *eWolf* electric tug, with both experiencing delays of multiple years from their original timelines.

Regulatory Requirements

The regulatory landscape for ZEAT vessels is still being established, and current projects face many different hurdles associated with their design, construction, and operation in California. The Applicable Code of Federal Regulations design standards are stringent and in many cases are not established for ZEAT technologies. Battery standards are more advanced than hydrogen but are still in early stages.

The USCG is generally supportive of new technologies but must currently approve first-of-kind vessels and infrastructure on a case-by-case basis using a design review basis pathway. It is expected that the process will become simpler and smoother as more experience is gained and protocols, education, training, and federal agency coordination are further developed. One step towards this would be the establishment of more efficient approval processes for ZEAT vessels which would streamline the regulatory process. Clarification of requirements including clear, detailed guidance on regulatory requirements, standards, and procedures associated with vessel design, construction, and inspection, provide consistency and predictability to reduce risk and increase vessel build efficiency with fewer barriers, expedite the review process which reduces timelines and cost, provide risk mitigation by identifying safety concerns and providing proactive guidance to mitigate them, and facilitate improved communication between designers, builders, regulators, and other stakeholders.

Several ship builders noted the increased cost associated with compliance with the Merchant Marine Act of 1920 (also known as the Jones Act), a federal law affecting vessel construction and operation. Under the Jones Act, U.S. Coast Guard regulations require that covered CHC must be manufactured entirely domestically and all "major components of the hull and superstructure" must be manufactured in the United States [207]. A "component" must exceed 1.5 percent of the vessel's steel weight to be considered "major". The requirement adds considerably to the overall cost of the vessel and has been cited as causing lengthier construction times [208]. Many of the companies that are currently active in the building of ZEAT compliant CHC are in Europe and have European shipyards. According to discussion with several foreign based shipbuilders, the ability to utilize foreign shipyards and foreign commodities in vessel construction (e.g., steel) would result in a more cost-effective and result in quicker and streamlined build times. It should be noted however, that all CHC must comply with these regulations including conventional, non-ZEAT vessels. However, the regulation may impact ZEAT vessels more as domestic production of conventional vessels is well established and not as reliant on foreign stakeholders.

Stakeholder Engagement

Deploying ZEAT vessels and infrastructure requires extensive collaborations with numerous stakeholders, potentially with competing priorities, including but not limited to the U.S. Coast Guard, Port Authorities, fire marshals, regional and local governments, neighboring tenants at ports and marinas, utilities, and vessel builders, owners, and operators. Navigating between diverse groups of stakeholders can be difficult and lead to challenges and project delays.

To address this challenge coordination should begin early and often with all stakeholders, including close collaboration with the U.S. Coast Guard during the vessel design phase and local utilities in regard to infrastructure. Generally, utilities get involved with projects during design and build phases, but it will be important to engage beginning during the planning phase given the challenges and cost of delays associated with infrastructure development.

In addition, workforce training will be needed including training captains and crews in how to operate a novel vessel structure. Similarly, engineers need to be trained on the electronics side of the vessel, e.g., how the battery system works, safety features, etc. To support this the development and publishing of training and operating manuals will be important.

Financial Risk

Vessel owners and operators may face financial risk by pursuing ZEAT CHC, particularly as most will currently serve as early adopters of new technologies. This is particularly true for smaller owner/operators such as Angel Island and Balboa Island short-run ferries which do not have the same financial capacities as larger companies. A further example of the financial risk includes those from unique and unexpected events, such as the recent COVID pandemic which added significant delays and costs to existing ZEAT vessel projects in California.

To address this issue, significant amounts of grant funding have been made available through numerous state and federal agencies (e.g., CARB, California Energy Commission, Air Quality Management Districts, etc.). Despite this, the current high costs of ZEAT technologies and infrastructure can still place sizeable financial burdens on owner operators, even if grant funding is achieved. Additionally, the structure and schedule of grant funding may still cause challenges for owner/operators as they may require the upfront costs be covered with grant funding being dispersed in a reimbursement approach. Given the high cost of current projects, this may be difficult for owner/operators to incur, particularly for smaller businesses. To address this, CARB's LCTI Advanced Tech. and Demo Pilot Projects Fund accounts for this disparity in the cost sharing requirements for small and micro-businesses.

Technology Availability

Currently, the available commercial marinized fuel cell systems, battery systems, and other required components may not be suitable for all vessel types and applications. Environmental conditions can be challenging for electrochemical devices including exposure to a saltwater environment. Meeting many CHC performance needs requires propulsion systems to be used heavily, often working at 80-90% power. This is challenging for current fuel cell systems, for example, as this requires pumps and blowers to be at or near capacity for extended periods of time. Similarly, energy density limitations of current batteries restrict their use to select CHC vocations.

According to the American Association of Port Authorities, domestic production of the majority of zero emission port equipment (i.e., not just harbor craft and associated infrastructure) is challenging as many types do not have American manufacturers [131]. Additionally, delivery lead times are typically 12-18 months and grant funding should be structured to reflect this. For example, through its experience developing the *eWolf,* Crowley claims there are only three battery developers operating in the U.S. and "this limited competition and the nascency of zero-emission vessels in the United States leads to challenges on cost and may inhibit the ability to achieve standardized charging systems for the maritime sector in the near future." [131]. According to Crowley, a lack of demand for vessel construction has also resulted in U.S. shipyards struggling against global competition and significant zero emission vessel technical expertise now lies with specialized foreign shipyards which can build vessels in much shorter timeframes.

However, it is likely that advancements in the commercialization of marinized battery and fuel cell systems will be achieved in coming years. Companies working on or providing commercial battery systems suitable for marine applications including ABB, Siemens Energy, Corvus Energy, Leclanche, Wartsila, DNV, Bureau Veritas, Asea Brown Boveri, EST-Floattech, Fleetzero, and Spear Power Systems among others. Currently, lithium-ion batteries are the primary battery type suitable for marine energy systems with various chemistries currently commercially available [31]. However, other battery chemistries are being explored with lithium nickel manganese cobalt oxide (NMC) appearing to be the most feasible for ship design due to a balance of cost, lifetime, specific energy and power, safety, and thermal performance. NMC batteries provide high specific energy and energy density, which is important given the limited space on vessels, while being able to satisfy high power needs.

Companies working on fuel cell systems for maritime applications include Corvus Energy, Wartsila, Siemens Energy, Ballard Power Systems, Cummins Inc., ABB, Yanmar, and others. With similarity to fuel cell systems used to power vehicles, proton exchange membrane (PEM) fuel cells are most often used due to their high power density, quick start-up times, and ability to support variable loads. Other fuel cell types including solid oxide fuel cells, phosphoric acid fuel cells, and molten carbonate fuel cells may have applications for larger vessels including the provision of auxiliary.

Summary and Conclusions

This study has summarized operational feasibility examples of multiplevessel types adopting Tier 4 clean combustion systems with associated after treatment, near-zero (i.e., hybrid systems) technology, and zero-emission technologies.

Tier 4 Engine and Aftertreatment

In the Tier 4 area, additional Tier 4 certified engines have appeared since 2018 including four in the sub 600kW power generation range. As of March 2024, 27 specific Tier 4 engines are available. Additional development of options in the sub 600kW range are expected soon which will give more options for repowering or new builds of smaller vessels in all vessel categoriesFor retrofit, consideration is required for fitment of a particular engine make and model along with the necessary aftertreatment systems to attain Tier 4 emissions levels. This is discussed in more detail below. For new build, the majority of the vessels besides some fishing vessels are either in-service or have feasibility to construct with available commercial Tier 4 engines.

To reach CARB compliance, DPF technology is generally required. Several engine OEMs are working to implement DPF technology for specific engines. Third party manufacturers are also developing "add-on" DPFs that are subject to CARB verification. DPFs from Rypos (Active Diesel Particulate Filter—ADPF) are currently CARB verified at Level 2 (meaning at least a 50% reduction in particulate matter) [67] and Nett Technologies products are actively seeking verification.

Consideration for the additional physical volume associated with aftertreatment systems is required, in particular for repower. However, the engine OEMs are offering add-on aftertreatment modules that can be configured in different geometries which provides some additional flexibility for installation. Accommodating the DPF filter that is necessary to meet the regulation particulate levels requires further considerations. The location of the DPF relative to the engine outlet and SCR system (if installed) remains an open question. While many SCR + DPF system feature the DPF before the SCR, some examples of on road installations have the DPF positioned after the SCR. Such an arrangement would add flexibility for retrofitting in marine applications. Rypos has tested DPFs downstream of the SCR and has observed good performance.

It is evident that because CHC vessels have unique designs, duty cycles, and other constraints, no assumptions can be made about the technological feasibility of adopting a particular engine certified for the in use performance standard. Consideration for adoption by a specific vessel in California requires thorough analysis of its design and operation to determine if and what engine or aftertreatment retrofit is possible.

As the market evolves, it is likely that additional options for DPFs or possibly other particulate removal technologies may emerge. In all cases, track record of use and demonstration of reliability and safety will continue to be critical for adoption.

Zero Emissions Advanced Technology

The overall conclusion from the study is that there are potentially feasible options for converting CHC to ZEAT vessels in California, and these opportunities are likely to grow as technical advancements and enhanced commercialization of vessel and infrastructure technologies is achieved. Additionally, it is likely that applicable regulatory processes will be streamlined, and stakeholders will develop a better understanding and familiarity with ZEAT vessels and infrastructure. In particular, the successful demonstration of the current ZEAT projects in California and other regions will inspire confidence for owner/operators to pursue such vessels.

However, because vessels have unique designs, duty cycles, and other constraints, no assumptions can be made about the technological feasibility regarding a specific vessel in California without a thorough analysis of its design and operation to determine if and what conversion is possible. If significant alterations to vessel construction and design are required (which is likely for ZEAT), assessments by naval architects will be needed to ensure changes will not adversely affect the vessel's stability, seaworthiness etc. Critically, this includes the consideration and analysis of the feasibility of developing shoreside charging and/or hydrogen fueling infrastructure to support ZEAT vessels. The number of variables impacting the feasibility of ZEAT vessels must be carefully and comprehensively assessed on a case-by-case basis. In addition to meeting all the applicable vessel design and safety standards, ZEAT options must also be able to conduct the work required by each vessel vocation and must meet performance and operational requirement such as duty cycle, vessel speed, range, engine throttle response times and vessel maneuvering characteristics, vessel design and structural layout, and possible changes to vessel weight.

In general, battery electric propulsion systems are currently more commercially advanced than hydrogen fuel cell propulsion systems and are most viable for slower vessels with shorter routes, lengthier periods of downtime for charging, vessels with low sensitivity to weight. If battery technology improves and reductions in energy density and weight are achieved additional CHC vocations and routes will become feasible. Nonetheless, several companies are working on hydrogen fuel cell vessels which are best suited for applications that require longer routes or higher power demands, and those that are sensitive to weight limitations. For example, smaller, faster vessels may require fuel cell propulsion due to the size and weight of the battery pack that would otherwise be required. Advancement in battery and fuel cell technologies including improved energy density, cost reductions, and improved reliability and durability are needed and will increase the flexibility and utility of ZEAT vessel design and operation.

In the near- to mid-term, it is likely that hybrid electric systems will be a more attractive option for many CHC vocations until full zero emission systems progress and are proven. Designing a hybrid propulsion system to maximize the efficiency and environmental benefits of ZEAT vessels will be based on the individual operating profile of the vessel under consideration, e.g., when shore-side charging is required, charging time and capacity are the most important factors for battery sizing relative to sailing considerations [90].

In summary, the following represent potentially feasible opportunities for converting some California CHC to ZEAT and further discussed in the following sections. However, it is essential that opportunities are considered on a case-by-case basis and thus the following list does NOT represent all vessels within those categories.

- **Short run ferries, passenger ferries with short- to medium- routes**
- **Excursion vessels with amenable routes and turnaround times**
- **Line tender tugs (or similar), select ship assist tugs with regular and amenable duty cycles**
- **Pilot, crew vessels, work boats with less rigorous routes and duty cycles**
- **Small harbor dredges operating close to shore and with access to appropriate infrastructure**
- **Some small or near-shore commercial fishing boats or commercial passenger fishing vessels that can handle vessel design and operational changes**

Ferries

Ferries represent a key opportunity for the deployment of ZEAT vessels, including both battery electric and hydrogen fuel cell vessels, due to advantages including operation on fixed, shorter routes with the potential for recharging/refueling opportunities while loading and unloading. While the *Sea Change* is currently not allowed to refuel at the dock during passenger loading and unloading, shifts in regulations as more experience is gained may permit this in the future. Generally, existing projects are medium-capacity vessels of up to 250 passengers with lengths up to 130’, and maximum cruising speeds of 20 knots. However, both larger and smaller zero emission ferry vessels and those designated as high speed are planned, under development, or being demonstrated in normal operations. Most battery electric ferries in service today are car ferries with short routes, longer dockside times in port, and additional space for equipment relative to passenger ferries. Car ferries are generally slow-speed which reduces power requirements and on-board energy storage requirements.

In California, some ferries and ferry routes are feasible for conversion to ZEAT and in many cases already being pursued including both short run and passenger ferries. Propulsion systems for current projects are largely battery electric as the technology is more mature and currently more cost effective [209], although several hydrogen fuel cell ferry projects are underway worldwide and hydrogen may be a more feasible and cost effective option for certain ferry routes [210]. [210]. It has been shown that using current battery technology, most passenger ferries of 180’ length or smaller operating on routes up to 200 km are feasible for battery electric propulsion [211]. However, longer ferry routes will be challenging with batteries alone as increasing battery capacities adds weight, slowing down the vessel and reducing available onboard space which thus reduces the number of people and vehicles that can be serviced. An example of this type of challenge includes the longer routes served by WETA’s ferries. Recharging electric ferries may require considerable amounts of power delivered relatively fast, likely requiring extensive and expensive upgrades to electricity systems at ports and ferry terminals. For these types of routes, it may be more feasible to consider hydrogen fuel cell vessels.

Tugboats

Both plug-in hybrid and full zero emission tugboats are being considered and increasingly adopted in many ports worldwide including in California, as evidenced by the current operation of the *eWolf* and several planned projects. For plug-in hybrid vessels, the incorporation of battery systems with diesel technology is attractive for several reasons. Hybrid systems can provide the required high power in tandem with the instant torque delivery characteristic of electric motors which supports the quick and precise maneuvers performed by tugs during maneuvering of large vessels in confined spaces. Hybrid systems can offer efficiency improvements as electric propulsion can be used during low-power operations or when maneuvering in ports which reduces fuel consumption and wear and tear relative to operating diesel engines constantly at varying power levels. Additionally, the flexibility afforded by multiple power systems provides redundancy in case of engine failures, ensuring continuous operation. Hybrid technology may have a higher initial investment cost but the potential long-term benefits in fuel savings, reduced maintenance costs, and environmental impacts make it a potentially attractive option for tugboat operators in California ports.

However, full ZEAT harbor tugs will not have the same duty cycle capability as a conventional diesel tug and must be dedicated to specific operating locations to have operational commercial readiness. The highly competitive business structure of the harbor tug industry in California essentially requires tug operators to utilize diesel vessels because they are operating on short term charter agreements and may be subject to change operating locations at any time, which is not conducive to investing in ZE vessels as those must be designed for specific operating locations. Currently, full-zero emission electric tugs have very limited operating radius away from charging infrastructure and hybrid ZE capable harbor tugs will have to operate onboard diesel backup generators to operate effectively outside of the full-ZE operating radius or intended full-ZE design duty cycle. Current examples of full electric tugs, such as the Zee-Tug in Turkey, operate in a very limited operating location. Similarly, a hybrid harbor tug in service in Auckland New Zealand has limited operating range and reduced vocational duty cycle capability compared to a diesel-powered tug, further emphasizing the important aspects of why vessel designs have commercial operational status in particular operating locations.

Despite the challenges, tugboats represent an important opportunity for ZEAT vessels due to the benefits mentioned and evidenced by several current and planned projects in California. The successful demonstration of those projects, such as the *eWolf*, will validate the feasibility of ZEAT tugboats and build confidence in stakeholders which can advance the commercial viability of the vessel technology.

Commercial Fishing Vessels

Commercial fishing vessels and commercial passenger fishing vessels represent one of the foremost challenges for incorporating ZEAT technologies as generally they transit longer routes in combination with smaller vessel sizes and the inclusion of fishing equipment limits available onboard mass and volume. Pure battery electric vessels are likely only feasible for smaller fishing vessels (less than 32 feet) with lower power and energy requirements [170]. There may be opportunities for battery electric vessels in certain non-offshore commercial fishery operations including those operating inshore and using static gear (e.g., potters, divers, netters). For example, zero-emission battery electric vessels are being pursued in Canada to support inshore lobster fishing operations as the usage pattern is conducive to deployment [169]. Most of the inshore lobster fleet travels about 12 miles from shore and maintains a consistent pattern of operation including leaving and returning to the same docking location on the same schedule daily. However, the conversion of a 22 foot fishing catamaran vessel for close-range lobster potting was estimated to cost three times more than the cost of replacing the original diesel engine with a new diesel engine [170].

However, for offshore fishing vessels all-electric systems are unsuitable due to the weight and volume of batteries required for higher power or longer routes between docking and advancements in battery technologies will be required. Hydrogen fuel cell powered vessels may represent a future possibility as a study of possible zero emission systems for a commercial crab fishing vessel in Alaska concluded the only potentially feasible option was the use of hydrogen fuel cells in combination with liquid hydrogen fuel [171]. However, it should be noted that the assessment only considered the one-way transit between port destinations and did not account for energy and endurance requirements when engaged in fishing activity, which could affect the feasibility. A similar conclusion was reached for a fishing trawler following an actual voyage of approximately 400 nautical miles and four days of fishing [171]. A system utilizing gaseous hydrogen could accomplish one trip and a system with liquid hydrogen could be sized to achieve six trips.

Commercial passenger fishing vessels carry paying passengers out to sea to fish for durations ranging from day trips to multi-day trips. Typically, single day and multi-day vessels carry dozens of passengers. Those referred to as "6-packs" are vessels that can carry up to six passengers in addition to two crew. Often, they will idle while warming up and loading passengers and equipment. Vessels then transit at high speed out to the open ocean to locate fishing grounds where they will troll at low speeds or maintain position.

Given these challenges and the lack of other planned projects in California, the planned conversion of the *Goldrush* to plug-in hybrid electric propulsion will serve as an initial test case for future fishing vessels.

Dredge

The suitability of zero emission technology for both propulsion and dredging equipment will depend on various factors, including the dredging operation requirements, the vessel's size, the type of dredging equipment used, and the specific conditions of the dredging site. As evidence by the *Sandpiper* dredge, smaller dredges utilized for harbor maintenance and other activities may be good opportunities to utilize all-electric technologies utilizing shore power, but individual applications will need to be evaluated to ensure operational feasibility on a case by case and location basis due to the variation in available infrastructure at harbors. Larger dredges such as the *DB Avalon* represent interesting opportunities to deploy ZEAT technology, but it is unclear how much of the vessel's operation could be met with shore power which would be required for Zero emission-capable hybriddesignation.

Excursion Vessels

Excursion vessels carry passengers and engage in recreational operations such as sightseeing, dinner cruises, ecotourism, diving, snorkel, etc. Excursion vessels can range in size from 20' to 1000' and capacity depending on factors including design, purpose, and regulations imposed by maritime authorities. Most excursion trips are 60 or 90 minutes. Most excursion vessels in California transit at ~10 knots and are typically powered by main propulsion engines in the 400-500hp range. However, some excursion operators transit hundreds of miles per trip out to multiple channel islands and stops and transit at 20+ knots, which complicates this sector's operational feasibility for ZEAT. An example of these vessels includes those that transit to Chanel Islands at 20 knots or higher for hundreds of miles per trip.

Due to the cyclical nature of excursion trips, trip frequencies, and the low power requirements and transit speeds, most excursion vessels represent an appropriate opportunity for the deployment of zero emission propulsion technologies.

Pilot Boats

In California, typical pilot run boats are 50-67' with V-shaped monohull designs and are generally operated 24/7 365 delivering pilots to vessels at anchorage, terminals, and pilot station boats. They are powered by large twin main engines of 800-1000 hp each to reach speeds of 20+ knots while maintaining high maneuverability and stability. The extremely busy schedule, irregular trips, and high-power requirements present significant challenges for replacement with ZEAT vessels.

The frequency and duration of routes varies dramatically depending on location with some needing short trips and others requiring substantial time at sea. Thus, the suitability of zero emission vessels will vary from location to location. For example, pilot vessels used by the San Francisco Bar Pilots of California operates nearly continuously and travels long distances in between docking which significantly complicates replacement by a zero-emission vessel [212]. Conversely, a pilot boat used by the Port of San Diego makes far fewer and shorter trips between docking and could represent a more realistic opportunity to deploy ZEAT technology. On the other hand, the *PV Pittsburgh* is a less busy run boat used to transfer pilots to/from OGVs heading up and down the Stockton Deepwater Shipping Channel. This vessel may be well suited for ZEAT operational feasibility. For example, led by Maritime Green Horizon the historic pilot boat *Maguelonne* was retrofitted to all-electric operation and is now operational at the commercial port of Sète-Frontignan [68]. The 39' *e-Maguelonne* can reach a top speed of 19 knots and has a 200 kW electric motor powered by six lithium ion batteries that provide a total capacity of 180 kWh. Charging is provided by a 120 kW shore power facility and takes approximately 90 minutes to recharge after three consecutive pilot transfer trips. Additionally, Robert Allan announced plans for a 53' aluminum all-electric pilot boat called the *RAlly 1600-E* that can reach a top speed of 20 knots in 2018 [69]. The *RAlly 1600-E* is planned to be equipped with 500 kW electric motors powered by an 815 kWh battery system. However, the vessel will be limited to jobs where the run to the ship is 5 nautical miles or less which guarantees approximately 30% remaining battery capacity. It should be noted that the plans for the *RAlly 1600-E* were released in 2018 but it is unclear if the vessel was constructed.

Pilot station boats in CA are unique to the SF Bar Pilots Bay Area operation. Pilot station boats are similar in hull design to the run boats except they are larger at 104' in length to accommodate six pilots living aboard for six-day shifts at their station point 11 nautical miles from San Francisco Bay. The vessels essentially function as floating hotels for SF Bar Pilots. SF Bar Pilots operate three station boats. One on-duty at the designated station point 24/7 365 days a year, and two spare vessels back in San Francisco.

The station boats are powered by 1000-2000 hp Cat 3508 engines and have a highly variable duty cycle like a harbor/ship assist or escort tug. The station boats are largely on standby maintaining position and then switch to brief periods of high load engine operation to maneuver rapidly and transfer a pilot. This is like ship assist or escort tugs, which only operate their main engines under heavy load ~1% of their operational time. Therefore, pilot station boats could potentially utilize hybrid propulsion system utilizing batteries and a diesel-electric power-take-in systems to reduce fuel consumption, reduce main engine hours/wear, and reduce ambient noise aboard the vessel when it is on standby.

Crew/Supply

Smaller crew boats and/or those with shorter routes likely represent more favorable, near-term opportunities for the deployment of zero emission technologies, potentially including the hydrogen fuel cell vessel being developed by ZEI. Additionally, examples worldwide include battery electric crew boats to service windfarms in Japan [180].

Conversely, larger vessels, including those operating for significant distances offshore will likely require additional technology advancement and proof of concept demonstration prior to commercialization. These vessels typically have two or four powerful Category 1 main propulsion engines comparable to those in a modern tractor tug (2300-3300hp range each). Larger vessels frequently have a flat extended main deck with a large hydraulic crane for cargo or machinery handling. Twin-screw propulsion and 10 knot transit speeds are common, although some faster vessels may operate with jet-drive propulsion for transit speeds up to 32 knots unloaded and 26 knots loaded.

Infrastructure

The current lack of available charging/fueling infrastructure represents one of the most important barriers for ZEAT vessel deployment and successful operation and the buildout of infrastructure will be critical to the commercial success of ZEAT.

Route length, power demands, service frequency, layover time, speed of travel, and passenger capacity/weight are all important to electrifying CHC as they impact vessel energy consumption and shore side charging needs. Appropriate design can help reduce the size of the battery systems and landside infrastructure, but efforts to reduce energy demands can also negatively impact the practicality, quality, and cost effectiveness of vessel service. Thus, a balanced approach is necessary to determine the parameters of each project.

The selection of shoreside infrastructure will be influenced both by vessel location and activity and planned construction and terminal upgrades are important because they represent a key opportunity to more cost effectively incorporate landside infrastructure as it is simpler to incorporate electrification improvements during the initial design and construction phases. Terminals that may be more amenable to infrastructure upgrades including those with local land availability (e.g., parking areas) or reduced shoreside infrastructure congestion. For example, the availability of land for developing solar PV and battery storage systems will be important to support the large power requirements for vessel charging.

Higher power (i.e., DC fast-charging) and/or charging systems with automation have higher costs but provide the benefits of minimal charging times. In contrast, lower power (i.e., AC charging) and/or manual charging systems are currently cheaper and offer the benefits of being more technologically advanced and available and can generally interface with existing infrastructure more smoothly. These charging strategies are not exclusive, e.g., a combination of fast-charging during operation and slow-charging during periods of inactivity may be optimal in some cases. Decisions will need to be made on a per-case basis to determine which approach will best serve ZEAT vessels.

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List of Inventions Reported and Publications Produced

None

Nomenclature of Terms, Abbreviations, and Symbols

AC Alternating Current

AEC Alternative Energy Carriers

AFT Adiabatic Flame Temperature

AOC Ammonia Oxidation Catalyst

ATB Articulated Tug Barge

CA California

CARB California Air Resources Board

CCS Combined Charging System

CHC Commercial Harbor Craft

CMA California Maritime Academy

CO Carbon Monoxide

CO2 Carbon Dioxide

DC Direct Current

DEF Diesel Exhaust Fluid

DME Dimethyl Ether

DNV Det Norske Veritas

DNV AFI Det Norske Veritas Alternative Fuels Insight

DOC Diesel Oxidation Catalyst

DoE US Department of Energy

DPF Diesel Particulate Filter

ECU Engine Control Unit

EGR Exhaust Gas Recirculation

EPA Environmental Protection Agency (U.S.)

ESP Electro Static Precipitator

EU European Union

g	gram
H2	Hydrogen
HC	Hydrocarbon
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
HP	Horsepower
HPCR	High pressure Common Rail
IMO	International Maritime Organization
ISOR	Initial Statement of Reasons
kW	kilo Watt
L	Liter
Li-Ion	Lithium Ion
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MAN	Maschinenfabrik Augsburg-Nurnberg
MWH	Megawatt Hour
NMC	Nickel Manganese Cobalt
NOx	Oxides of Nitrogen (Nitric Oxide and Nitrogen Dioxide)
OBD	On Board Diagnostics
OEM	Original Equipment Manufacturer
OSHA	Occupational Safety and Health Administration
PM	Particulate Matter
R&D	Research and Development
RPM	Revolutions per minute
SCR	Selective Catalytic Reduction
WESP	Wet Electrostatic Precipitator
WETA	Water Emergency Transportation Authority
ZE	Zero Emissions
ZEAT	Zero Emissions and Advanced Technology

Appendices

None