Report Title:

A FEASIBILITY STUDY ON FUTURE ENERGY OPTIONS FOR COMMERCIAL HARBOR CRAFT OPERATING IN CALIFORNIA

Date:
AUGUST 16, 2024

Report prepared for and submitted to:
MARITIME ADMINISTRATION
United States of America

Submitted by:
AMERICAN BUREAU OF SHIPPING
Global Sustainability Center, Houston, TX, USA

Agreement No. 693JF722R000017

EXECUTIVE SUMMARY

OVERVIEW OF THE STUDY

This feasibility study explores future energy options for commercial harbor craft operating in California. The report assesses the readiness of California to transition to alternative energy sources and analyzes the characteristics and operational profiles of harbor craft. It also evaluates the suitability of various alternative fuels and power options.

HOW TO READ THIS REPORT

This report is a compilation of seven workstreams. The workstreams should be viewed as separate chapters. Each chapter provides a different insight for the feasibility of implementing alternative fuel and power options into the harbor craft in California. The exceptions to this are Workstream 3 and 5, as well as 4 and 6 respectively, where the latter section expands on the former by providing projections into the future.

Workstream 1	**Profiling Harbor Craft in California:** This section of the report provides an overview of the vessels in California harbors. This is both craft-specific information, such as types, sizes, and draft, as well as operational information, such as power usage and emissions.
Workstream 2	**Profiling California Ports and Infrastructure and Bunkering Operations:** This section looks to identify the steps that ports take toward alternative fuels and power options. It surveyed various ports around California to determine the current infrastructure and ability to provide both alternative power options and fuels to these vessels.
Workstream 3	**Assessing the Suitability of Alternative Fuel Options for Commercial Harbor Craft in California:** In this workstream, various fuel options were assessed for their current suitability with harbor craft across various metrics.
Workstream 4	**Assessing the Suitability of Power Choices for Commercial Harbor Vessels:** In this workstream, various power options were assessed for their current suitability with harbor craft across various metrics.
Workstream 5	**Projection of the Suitability of Fuel Options:** This section continues the analysis performed in section 3 with a projection for the studied fuel options into 2050.
Workstream 6	**Projection of the Suitability of Power Options:** This section continues the analysis performed in section 4 with a projection of the studied power options into 2050.
Workstream 7	**Applicable Federal, State, and Local Environmental Regulations:** This section summarizes the regulatory requirements for Harbor Crafts as defined by the state regulatory body, the California Air Resources Board (CARB), federal regulatory bodies (USCG, EPA, etc.), Classification Societies (DNV, ABS, LR, etc.), and international regulatory body (IMO).

CALIFORNIA'S READINESS FOR ALTERNATIVE ENERGY TRANSITION

California's commercial harbor craft industry is characterized by diverse vessel types, including tugs, ferries, crew supply vessels, and workboats. The transition to alternative fuels is essential to these vessels for reducing emissions and meeting regulatory requirements. The study profiles the harbor craft based on type, size, age, propulsion mode, fuel type, and operational routes. The power demand and emissions for each vessel are estimated using 2020 data.

MAJOR TAKEAWAYS

1. **Harbor Craft Characteristics**
    - The study includes 238 vessels, with tugs being the most common type. This category is further divided into offshore tugs, harbor tugs, and articulated tugs. Over half of the vessels fall into this category.
    - Vessel sizes vary significantly, with most tugs having a GT of less than or equal to 1,200. Only a few tugs exceed this limit, indicating a majority of smaller-sized tugs in operation.
    - The age distribution of vessels shows a significant number of vessels under 20 years old. There is a notable decline in older age groups, with less vessels in each category past 40 years old. However, a considerable percentage remains in this older age group, which suggests an aging fleet that needs modernization.
2. **Operational Profile Analysis**
    - Operational statuses, such as cruising, at berth, at anchor, and maneuvering, are classified based on speed, distance traveled, and geofencing data. The operational profile helps understand how vessels use power and generate emissions.
    - The total duration spent in each operational status is calculated. It reveals that in 2020, for example, articulated tugs spent 60,271 hours cruising and 77,148 hours at anchor. This extensive time at anchor suggests significant fuel savings potential if alternative energy sources are used.
3. **Emissions Estimations**
    - Emissions from main and auxiliary engines are calculated using emission factors based on horsepower and tier standards. The report highlights the emissions produced by various vessel types, focusing on NO_x, CO_2, and Diesel Particulate Matter (DPM).
    - Offshore tugs have the highest emissions among all vessel types, primarily due to their higher number and extensive operational hours. For instance, offshore tugs produced significantly greater amounts of NO_x, CO_2, and DPM than all other categories. This indicates a pressing need for cleaner alternatives in these vessels.
4. **Bunkering Infrastructure**
    - The current bunkering infrastructure in California primarily involves truck-to-ship or ship-to-ship methods. There is a noticeable lack of land-based bunkering facilities for both traditional and alternative fuels.
    - Notably, the Ports of Los Angeles and Long Beach provide LNG bunkering via truck-to-ship operations. Plans are in place to introduce green LNG (bio-LNG or synthetic LNG) by 2030, aligning with the state's environmental goals.
5. **Electrification and Shore Power**
    - Major ports like Los Angeles and Long Beach have implemented high-voltage (HVSC) and low-voltage shore power (LVSC) systems. This allows vessels to plug into the electric grid and shut down their auxiliary engines while at berth. This significantly reduces emissions at the ports.
    - Smaller ports lack such facilities, indicating a need for further investment in shore power infrastructure. Enhancing shore power capabilities at smaller ports could contribute to statewide emission reduction targets.
6. **Future Sustainability Initiatives**
    - Ports are actively planning and implementing initiatives to reduce emissions and adopt renewable energy solutions. For example, the Port of Long Beach's Zero Emissions Energy Resilient Operations (ZEERO) Policy focuses on advancing green power generation and procurement and improving overall energy efficiency. It also provides cost-effective alternative fueling options.
    - The Port of San Diego is exploring hybrid tug designs and other electrification projects, such as the "eWolf." It is the first all-electric tug built and home-ported in the United States. This effort showcases the growing interest in hybrid and fully electric tug designs, demonstrating the industry's dedication to clean energy solutions.

SUITABILITY OF ALTERNATIVE FUELS

The study assesses various alternative fuels based on factors such as storage, cost, feedstock availability, technological readiness, compatibility with current systems, and environmental impact. Key alternative fuels evaluated include the following:

Biocrude	Derived from manure or sludge, biocrude offers significant emissions reductions but requires further processing to be used in diesel engines. Its lower energy density and higher viscosity pose challenges for storage and usage without additional modifications.
Biodiesel	Made from soybean oil, biodiesel is a drop-in fuel that can be used without major modifications to existing systems. It has moderate costs and environmental benefits but faces competition for feedstock and has a lower shelf life.
Renewable Diesel	Similar to biodiesel but derived from different feedstocks, renewable diesel provides better performance and lower emissions. It is compatible with current systems and offers a practical pathway to reducing emissions.
Hydrogen	Hydrogen internal combustion engines (ICE) offer zero emissions at the point of use but pose challenges in storage, distribution, and onboard safety. The low energy density of hydrogen requires larger storage volumes, which impacts vessel design.
Methanol	A viable option with lower emissions and good compatibility with current systems, methanol requires significant bunkering infrastructure upgrades. It is a promising alternative but needs further development to become widely adopted.

SUITABILITY OF ALTERNATIVE POWER OPTIONS

The study also assessed various power options using similar factors. This includes technical readiness, infrastructure readiness, cost competitiveness, safety performance, emission reduction potential, and regulatory conformance. Key alternative evaluated include the following:

- **Lithium-Ion Batteries:** This is an electrochemical device that consists of two electrodes that are isolated by a separator and soaked in electrolyte to promote the movement of ions. They store chemical energy and release electrical energy. The main chemistry studied was lithium-ion batteries due to their high energy density and reduced costs.
- **Fuel Cells:** This is a device that continuously converts an oxidizing fuel (e.g., hydrogen, methane) into electricity and water through an electrochemical reaction. These fuel cells are an attractive option due to their high energy density and zero emissions.
- **Hybrid Power Systems:** Hybrid systems combine internal combustion engine-driven generators and/or shaft generators/motors driven by main engines with an energy storage system (ESS) consisting of batteries, fuel cells, or other technologies. The architecture of a hybrid system can be designed specifically for each vessel. This optimizes the use of each component for maximum efficiency.
- **Shore Power:** Shore power has two main types: onshore power supply (OPS) and shore-side battery charging (SBC). OPS supplies electrical power directly to ships at berth from a shore-side source and replaces the onboard electricity generation from auxiliary generators. SBC, on the other hand, charges the onboard battery energy storage systems using a connection standard suitable for the specific system onboard.
- **Wind Power:** Wind is used to produce electricity by converting the kinetic energy of air in motion into electricity. In conventional wind turbines, wind rotates the rotor blades, which converts kinetic energy into rotational energy. The rotational energy is conveyed through a shaft to the generator, which in turn produces electrical energy. Wind can also be utilized through several different methods to generate propulsion for vessels.

CONCLUSIONS

The feasibility study concludes that while California has made significant strides toward adopting alternative energy solutions for harbor craft, several challenges remain. These include the need for infrastructure upgrades, investment in new technologies, and integration of alternative fuels with other decarbonization strategies. Continued efforts and collaboration between ports, regulatory bodies, and industry stakeholders are essential to achieve the state's emission reduction goals and transition to a sustainable maritime future.

The detailed analysis in the report supports these conclusions. It offers specific insights into the operational and environmental aspects of California's commercial harbor craft industry. Investing in cleaner technologies and alternative fuels is crucial for reducing emissions and achieving long-term sustainability in the maritime sector.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

Workstream 1:

PROFILING HARBOR CRAFT IN CALIFORNIA

LIST OF ACRONYMS AND ABBREVIATIONS

AIS	Automatic Identification System
BHP	Brake Horsepower
CARB	California Air Resources Board
CO_2	Carbon Dioxide
CRS	Coordinate Reference System
DPM	Diesel Particulate Matter
GT	Gross Tonnage
IHS	Information Handling Services
LLI	Lloyd’s List Intelligence
LOA	Liquid Organic Hydrogen Carrier
MMSI	Maritime Mobile Service Identity
MSE	Mean Squared Error
NO_x	Nitrogen Oxide

1 PROFILING HARBOR CRAFT IN CALIFORNIA

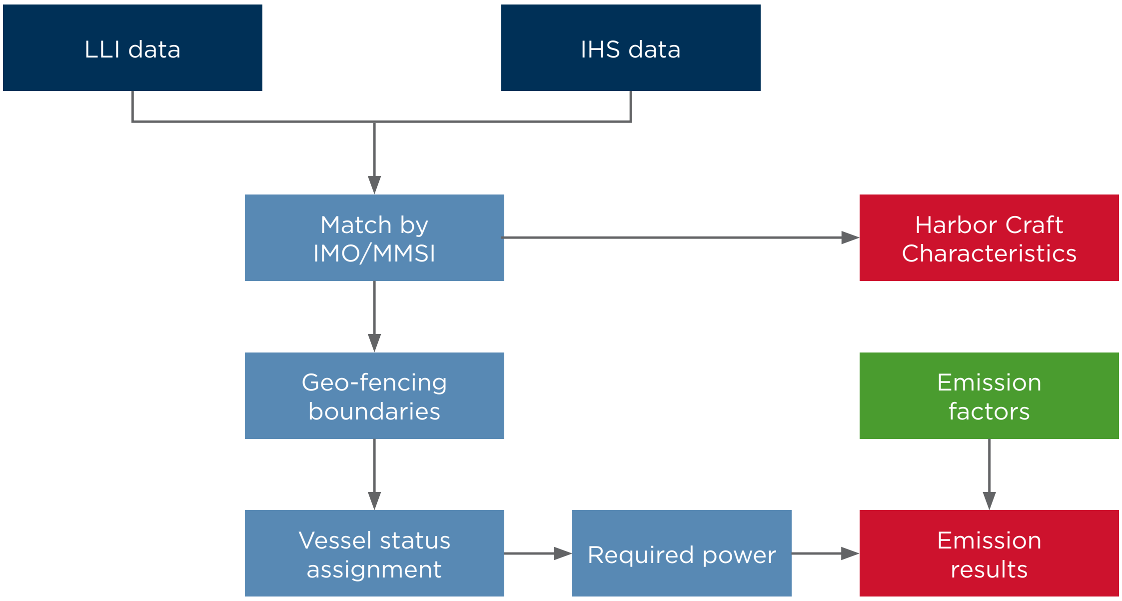
1 – 1. INTRODUCTION

This section details the profile of the CHC Industry in California. Through compilation of harbor craft characteristics from ABS Class databases, industry standard databases, the CARB reporting database, and the analysis of AIS data and port operations data, a preliminary profile of identified vessel types in California is created. The identifiers included in the report are craft type, size, age, propulsion mode, fuel onboard, and operational route. The power demand and emissions of each vessel throughout the year are estimated by categorizing the status and corresponding duration time of each vessel based on the year 2020 historical tracking data. They are presented in the operational profile analysis section.

1 – 2. METHOD

The following flow chart summarizes how data was collected and how the emissions were estimated. The calculation used Lloyd's List Intelligence (LLI) to obtain statistics on total port calls for the vessel types included in this study for all California ports in 2020. It also used the Information Handling Services (IHS) database to collect vessel characteristics data. Retrieved relevant data fields include port call dates, vessel names, LLI vessel IDs, vessel IMOs, vessel GT, vessel net tonnage, and vessel draft.

Figure 1: Profiling Flow



The profiling summarizes characteristics of California Harbor Crafts, including information on:

- Craft type
- Craft size
- Craft age
- Maximum draft

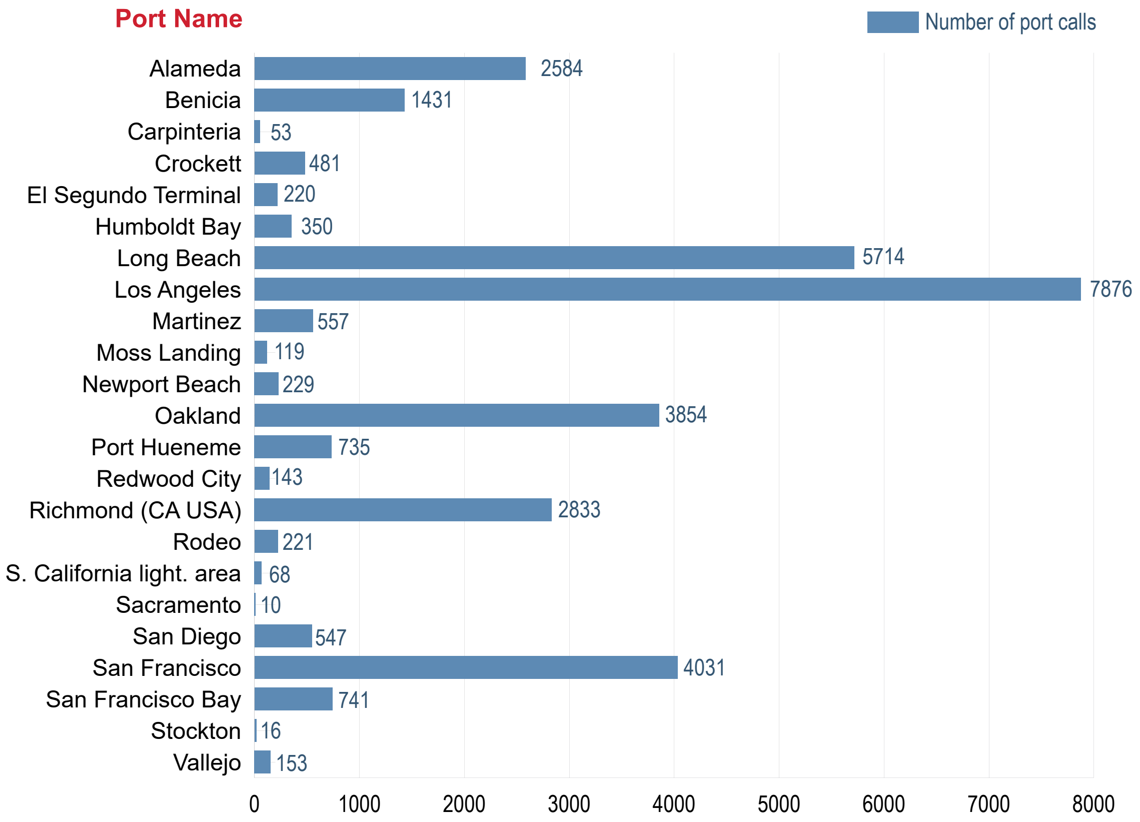
The estimated emission summarizes how much CO_2, NO_x, and DPM main engines and auxiliary engines respectively were supposed to emit during the year 2020.

1 – 3. HARBOR CRAFT ANALYSIS

1 – 3.1 PORT CALLS

With a land area and water area of 7,500 acres and a coastline 43 miles long, the Port of Los Angeles is the busiest container port on the western side of the United States. It had 7,876 port calls in 2020, followed by Port of Long Beach with 5,714 port calls. Other major ports in the California area include Port of San Francisco, Port of Oakland, Port of Richmond, Port of Alameda, and Port of Benicia.

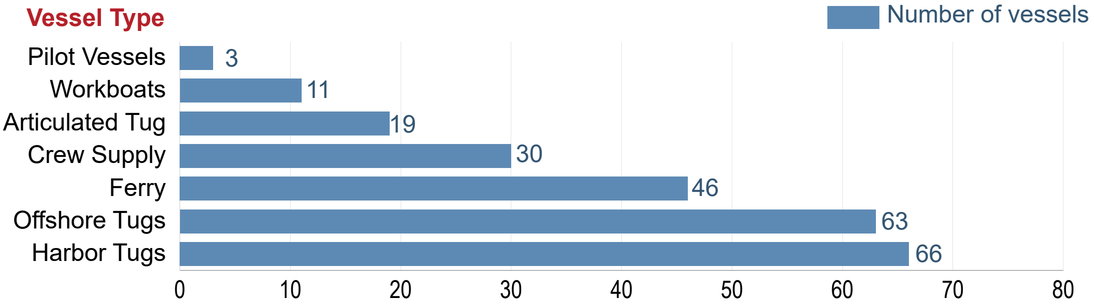
Figure 2: 2020 Port Calls



1 – 3.2 CRAFT TYPES

There are 238 vessels within the studied vessel types in the California area. Over half of the vessels are tugs (63 offshore tugs, 66 harbor tugs, 19 articulated tugs). Nineteen percent are ferry vessels, 13% are crew supply vessels, and a few are workboats and pilot vessels. Figure 3 displays the number of vessels identified in each category for this study.

Figure 3: Vessel Count Based on Craft Type



1 – 3.3 CRAFT SIZE

Due to the unavailability of deadweight data for a considerable number of vessels in the dataset, the analysis focused primarily on the GT as a measure of craft size.

Tugs were plotted separately to examine the craft size within this category. They were divided into two groups based on their GT: those with a GT of less than or equal to 1,200 (Figure 5) and those with a GT of greater than 1,200 (Figure 4). There are only three tugs with GT greater than 1,200, among which two are around 2,000 GT and one is around 12,000 GT. For tugs with a GT of less than or equal to 1,200, most of them are under 600 GT, and only less than 10% are over 600 GT.

Most of the ferry vessels (Figure 7) are of small size with less than 200 GT. Most of the crew supply vessels (Figure 8) are under 1,000 GT.

Indications suggest that large tonnage types with hybrid systems have lower emissions per unit of work. However, based on the profiling of crafts available, demand requirement for high-tonnage tugs is very limited, thereby sometimes making these types of tugs not viable for ports.

GT of tug with less than 1,200 are all operating with oil and engine type are oil engine .

Figure 4: Size Distribution of Tugs with GT >1,200

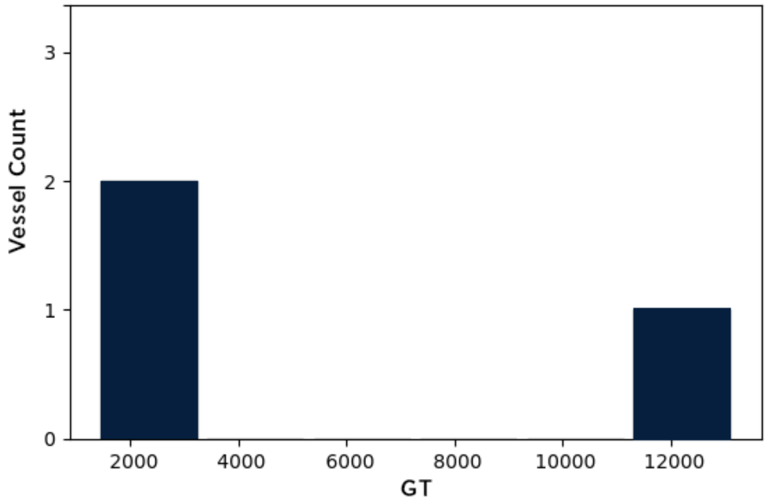


Figure 5: Size Distribution of Tugs with GT ≤1,200

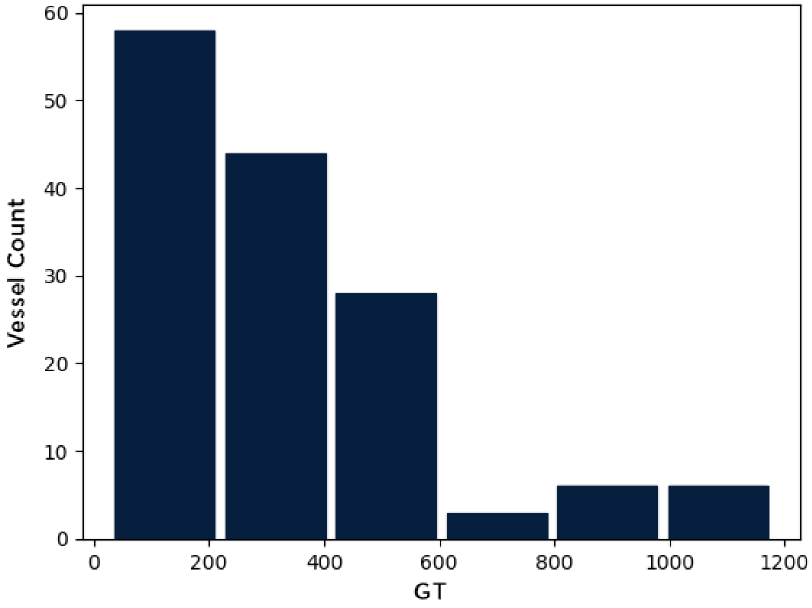


Figure 6: Size Distribution of Pilot Vessels

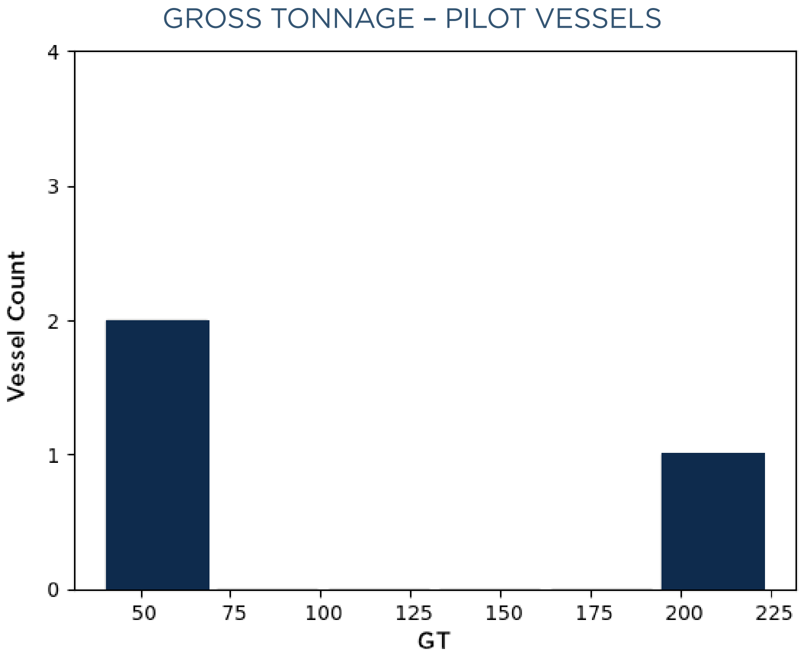


Figure 7: Size Distribution of Ferry Vessels

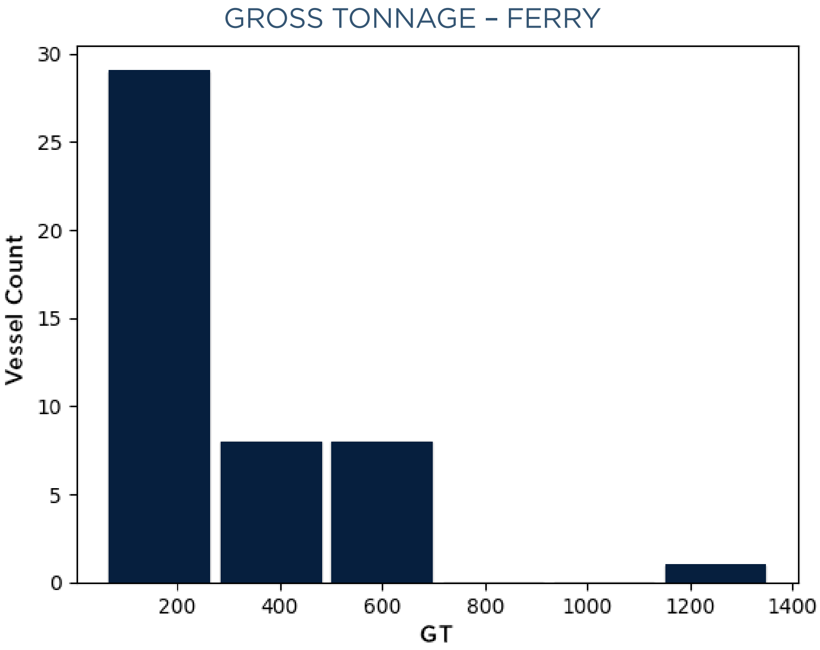


Figure 8: Size Distribution of Crew & Supply Vessels

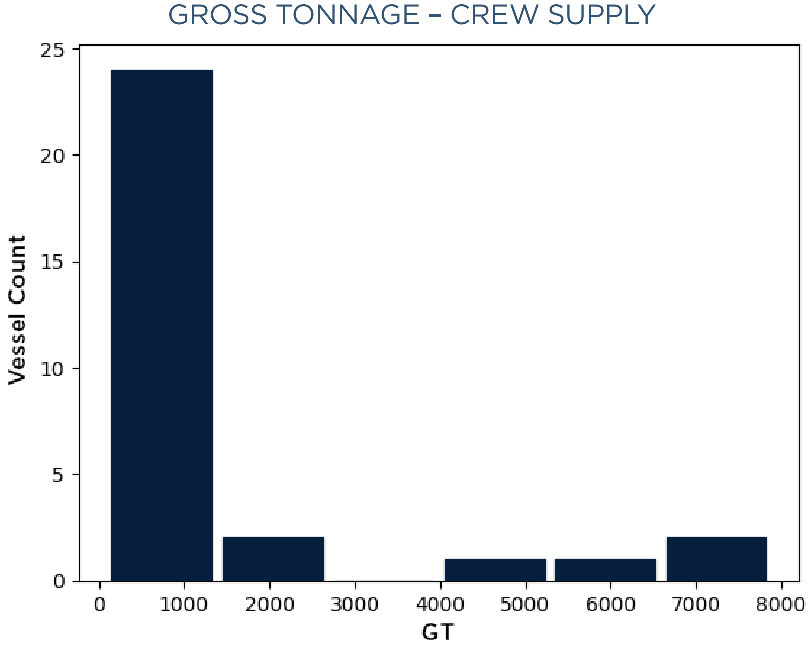
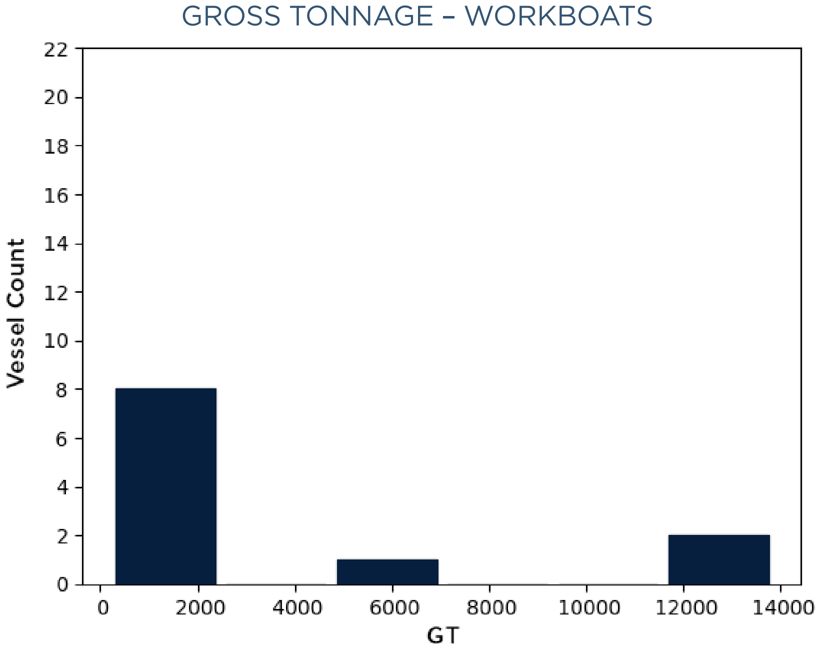


Figure 9: Size Distribution of Workboats



CRAFT AGE

Figure 10 shows the age distribution of the vessels, classified in 10 bins. The highest percentages are in the age. groups under 20 and over 40. There is a noticeable drop in percentages after age 40, with a significant decrease in the 50s and onwards.

Based on the age distribution, there is a significant demographic skew toward younger age groups, with a notable decline in older age groups.

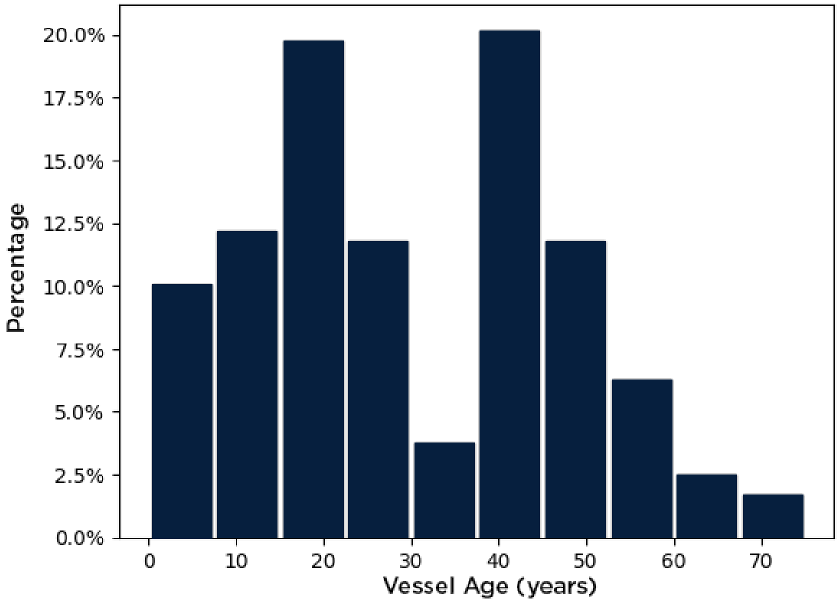
In general, based on the trend from Table 1, newer crafts tend to be larger than older crafts in terms of GT, draft, LOA, breadth, and engine power. This is consistent with the general industry trend toward larger vessels to achieve economy of scale. Under normal circumstances, with no further action taken, this trend toward larger crafts will lead to increased demand of fuel in the maritime services to maintain current volume production requirements unless new efficient technologies are developed.

This suggests that a do-nothing approach is not a viable option. New innovative technologies that seek to increase efficiency and reduce emissions shall be promoted.

Table 1: Average of Vessel Particulars Across Various Age Ranges

Age	**(0, 7.5]**	**(7.5, 15.0]**	**(15.0, 22.5]**	**(22.5, 30.0]**	**(30.0, 37.5]**	**(37.5, 45.0]**	**(45.0, 52.5]**	**(52.5, 60.0]**	**(60.0, 67.5]**	**(67.5, 75.0]**
AIS_dwt	804	673	1440	368	767	720	341		#DIV/O!	345
AIS_gross Tonnage	962	917	1235	297	240	473	234	225	111	133
AIS_net Tonnage	309	285	371	108	116	303	90	82	59	69
IHS_Gross Tonnage	961	917	1235	315	258	500	256		115	133
IHS_Draught	5	5	4	4	3	4	4	4	3	4
LOA	38	39	46	32	40	33	29	28	23	23
Breadth Moulded (m)		12	12	9	12	9	9	8	7	7
Powerbhpih pshpmax	5805	7262	5138	2440	2186	3925	2376		1565	1687
Powerkw max	4270	5342	3780	1798	1618	2894	1753	1643	1158	1243
IHS_ DesignSpeed		15	16	15	15	14	13		13	12
IHS_Net Tonnage		281	383	120	130	341	102		70	82
bhp/engine	2595	3356	2181	1251	1093	1583	1288		973	1050
kw/engine	1908	2469	1605	922	809	1169	951	1029	721	774
VesselAge	4	12	19	26	33	41	49	56	65	72

Figure 10: Age Distribution of Vessels



1 – 3.4 MAXIMUM DRAFT (TMAX)

For the maximum draft analysis, the IHS design draft data was used as a metric to examine the draft characteristics of the vessels. Most of the harbor tugs have less than 6 draft (Figure 11, Figure 12, and Figure 13), most of the ferry vessels have 1 to 4 draft (Figure 15), and most of the crew supply vessels have 2 to 4 draft (Figure 16).

Figure 11: Design Draft Distribution of Harbor Tugs

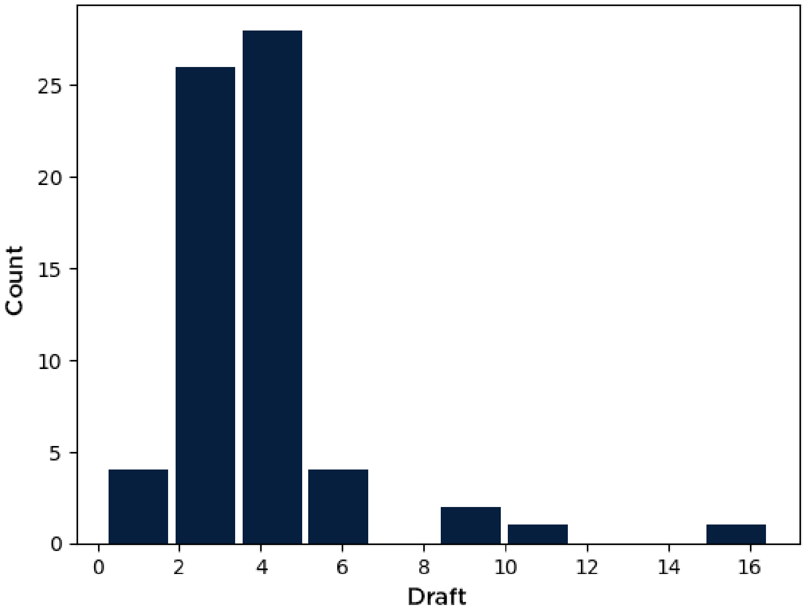


Figure 12: Design Draft Distribution of Articulated Tugs

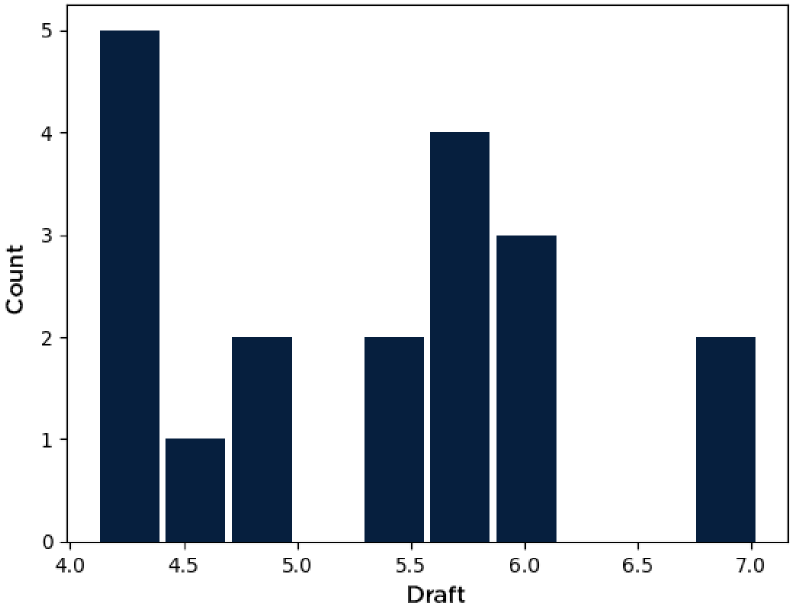


Figure 13: Design Draft Distribution of Offshore Tugs

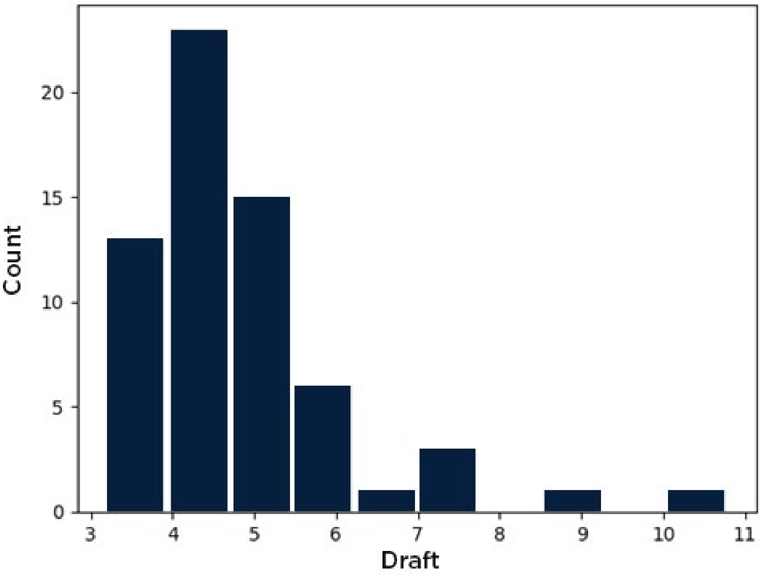


Figure 14: Design Draft Distribution of Pilot Vessels

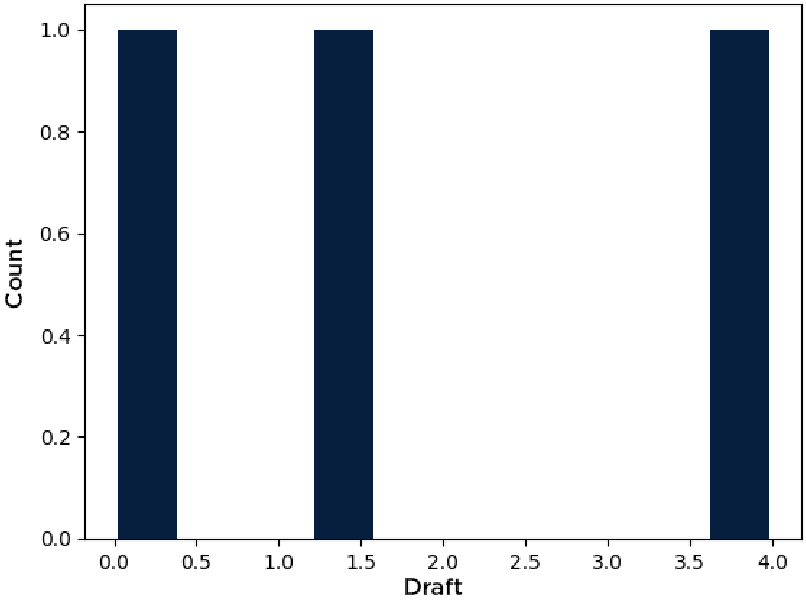


Figure 15: Design Draft Distribution of Ferries

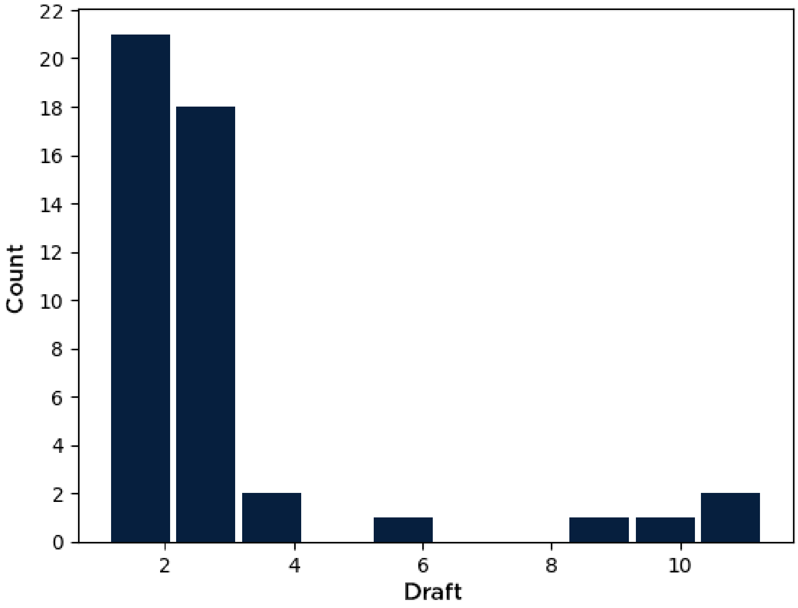


Figure 16: Design Draft Distribution of Crew & Supply Vessels

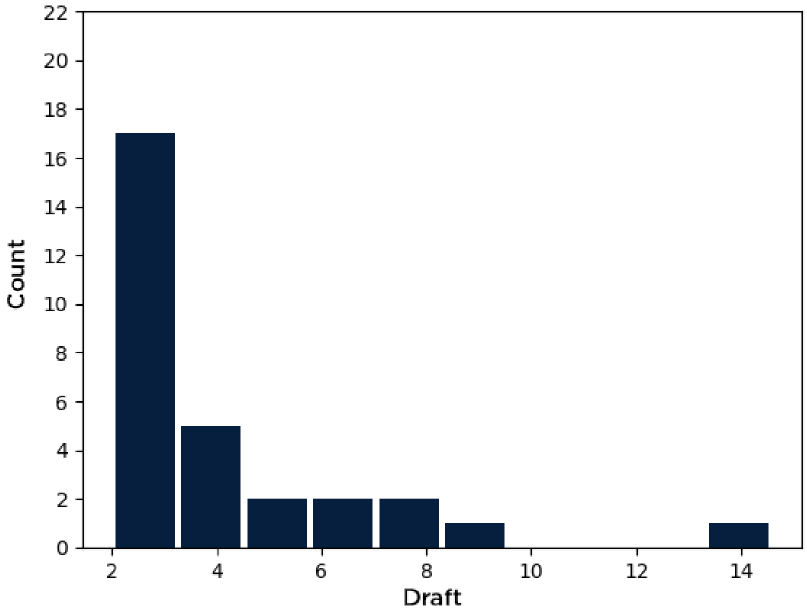
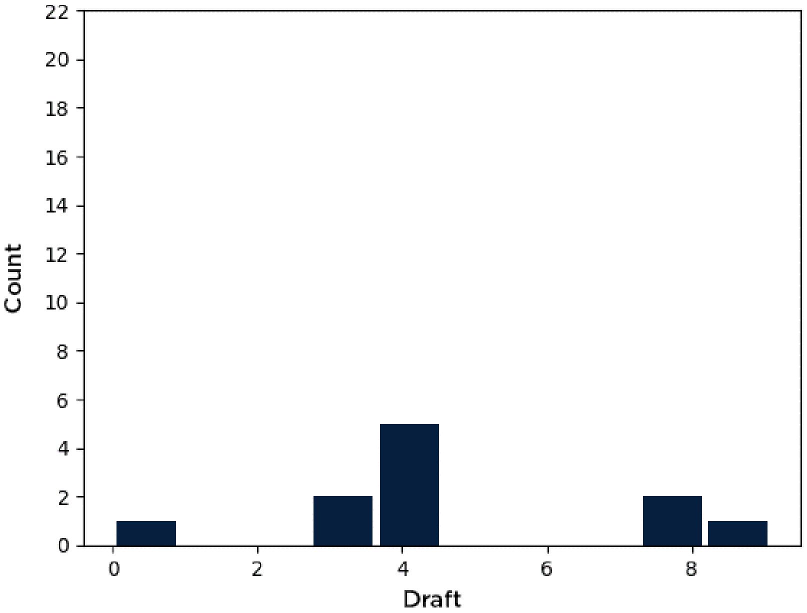


Figure 17: Design Draft Distribution of Workboats



1 – 4. OPERATIONAL PROFILE ANALYSIS

The operational profile analysis aimed to explore and understand the operational characteristics of the vessel types was considered for this study. Given the lack of information on propulsion engine type, fuel usage, and fuel type, the required power for the vessels was determined using the Admiralty method, as recommended by the ***4th IMO GHG study***[1].

Equation 1: Admiralty Method

$$W_i = \frac{\delta_w * \ W_{ref} * \left(\frac{t_i}{t_{ref}}\right)^m * \left(\frac{v_i}{v_{ref}}\right)^n}{n_w * n_f}$$

Where,

W_{ref} – reference power as given in the IHS dataset and by imputing

t_i and t_{ref} – instantaneous draft and IHS design draft respectively

v_i and v_{ref} – instantaneous speed and IHS design speed respectively

δ_w – speed-power correction factor, 1.0

m – draft ratio, 0.66

n – speed ratio, 3

n_w – weather correction factor, 0.909

n_f – fouling correction factor, 0.917

There are other methods that can also be used to estimate required power. For example, modern methods normally involve detailed hydrodynamic analysis and computational fluid dynamics simulations. These techniques consider factors such as hull form, resistance, propulsion efficiency, and operating conditions. Computational models are used to simulate the flow of water around the hull, propeller performance, and other hydrodynamic effects. However, the Admiralty method is relatively straightforward and does not require complex mathematical calculations. It relies on empirical data and practical experience, making it accessible with limited resources.

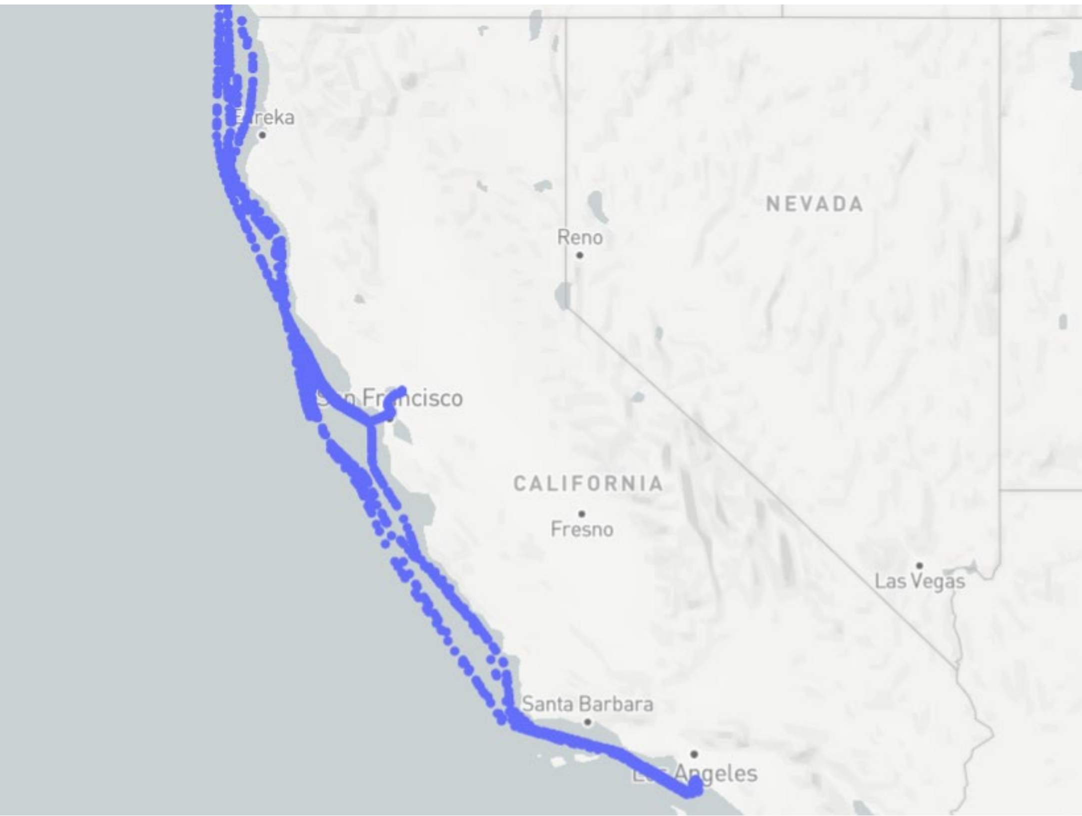
To estimate the emissions, emission factors for the engines based on horsepower were used as per the “Appendix H – 2021 Update to the Emission Inventory for Commercial Harbor Craft: Methodology and Results.” These emission factors provided a basis for estimating the emissions associated with the vessel operations. By considering the estimated power requirements and emission factors, the analysis provided insights into the potential emissions from different vessel types.

1 – 4.1 GEOFENCING

To determine if the vessels were operating within specific geographic areas, a geofencing approach was employed. This consists of defining the coordinates (latitude, longitude) of each port as a predefined center point, each with a 1 nm radius as the proximity around each port. Assumption was based on the fact that if the vessel is traveling within the proximity area, then it is regarded as operating within that port. By applying this geofencing approach, it became possible to classify vessels based on their operational location. It provided valuable insights into their spatial distribution and adherence to predefined operational boundaries.

The static map in Figure 18 portrays the movements of a vessel with points marked in red that indicate when the vessel enters the port areas. As the figure shows, this vessel has operated within the ports of Los Angeles and San Francisco.

Figure 18: Static Map Showing the Movement of a Vessel in 2020



1 – 4.2 OPERATIONAL PHASES AND POWER USAGE

To estimate the power usage, an estimation of the operational status and corresponding operating time of each vessel is required.

The conditions for classification of the operational status are derived from Table 16 **Operational Phase Assignment Decision Matrix** of the ***4th IMO GHG study*** **[1]**. By applying this logic, it allows for further analysis of the activities and power usage of the vessel during different operational states.

The operational status of the vessel is determined based on a set of predefined criteria. These criteria consider factors such as speed, status code, distance traveled, geofence status, draft, and power. The operational status can be categorized as **Cruising** , **at berth**, **at anchor**, or **Maneuvering** based on these conditions.

The logic from Table 16 **Operational Phase Assignment Decision Matrix** of the ***4th IMO GHG study*** for classifying the operational status of vessels is as follows:

- Condition 1: If the status of the vessel is **at anchor** or **at berth**, and either the speed is greater than 5 knots or the distance traveled is greater than the minimum distance of 1 nm, and the vessel is operating outside any port, then the operation is classified as **Cruising.**

  This condition captures cases where the vessel was previously in a cruising status and has now entered the **at anchor** or **at berth** status, but still shows signs of cruising activity based on the speed or distance criteria.

- Condition 2: If the status of the vessel is **at anchor**, **Cruising**, or **at berth**, the speed is less than or equal to 1 knot, and the vessel is operating within any port, then the operation is classified as **at berth.**

  This condition identifies cases where the vessel is stationary or moving very slowly within the predefined port area, indicating it is at a berth.

- Condition 3: If the status of the vessel is **at anchor**, **Cruising**, or **at berth**, the speed is less than or equal to 1 knot, and the vessel is operating outside any port, then the operation is classified as **at anchor.**

  This condition is an additional check to classify cases where the vessel is in **at anchor**, **Cruising**, or **at berth** but has moved outside the predefined port area, suggesting it is **at anchor**.

- Condition 4: If the status of the vessel is **at anchor**, **Cruising**, or **at berth**, the speed is between 1 and 3 knots, and the distance traveled is less than the minimum distance of 1 nm, then the operation is classified as **at anchor.**

  This condition handles cases where the speed of the vessel falls within the specified range and has covered a small distance, indicating it is likely **at anchor**.

- Condition 5: If the status of the vessel is **at anchor, Cruising**, or **at berth** status codes, the speed is between 1 and 3 knots, and the distance traveled is greater than the minimum distance, then the operation is classified as **Cruising.**

  This condition identifies cases where the speed of the vessel falls within the specified range but has covered a significant distance, suggesting it is engaged in cruising activity.

- Condition 6: If the status of the vessel is **at anchor, Cruising**, or **at berth**, the speed is between 3 and 5 knots, the vessel is operating outside any port, and the distance traveled is greater than the minimum distance, then the operation is classified as **Cruising.**

  This condition captures cases where the speed of the vessel falls within the specified range, it is outside the predefined port area, and has covered a significant distance, indicating it is cruising.

- Condition 7: If the status of the vessel is **at anchor**, **Cruising**, or **at berth**, and the speed is between 3 and 5 knots, and the vessel is operating within any port, then the operation is classified as **Maneuvering**.

  This condition identifies cases where the speed of the vessel falls within the specified range, it is within the predefined port area, and suggests it is maneuvering within the port.

- Condition 8: For all other cases, when none of the above conditions are met, the operation is classified as **Cruising** by default.

  This handles cases where the status or speed of the vessel does not match any specific condition, and it is assumed to be engaged in cruising activity.

For each operational status category, the total duration is then computed. The table below (Table 2: Operational Profile Duration per Vessel Category) shows a snapshot. For instance, articulated tug vessels have spent 60,271 hours on **Cruising** and 118 hours in **Maneuvering** during the year 2020.

Table 2: Operational Profile Duration per Vessel Category

Operation	Category	Duration (hours)
Cruising	Articulated Tug	60,271
Cruising	Harbor Tugs	86,336
Cruising	Offshore Tugs	147,840
Maneuvering	Articulated Tug	118
Maneuvering	Harbor Tugs	5,940
Maneuvering	Offshore Tugs	5,930
At anchor	Articulated Tug	77,148
At anchor	Harbor Tugs	158,742
At anchor	Offshore Tugs	164,722

Efforts to reduce emissions in the marine services shall focus on tugs as a major emitter in the port area. They represent 61% of total craft emissions (Figure 20), specifically offshore and harbor tugs that have recorded the highest number spent on cruising and maneuvering during the year 2020 (Table 2).

1 – 4.3 ESTIMATION OF AUXILIARY ENGINE POWER DEMAND

Auxiliary power consumption was calculated based on the operational phase of the vessel, total duration in hours, and specific constant values for different operational phases. These constant values are obtained from Table 17 of the ***4th IMO Greenhouse Gas Study*** [1] and are specific to each vessel type and GT. The constants used for vessel types other than **ferry** would be fixed values without any dependency on GT. In this study, the ferry vessels were categorized into two groups based on their GT: those with a GT less than 2,000 and those with a GT greater than or equal to 2,000. This classification was considered in the calculation of auxiliary power. The constants used for calculating the auxiliary power were specific to these two categories of ferry vessels.

The constants are shown in Table 3: Auxiliary Engine Power Output by Ship Type, Size, and Operational Phase below.

Table 3: Auxiliary Engine Power Output by Ship Type, Size, and Operational Phase

Ship Type	Size	At Berth	Anchored	Maneuvering	Cruising
Ferry	GT <2,000	190/hr	190/hr	190/hr	190/hr
Ferry	GT ≥2,000	520/hr	520/hr	520/hr	520/hr
Tugs	GT >0	100/hr	80/hr	210/hr	80/hr
Crew Supply	GT >0	320/hr	320/hr	320/hr	320/hr
Work Boats	GT >0	150/hr	150/hr	430/hr	410/hr
Pilot Vessels	GT >0	220/hr	220/hr	220/hr	220/hr

1 – 4.4 EMISSIONS CALCULATIONS

An emissions tier is assigned to each vessel based on its built year and main engine horsepower to calculate its emissions:

- For engines with horsepower between 175 and 800:
  - If the vessel was built before 1996, it is assigned to Tier 0.
  - If the vessel was built between 1996 and 2003, it is assigned to Tier 1.
  - If the vessel was built between 2003 and 2006, it is assigned to Tier 2.
  - If the vessel was built in 2006 or later, it is assigned to Tier 3.
- For engines with horsepower greater than or equal to 800:
  - If the vessel was built before 1998, it is assigned to Tier 0.
  - If the vessel was built between 1998 and 2005, it is assigned to Tier 1.
  - If the vessel was built between 2005 and 2011, it is assigned to Tier 2.
  - If the vessel was built in 2011 or later, it is assigned to Tier 3.

The assigned emissions tier for each engine was based on its characteristics. Table H-5 **Emission Factors (gram/bhp-hr) of CHC Engines by Horsepower Bin and Tier Standard** from ***CARB CHC Emission Inventory Report*** [2] was referenced for this calculation (Table 4).

Table 4: NO_x and CO_2 Emission Factors (g/bhp-hr) of CHC Engines by Horsepower and Tier Standard

Pollutant	Horsepower Bin	Tier Standard	Main Engine	Auxiliary Engine
NO_x	175 – 800	0 (before 1996)	12.20	12.20
NO_x	175 – 800	1 (1996 – 2003)	5.20	4.17
NO_x	175 – 800	2 (2003 – 2006)	4.76	3.02
NO_x	175 – 800	3 (2006 or later)	3.73	3.22
NO_x	≥800	0 (before 1998)	12.20	12.20
NO_x	≥800	1 (1998 – 2005)	6.97	6.97
NO_x	≥800	2 (2005 – 2011)	5.08	5.08
NO_x	≥800	3 (2011 or later)	3.69	3.69
DPM	175 – 800	0 (before 1996)	0.62	0.62
DPM	175 – 800	1 (1996 – 2003)	0.09	0.13
DPM	175 – 800	2 (2003 – 2006)	0.09	0.11
DPM	175 – 800	3 (2006 or later)	0.05	0.07
DPM	≥800	0 (before 1998)	0.59	0.59
DPM	≥800	1 (1998 – 2005)	0.12	0.12
DPM	≥800	2 (2005 – 2011)	0.09	0.09
DPM	≥800	3 (2011 or later)	0.05	0.05

The methodology ensures that the NO_x and DPM emissions for the main and auxiliary engines of each vessel are accurately calculated based on their specific characteristics and the emissions standards associated with their horsepower range and tier.

For CO_2 emissions calculations, Table H-6 **CO_2 Emission Factors and BSFC Rates of CHC Engines by Tier Standard and Horsepower Bin** from ***CARB CHC Emission Inventory Report*** [2] was referenced (Table 5).

Table 6 summarizes emissions for various vessel types from both main and auxiliary engines.

Figure 19, Figure 20, and Figure 21 show visualized emissions of NO_x, CO_2, and DPM by various vessel types. Offshore tugs have the highest emissions of NO_x, CO_2, and DPM among all vessel types. This is mainly due to their high number (63 out of 238 total vessels are offshore tugs) while pilot vessels and workboats have the least emissions.

Table 5: CO_2 Emission Factors of CHC Engines by Tier Standard and Horsepower Bin

Tier Standard	Horsepower Bin	CO_2 EF (gram/bhp-hr)
0/1/2	≥100	533
3	175 - 800	531
3	≥800	515

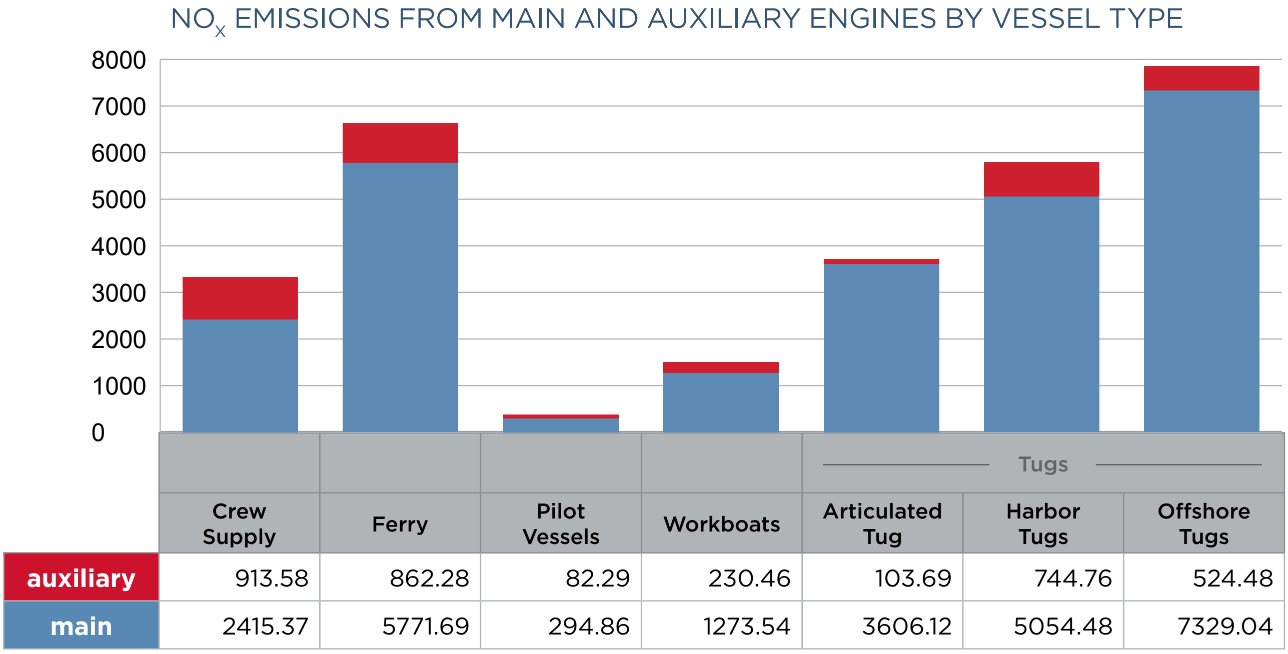
Table 6: Emissions from Vessel Types[1]

		NO_x		CO_2		DPM	
Vessel Category	**Subcategory**	**main**	**aux**	**main**	**aux**	**main**	**aux**
Crew Supply	–	2415.37	913.58	214680.00	56706.70	61.62	33.64
Ferry	–	5771.69	862.28	361915 .00	49435.10	191.91	35.33
Pilot Vessels	–	294.86	82.29	14728.00	4191.88	13.09	3.56
Workboats	–	1273.54	230.46	89561.80	13024.60	29.41	8.48
Tugs	Articulated Tug	3606.12	103.69	358046 .00	9199.21	71.49	2.81
	Harbor Tugs	5054.48	744.76	262810 .00	36198.60	221.54	34.34
	Offshore Tugs	7329.04	524.48	444981.00	31578.00	278.69	20.04

---

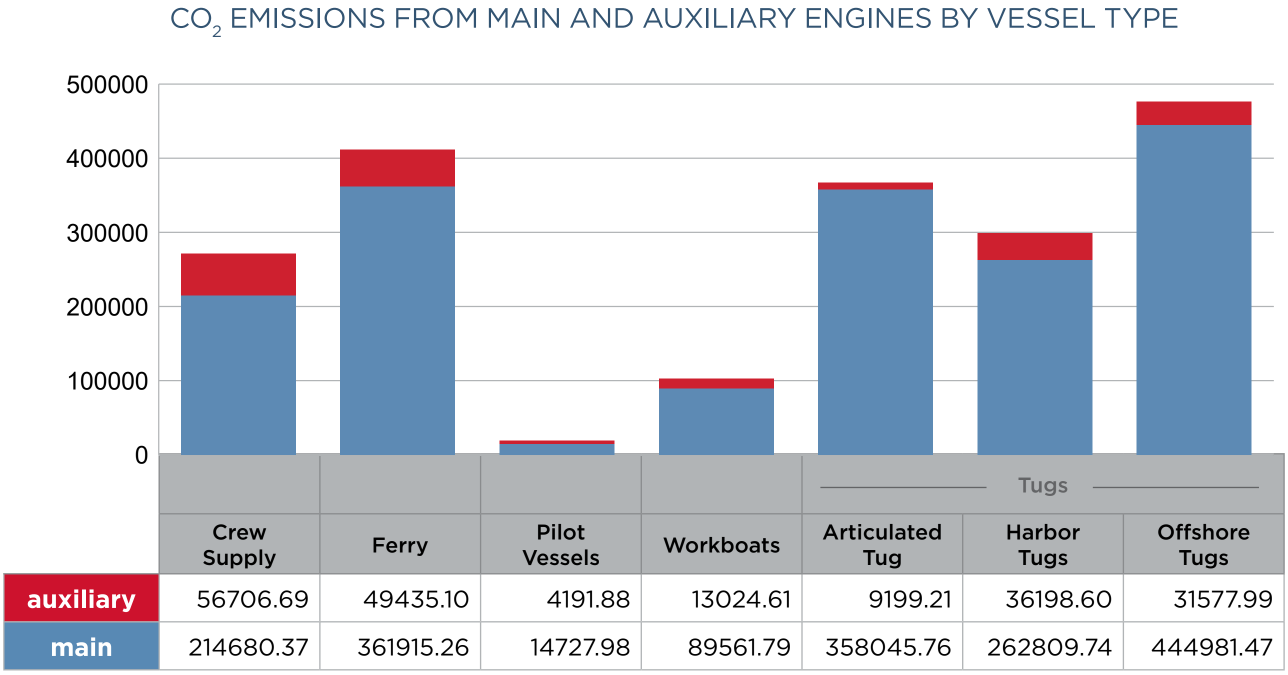
[1] All values indicated are given in units of g of CO_2/vessel/hour.

Figure 19: NO_x Emissions from Main and Auxiliary Engines by Vessel Type[1]



					Tugs		
	Crew Supply	Ferry	Pilot Vessels	Workboats	Articulated Tug	Harbor Tugs	Offshore Tugs
auxiliary	913.58	862.28	82.29	230.46	103.69	744.76	524.48
main	2415.37	5771.69	294.86	1273.54	3606.12	5054.48	7329.04

Figure 20: CO_2 Emissions from Main and Auxiliary Engines by Vessel Type[2]

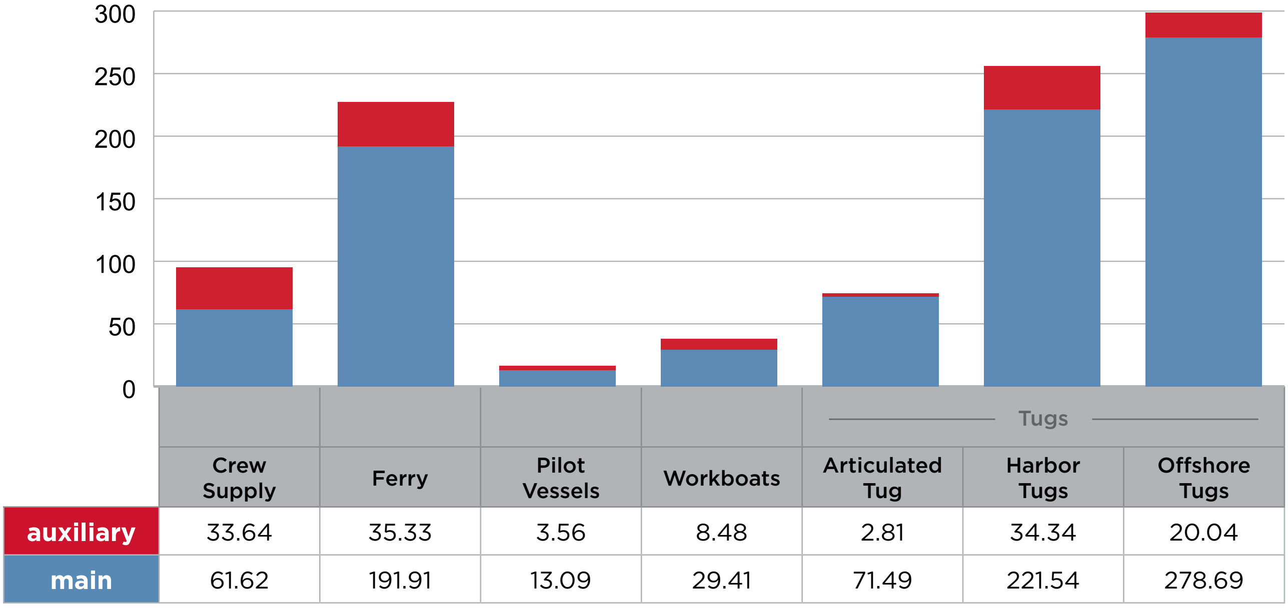


					Tugs		
	Crew Supply	Ferry	Pilot Vessels	Workboats	Articulated Tug	Harbor Tugs	Offshore Tugs
auxiliary	56706.69	49435.10	4191.88	13024.61	9199.21	36198.60	31577.99
main	214680.37	361915.26	14727.98	89561.79	358045.76	262809.74	444981.47

---

[2] All values indicated are given in units of g of CO_2/vessel/hour.

Figure 21: DPM Emissions from Main and Auxiliary Engines by Vessel Type[2]



DPM EMISSIONS FROM MAIN AND AUXILIARY ENGINES BY VESSEL TYPE

					Tugs		
	Crew Supply	Ferry	Pilot Vessels	Workboats	Articulated Tug	Harbor Tugs	Offshore Tugs
auxiliary	33.64	35.33	3.56	8.48	2.81	34.34	20.04
main	61.62	191.91	13.09	29.41	71.49	221.54	278.69

1 – 4.5 EMISSIONS INTENSITY METRICS

Emissions intensity metrics per tonnage were calculated for vessels across all categories by adding emissions (NO_x, CO_2, and DPM) from both main and auxiliary engines and dividing by GT. This can be used for assessing the overall environmental impact of various categories.

The main engines of harbor tugs have the highest emission intensity of CO_2 (over 2,000/GT), which is nearly twice the size of that seen in ferries or offshore tugs. It is also the case for NO_x and DPM emissions, while workboats have the least emission intensity among all crafts.

Although in small number, ferries are also major emitters per unit of travel; therefore, they need additional attention. In addition, Figure 21, Figure 22, and Figure 23 indicate that ferry and tugs display the highest emission intensity among all crafts. This supports the claim of the need to focus on these crafts.

Figure 22: Carbon Intensity Metric from Main and Auxiliary Engines

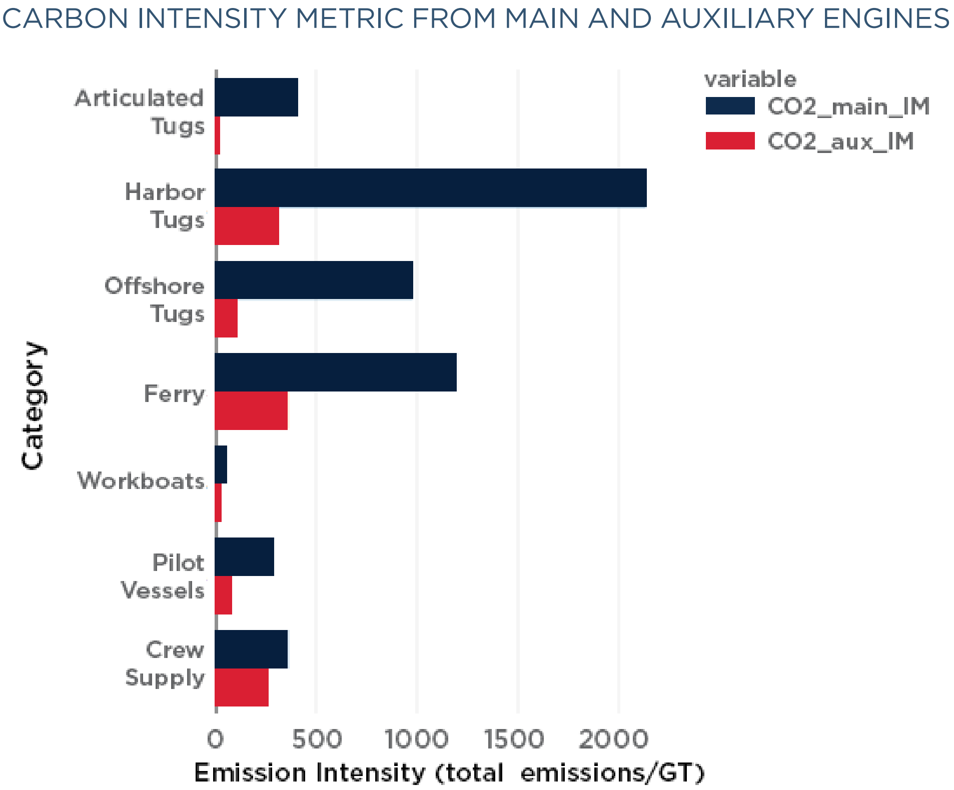
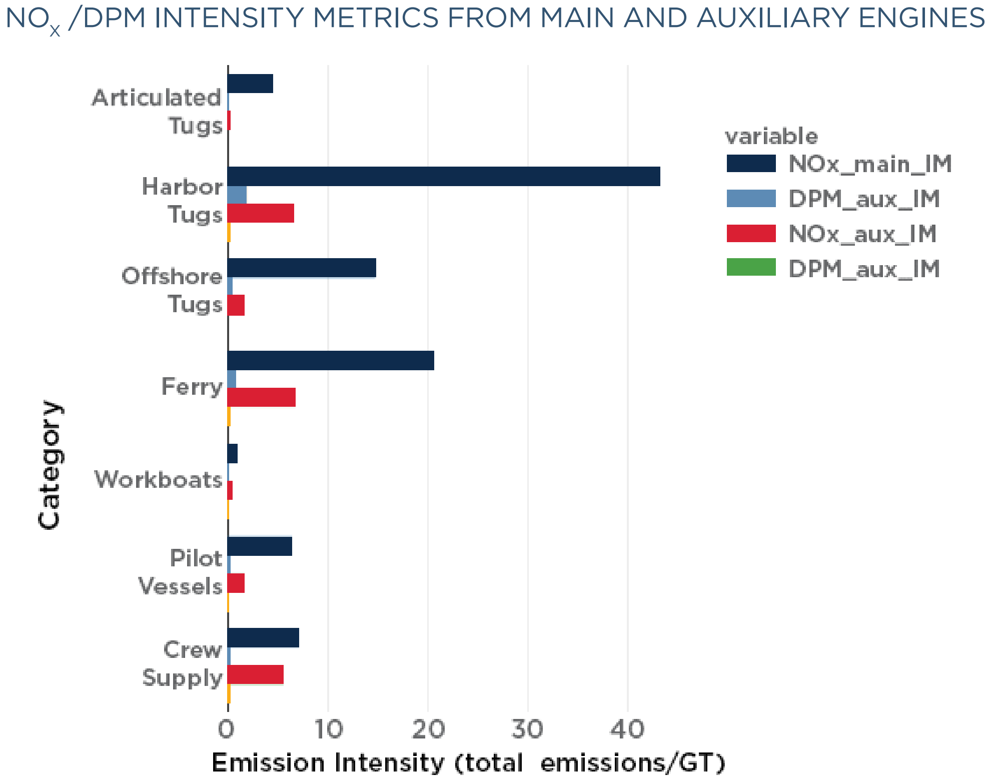


Figure 23: NO$_x$ /DPM Intensity Metrics from Main and Auxiliary Engines



1 – 5. CONCLUSION

Work boats, pilot boats, and crew supply boats display low emissions intensity and an insignificant share of the total marine service emissions. Therefore, it is recommended that as an intermediate solution, marine operation services shall be planned in a way to increase utilization ratio of workboats, pilot boats, and crew supply boats while minimizing the primary demand of tugs and ferries. This necessitates an adaptive management approach that will facilitate conversion in the planning and operationalization of marine services to fit the new normal.

For low emitting crafts (work boats, pilot boats, and crew supply boats), depending on the age of the craft, retrofitting might be the best option since it involves a lower capital investment. Consideration shall be made on solutions such as hybrid battery energy storage systems and/or dual fuel capabilities. Meanwhile, for high-emitting crafts like tugs, they may be well suited for zero-emission technologies such as alternative fuels and electrification.

For high-emitting aging crafts, redesigning new builds is necessary, taking into account technologies, such as:

- Hull form, ship size, propulsion improving devices (e.g., ducts, fins, and bulbs), propellers, rudders, and material optimization
- Air lubrication (e.g., microbubble drag reduction, air cavity, air layer, and air chamber)
- Hull coating and cleaning to reduce biofouling
- Propeller cleaning to reduce biofouling

Zero-emission harbor craft deployments will not succeed without access to electrical charging and alternative fuel production and distribution infrastructure. Transition to zero emission will not happen at scale until there is sufficient charging infrastructure and alternative fuel supply. Adding to this challenge is the high uncertainty surrounding future fuel projection. In view of the growing size of crafts and the increased demand of maritime transportation, there is compelling need for scaling technologies, both electricity and alternative fuels, to reach net zero.

Workstream 2:

PROFILING CALIFORNIA PORTS AND INFRASTRUCTURE, AND BUNKERING OPERATIONS

2 PROFILING CALIFORNIA PORTS AND INFRASTRUCTURE AND BUNKERING OPERATIONS

2 – 1. INTRODUCTION

In an effort to reduce air emissions and improve energy efficiency from vessels, ports, and marine terminal operations, the Maritime Administration's (MARAD) Office of Environment and Innovation as part of the Maritime Environmental and Technical Assistance Program (META) commissioned Workstream 2, which focuses on a comprehensive analysis of California's port infrastructure. Through a detailed survey and analysis of publicly available information, this section examines key aspects such as port characteristics, available bunkering fuels, and electrification infrastructure. It also examines shore power capabilities and planned sustainability initiatives. In the survey, key findings include the following:

- **Port Characteristics:** California's ports exhibit significant variations in size, capacity, and operational scope. The Port of Los Angeles, spanning approximately 7,500 acres, and the Port of Long Beach, covering 3,520 acres, are the largest in the state. These ports also lead in berth length, with Long Beach offering 60,000 feet and Los Angeles 49,117 feet. In contrast, smaller ports like West Sacramento operate on a more focused scale with only one terminal and five berths.

- **Bunkering Infrastructure:** There is strong drive toward ship-to-ship bunkering on alternative fuels, such as ammonia and hydrogen, to meet green shipping corridor specifications. Truck-to-ships are also considered viable options, mainly for LNG, which is considered an interim fuel solution for decarbonization.

  Furthermore, the study found a lack of land-based bunkering facilities for both traditional fuels (MDO/MGO, HFO, LFO) and alternative fuels across all surveyed ports. Bunkering primarily occurs via truck-to-ship or barge-to-ship methods. However, the Ports of Los Angeles and Long Beach currently provide LNG bunkering through truck-to-ship operations with plans to introduce green LNG (bio-LNG or synthetic LNG) by 2030.

- **Electrification Infrastructure:** The survey indicated a general interest among ports in adopting renewable energy solutions such as solar panels and wind turbines for on-site power generation. The deployment of solar and wind projects varies across ports, with larger ports tending to have more equipped facilities.

- **Shore Power:** Shore power availability also varies across California's ports. Major ports like Los Angeles and Long Beach have implemented both high-voltage shore connection (HVSC) and low-voltage shore connection (LVSC) systems. They have maximum capacities of 40 MW and 16 MW, respectively. While other ports like Oakland and San Diego also offer shore power, some smaller ports lack these facilities. This indicates a need for further investment in this technology.

- **Financial Support:** This investigation reveals that access to funding through Sustainability-Linked Loans (SLLs) favors larger ports. This demonstrates higher success rates in loan applications compared to smaller ports. This may necessitate further policy intervention to support smaller ports with decarbonization initiatives.

- **Future Initiatives:** California's ports are actively planning and implementing various sustainability initiatives. These include exploring alternative fuel options, such as hydrogen and methanol, and expanding shore power capabilities to accommodate a wider range of vessels. These also include investing in on-site renewable energy generation through solar and wind power projects.

  Major ports, particularly the Ports of Los Angeles and Long Beach, are taking steps to expand bunkering operations and supply lower- and net-zero-emission marine fuels. These efforts are part of a broader initiative to establish a green and digital shipping corridor with the Port of Singapore, involving collaboration with industry partners. A comprehensive baseline study has already been completed to understand shipping activities and identify decarbonization opportunities along the trans-Pacific shipping corridor.

2 – 2. METHOD

To assess the feasibility of alternative energy solutions for commercial harbor craft, a comprehensive analysis of California's port infrastructure was conducted. The approach is illustrated in Figure 24. This analysis involves a detailed survey focusing on key aspects, such as port size and characteristics, and available bunkering fuels. It also focuses on existing electrification infrastructure, shore power capabilities, and planned sustainability initiatives. Data collected through the survey, along with publicly available information, provided the foundation for analyzing the profile and the potential for transitioning toward cleaner solutions within California's ports.

Figure 24: Port Study Approach

2 – 2.1 PORTS IDENTIFIED

California has a diverse landscape of ports, each playing a crucial role in the state's economy and global trade. Twelve main ports were identified as the primary focus of this study, as outlined in Table 7. These include the Ports of Los Angeles and Long Beach, which together handle over 40% of the nation's maritime trade, and other key ports, such as Port of Oakland, Port of Richmond, Port of Stockton, and Port of San Diego. Additionally, several smaller, private ports were included to provide a more comprehensive understanding of California's port profile and potential for alternative energy adoption. Those are Port of Alameda, Port of Martinez, Moss Landing Harbor, Newport Beach Harbor, Port of Crocket C&H Sugar, and Port of Vallejo.

Table 7: Identified Ports

Identified Ports	
Port of Richmond	Port of San Diego
Port of Hueneme	Port of San Francisco
Port of Long Beach	Port of Stockton
Port of Los Angeles	Port of West Sacramento
Port of Oakland	Port of Humboldt Bay
Port of Redwood City	Port of Benicia

2 – 2.2 SURVEY CREATION

To gather detailed information about the infrastructure and capabilities of each port, a survey was conducted focusing on five key areas. Those areas include port characteristics, available bunkering fuels, electrification infrastructure with an emphasis on renewable energy sources, shore power capabilities, and planned sustainability initiatives. These areas were identified as crucial for evaluating the feasibility and potential for transitioning toward alternative fuel solutions within California's ports. The survey was distributed to the relevant port authorities, who were invited to provide responses. Additionally, interview calls were scheduled with selected ports to gather further insights and clarifications. The detailed survey instrument can be found in the Appendix.

2 – 2.3 DATA COLLECTION AND LIMITATION

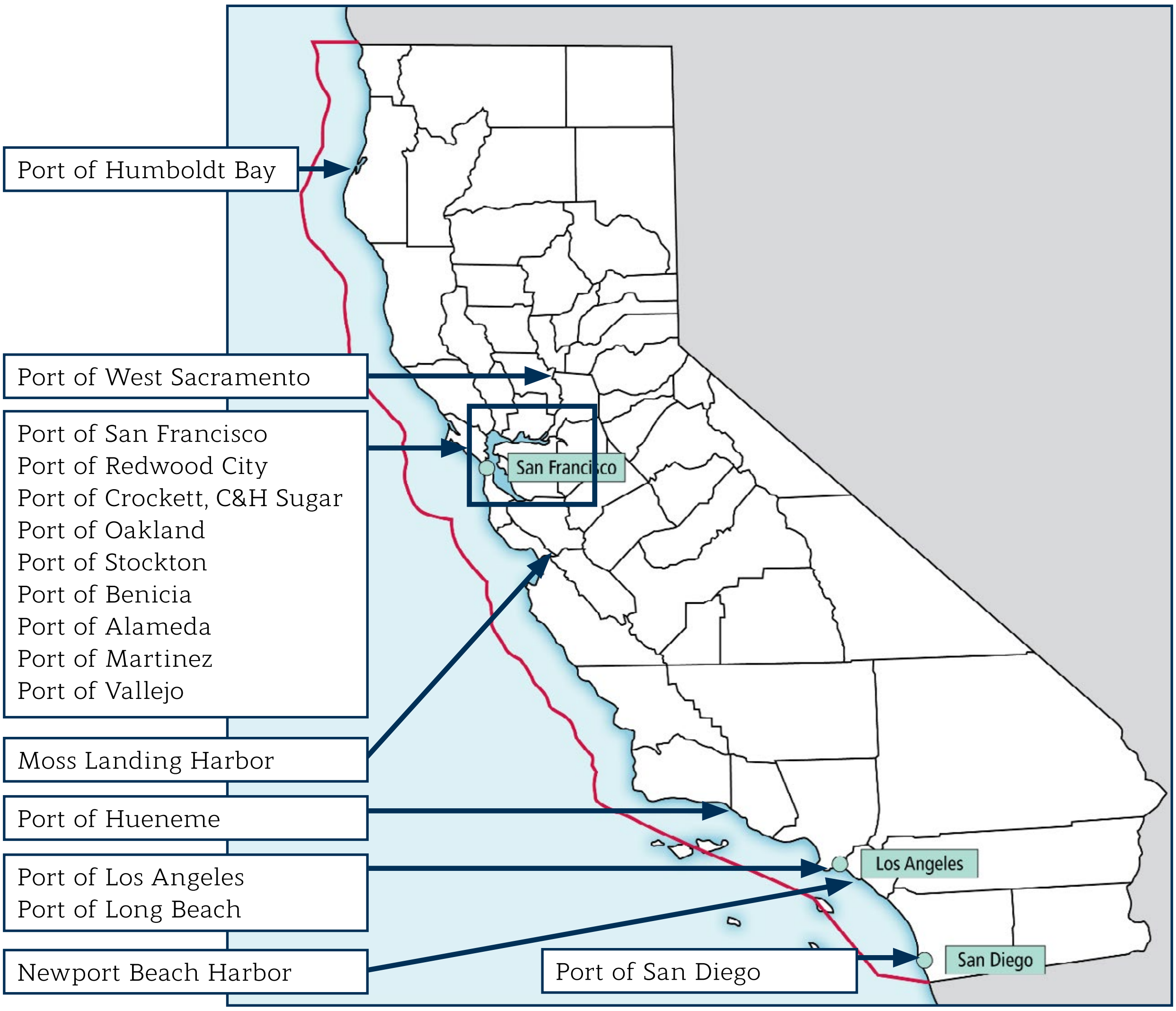
In this study, data was collected through a combination of direct engagement with port personnel and publicly available information sourced from port websites, whitepapers, and other relevant online resources.

While efforts were made to gather comprehensive data, limitations arose due to the organizational structure and management model of various ports. Port authorities often lacked complete information about facilities they did not directly own or manage, particularly for small private ports. This varying degree of familiarity may have influenced the accuracy and detail of responses. Additionally, certain survey questions, particularly those related to electrification and natural gas infrastructure, demonstrated a challenge for port authorities to answer without consulting other stakeholders.

2 – 3. RESULTS

The majority of California's major ports are concentrated around the San Francisco Bay Area and the adjacent San Pedro Bay near Los Angeles. This includes the massive Ports of Los Angeles and Long Beach in San Pedro Bay, as well as the Ports of Oakland, Richmond, Stockton, Redwood City, Benicia, and San Francisco clustered around San Francisco Bay. Other significant ports are located in San Diego Bay (Port of San Diego), Humboldt Bay (Humboldt Bay Harbor), and the Port of Hueneme in Ventura County. The map in Figure 25 illustrates the locations of California's ports being studied.

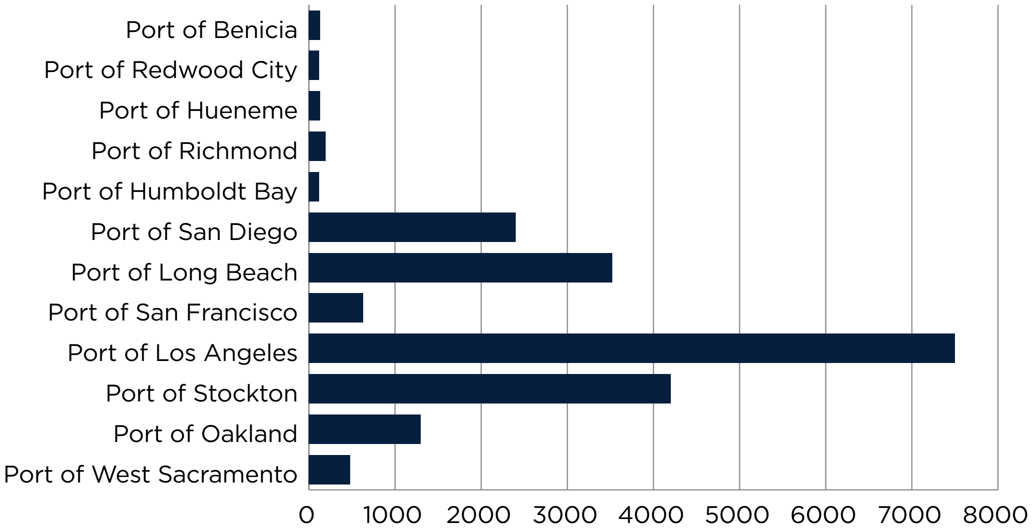
Figure 25: California Port Locations



2 – 3.1 PORT CHARACTERISTICS

The main ports in California show significant variations in size, capacity, and operational scope. The Port of Los Angeles is the largest, covering approximately 7,500 acres of land area, followed by the Port of Long Beach with 3,520 acres (Figure 26). These ports also lead in berth length, with Long Beach featuring 80 berths with a combined length of 60,000 feet and Los Angeles at 49,117 feet. These ports accommodate the largest vessels and reflect their ability to expand clean energy infrastructure, such as shore power. This contrasts with smaller ports like West Sacramento, which operates on a more focused scale with only one terminal and five berths.

Figure 26: Comparison of Land Areas of California Ports



Annual tonnage also shows a significant difference among California's ports. The Port of Long Beach leads the way at 90 million tons and is followed by the Port of Los Angeles at 60 million tons. Figure 27 provides a comparison of tonnage across the state's ports.

Figure 27: Annual Tonnage of California Ports

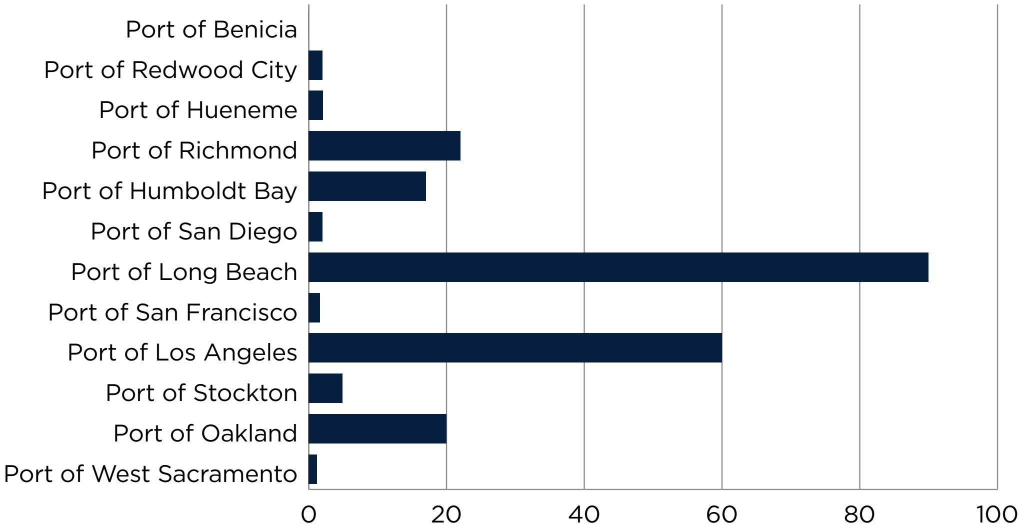


Table 8 and Table 9 below detail the 12 main California ports and include information on six smaller ports for a comprehensive overview. Due to organizational structures and limited data availability, some parameters for smaller ports remain unknown. Additionally, since smaller ports often primarily serve recreational purposes, boat slip information is included to better reflect the scale of these facilities.

Table 8: Detailed Characteristics of 12 Main Ports

Detailed 12 Main Ports Characteristics

	Port of Benicia	Port of Redwood City	Port of Hueneme
Operating Entity	Amports	City of Redwood City	Oxnard Harbor District
Ownership	Private	Public	Public
Cargos	RoRo, Liquid Fertilizer	Cement, Scrap Metal, Lumber, etc.	Autos, Fresh Produce, Fertilizer etc.
Tonnage/year	unknown	~2 million	2.1 million
Land area	~132 ac[3]	~120 ac	~130 ac[4]
# of terminals	1	3	3
# of berths	4[5]	5[6]	6
Length of berth	~2,400 ft[7]	3,125 ft	5,120 ft

	Port of Richmond	Port of Humboldt Bay	Port of San Diego
Operating Entity	City of Richmond	Humboldt Bay Harbor, Recreation and Conservation District	Oxnard Harbor District
Ownership	Public	Public	San Diego Unified Port District
Cargos	Petroleum, Autos, Minerals, etc.	Logs, Wood Chips	Autos, machinery, heavy equipment, etc.
Tonnage/year	~22 million	more than 17 million[8]	2 million
Land area	more than 195 ac[9]	~120 ac[10]	2,400 ac
# of terminals	5[11]	7	2
# of berths	7	7	21
Length of berth	more than 5540 ft[12]	5,627 ft	~8,000 ft[13]

---

[3] The acreage is from Amports' fact sheet, referring to the port's storage yard space on automobiles.

[4] The port occupies up to 131 acres, comprising its 120-acre terminal area. It also has around 30 additional acres of joint facility with the Navy.

[5] There are four berths: three for RoRo and auto discharge and one for liquid fertilizer.

[6] There are three deep-water berths across five wharves.

[7] This is a rough estimate of the berth length because it represents the linear space available along the pier for docking vessels, although it may include multiple docking points or segments along its entirety.

[8] It has an average of over 17 million tons of annual dry bulk tonnage in the years leading up to 2018. This tonnage figure is expected to have increased.

[9] The total land area reflects the sum of land areas for Terminals 2, 3, 4, and Pt. Potrero Marine Terminal (5, 6, 7). Land area for Terminal 1 and other privately owned terminals are not included due to unavailable data.

[10] The Humboldt Bay Harbor District controls approximately 118.2 acres of land and 35.6 acres of water area, according to Humboldt County Planning Department in 2018.

[11] The Port of Richmond includes five city-owned terminals, 10 privately owned terminals, and five dry-docks. The private terminals are responsible for close to 90% of the port's annual tonnage.

[12] Berth length excludes Terminal 1 and privately owned terminals due to unavailable data.

[13] Berth lengths are calculated by converting meter measurements to feet and adding the lengths of all available berthing spaces.

	Port of Long Beach	Port of San Francisco	Port of Los Angeles
Operating Entity	City of Long Beach Harbor Department	City and County of San Francisco	City of Los Angeles Harbor Department
Ownership	Public	Public	Public
Cargos	Containers, autos, petroleum coke, etc.	Steel products, boats, wind turbines, etc.	Autos, wastepaper, etc.
Tonnage/year	90 million	~1.6 million	~60 million[14]
Land area	3,520 ac[15]	629 ac[16]	7,500 ac[17]
# of terminals	22	4[18]	25
# of berths	80	12	50
Length of berth	~60,000 ft	>5,150 ft[19]	49,117 ft

	Port of Stockton	Port of Oakland	Port of West Sacramento
Operating Entity	Stockton Port District	City of Oakland	City of West Sacramento
Ownership	Public	Public	Public
Cargos	Liquid fertilizer, coal, cement, etc.	Fruits & nuts, machinery, electronics, etc.	Agricultural and industrial products
Tonnage/year	4.9 million	~20 million	~1.2 million
Land area	4,200 ac	1,300 ac	480 ac
# of terminals	Unknown	4	1
# of berths	14	49	5
Length of berth	1,200 ft	22,165 ft[20]	3,750 ft

---

[14] This reflects total cargo transported. Trade values are cargo revenue tonnage (170 million metric revenue), container volume (10.7 million TEUs), automobiles (102,767 units), and cruise passengers (151,837).

[15] Port of Long Beach comprises 3,520 acres of land and 4,600 acres of water.

[16] There is land area of 629 acres and 205 acres of waterfront.

[17] Port of Los Angeles has 7,500 acres (4,300 land/3,200 water).

[18] Terminal count is based on identified piers with distinct cargo handling functionalities (pier 80, 92, 94, 96). Additional terminals or facilities exist within the port complex.

[19] Berth length is calculated based on available data for Pier 90 and 94/96. Additional lengths exist within the port complex.

[20] Berth lengths are based on the port map; the number includes dolphins, which are mooring structures extending from the pier.

Table 9: Six Smaller Ports Characteristics

Six Smaller Ports Characteristics			
	Port of Alameda	**Port of Martinez**	**Port of Moss Landing**
Operating Entity	City of Alameda	Shell Oil Company[21]	Moss Landing Harbor District
Ownership	Public	Private	Public
Cargos	Chemicals, fuels, etc.	Petroleum, chemicals, etc.	Petroleum, plastics, etc.
Tonnage/year	Unknown	~2.7 million[22]	Unknown
Land area	Unknown	Unknown, but very small	Unknown
# of terminals	3	300 boat slips	610 boat slips
# of berths	5[23]	Unknown	Unknown
Length of berth	1,000 ft	Unknown	Unknown

	Newport Beach Harbor	**Port of Crockett**	**Port of Vallejo**
Operating Entity	City of Newport Beach	C and H Sugar Company	City of Vallejo
Ownership	Public	Private	Public
Cargos	Consumer goods, etc.	Sugar	Unknown
Tonnage/year	Unknown	Unknown	0.5 – 0.9 million
Land area	16,234 acres[24]	Unknown, but small	Unknown
# of terminals	Unknown	Unknown	Unknown
# of berths	3	5	2
Length of berth	660 ft	2,815 ft	Unknown

---

[21] Operating facility is estimated based on available data from SEARATES.

[22] This estimate is based on extrapolating the total weight unloaded at the port over the last 90 days (682,000 metric tons) to an annual basis.

[23] Berth number is estimated based on available data from SHIPNEXT.

[24] This includes ocean, bay, and harbor area within the city of Newport Beach.

2 – 3.2 BUNKERING INFRASTRUCTURE

This part of the survey investigated the bunkering infrastructure in California ports while examining traditional fuels. These fuels include MDO/MGO, HFO, LFO, and alternative fuel options. Key takeaways from the survey include the following:

- All surveyed ports reported lack of land-based bunkering facilities for both traditional (MDO/MGO, HFO, LFO) and alternative (LNG) fuels. Marine fuels are bunkered truck-to-ship or ship-to-ship[25].
- For alternative fuels, there is strong drive toward barge-to-ship bunkering on ammonia and hydrogen.
- The Ports of Los Angeles and Long Beach provide LNG bunkering via truck-to-ship, with plans for green LNG (bio-LNG or synthetic LNG) by 2030[26].

Among the three bunkering methods—ship-to-ship, truck-to-ship, and terminal-to-ship—the investigation into California's port bunkering infrastructure revealed a lack of dedicated land-based facilities for traditional fuels like MDO/MGO, HFO, and LFO, as well as alternative options such as LNG. Notably, none of the surveyed ports offered terminal-to-ship bunkering. As a result, large vessels primarily rely on third-party services for refueling, utilizing ship-to-ship transfer via barges, or truck-to-ship operations from shore. While smaller ports and marinas possess limited ground storage for diesel and gasoline, their capacity, typically around 10,000 gallons, caters primarily to smaller vessels and port vehicles.

Currently, the Ports of Los Angeles and Long Beach are the sole providers of LNG bunkering via truck-to-ship transfer facilitated by Clean Energy Fuels Corp. This service, operational since Q3 2022, has a 300,000-gallon capacity and represents a significant step toward cleaner marine fuels. TotalEnergies has plans to introduce green LNG bunkering (bio-LNG or synthetic LNG) by 2030, further expanding the availability of sustainable fuel options for vessels operating in California.

2 – 3.3 ELECTRIFICATION INFRASTRUCTURE

The next section of the survey examined the adoption of renewable energy sources, specifically solar panels and wind turbines, within California's port infrastructure. Ports were asked about existing or planned projects and their respective capacities. While the responses indicated a widespread interest in embracing renewable energy solutions for on-site power generation, detailed information on specific projects and capacities was limited. Table 10 summarizes the ports that have expressed initiatives to incorporate solar and/or wind power into their infrastructure.

---

[25] It is important to note that the findings presented here are based on survey responses. While efforts were made to ensure comprehensive participation, it is possible that some existing infrastructure may have been omitted due to incomplete knowledge.

[26] Information regarding LNG bunkering operations was sourced from Clean Energy.

Table 10: Electrification of California's Ports

California Ports	Existing Solar Project?	Existing Wind Project?
Port of Benicia	**No**	**No**
Port of Hueneme	**Yes**	**In Plan**[27]
Port of Humboldt Bay	**Yes**[28]	**In Plan**[29]
Port of Long Beach	**Yes**[30]	**In Plan**[31]
Port of Los Angeles	**Yes**[32]	**No**
Port of Oakland	**Yes**	**No**
Port of Redwood City	**Yes**	**No**
Port of Richmond[33]	**No**	**In Plan**
Port of San Diego	**Yes**[34]	**No**
Port of San Francisco	**Yes**	**No**[35]
Port of Stockton	**Yes**[36]	**No**
Port of West Sacramento	**Yes**	**No**

2 – 3.4 SHORE POWER

Shore power has emerged as a proven and effective method for reducing air pollution from vessels at berth. By enabling vessels to shut down their auxiliary engines and connect to the electrical grid while docking, shore power reduces emissions associated with onboard power generation. While emissions may still occur at the power generation facilities supplying electricity to the shore power systems, these emissions are typically lower than those produced by auxiliary engines. They are expected to decrease further as renewable energy sources become more prevalent.

---

[27] In the 10-Year Strategy Plan, The Port of Hueneme has been involved in the preliminary planning discussions, which have been occurring for several years on offshore wind.

[28] Port of Humboldt Bay in the survey mentioned there is 750,000 kV solar for port administration and operation buildings.

[29] There is an offshore wind farm planned for 2030.

[30] Port of Long Beach has installed 3,290 kV solar panels; there is also a micro-grid in construction, 300,000 kV solar for port security headquarters.

[31] Port of Long Beach's $4.7 billion "Pier Wind" project involves constructing a 400-acre floating pier/terminal to support the assembly and deployment of offshore wind turbines.

[32] Port of Los Angeles has already implemented several solar power installations totaling around 3 MW in capacity across various sites like the World Cruise Center, with additional solar projects planned for the future.

[33] The Port of Richmond only has limited solar panels for parking areas; however, there is a plan to develop floating offshore wind turbines as it is a good candidate site to support the offshore wind.

[34] Besides port administration building, Port of San Diego has implemented solar power projects at its B Street Cruise Terminal and port pavilion on Broadway Pier.

[35] Although there is no current wind project, Port of San Francisco is actively positioning itself to become a manufacturing hub for floating offshore wind turbine components.

[36] There is an onsite solar installation to provide renewable power to its facilities from the survey.

The survey assessed the current state of shore power availability across California's ports. It revealed existing facilities and ongoing expansion projects aimed at reducing portside emissions. Table 11 summarizes the current level of shore power availability at the major ports included in the study.

Table 11: Shore Power of California's Ports

California Ports	Existing Shore Power	HVSC[37]	LVSC[38]	Maximum Capacity (MW)	Average Annual Usage (MWh)
Port of Benicia	**No**	**No**	**No**	N/A	N/A
Port of Hueneme	**Yes**	**Yes**	**Yes**	3	4,420
Port of Humboldt Bay	**No**	**No**	**No**	N/A	N/A
Port of Long Beach	**Yes**	**Yes**	**Yes**	16	10,182 (2019)
Port of Los Angeles	**Yes**	**Yes**	**Yes**	40	19,560
Port of Oakland	**Yes**	**Yes**	**No**	8	32,087
Port of Redwood City[39]	**Yes**	**No**	**Yes**	N/A	Unknown
Port of Richmond[40]	**Yes**	**No**	**Yes**	0.192	Unknown
Port of San Diego	**Yes**	**Yes**	**Yes**	12	3,308
Port of San Francisco	**Yes**	**Yes**	**Yes**	12	3,972
Port of Stockton[41]	**Yes**	**No**	**Yes**	~2	Unknown
Port of West Sacramento	**No**	**No**	**No**	N/A	N/A

---

[37] HVSC systems typically operate at 6,600 or 11,000V. They are used to power larger vessels such as cruise ships, container ships, and refrigerated cargo vessels.

[38] LVSC systems operate at 220 – 480V. They are used to power smaller vessels such as fishing boats, tugboats, workboats, ferries, and service vessels.

[39] The Port of Redwood City survey confirmed the availability of 120V shore power at boat slips within municipal marinas, suitable for small recreational vessels. However, the port lacks shore power infrastructure for large ocean-going vessels at its terminals. Data on capacity and annual usage was not provided.

[40] The Port of Richmond survey confirmed that Terminal 3 currently provides 480V/400A shore power for docked vessels. Additional installations are planned and under construction to expand capacity to other terminals.

[41] The Port of Stockton survey confirmed the availability of shore-side electrical power for tugboats. While the port offers 440V three-phase power at wharves, it currently lacks shore-power infrastructure for heavy marine use. Data on overall annual shore power usage across the port was not available.

2 – 3.5 FUTURE INITIATIVES

The final section of the survey explored the future sustainability initiatives planned by California's ports. Port authorities were asked to share information about upcoming projects and programs aimed at reducing environmental impact and promoting clean energy solutions. The following summary highlights some of the notable initiatives the ports reported, supplemented by publicly available information where possible. It is important to acknowledge that the level of detail provided may vary based on the knowledge of the survey respondents and that specific initiatives may evolve over time.

There are still a lot of uncertainties around future fuels mix, making it very hard for ports to develop robust future plans. Major ports have opted for the concept of green shipping, which allows them to specify their chosen fuel mix for further development. The success of this approach is yet to be proven.

Port of Benicia

While the Port of Benicia directly mentions no-sustainability initiatives, the survey with port authorities found that the port is exploring barge-located carbon-capture technology. Utilizing barges for carbon capture could allow the port to reduce its overall carbon footprint from operations.

Port of Hueneme

The Port of Hueneme will keep exploring shore power. Current initiatives include the implementation of a major Grid-Connected Shore Power System project. This allows ships to reduce emissions like nitrogen oxides and greenhouse gases by plugging into shore-side electricity instead of running diesel engines.

Furthermore, the port is actively transitioning to zero- and near-zero-emission technologies. They welcomed another electric-hybrid crane in November 2022 and developed an Electric Vehicle Accelerator Plan to support electrification and alternative fuel adoption across its operations.

Port of Long Beach

The Port of Long Beach has implemented an ambitious Zero Emissions, Energy Resilient Operations (ZEERO) Policy. It focuses on advancing green power generation and procurement utilizing distributed self-generation with microgrid connectivity for energy security and sustainability. It also provides cost-effective alternative fueling options and improves overall energy efficiency. This aligns with the port's major $4.7 billion "Pier Wind" offshore wind power project concept to construct a floating terminal supporting wind turbine assembly and deployment. The port has also launched initiatives like a 300-kilowatt solar panel microgrid, the Sustainable Terminals Accelerating Regional Transformation (START) project to demonstrate zero-emission equipment.

Port of Los Angeles

The ports have been actively exploring and implementing various electrification and alternative fuel technologies, including for their harbor craft fleets. This includes early adoption of hybrid tug designs. For ferries, there are efforts to upgrade to Tier 4 engines and explore diesel particulate filters once approved, despite controversy around their safety. Battery-to-battery charging is also being discussed for harbor craft. The ports have around 50 tugs operating—some overlapping between Los Angeles and Long Beach.

In the interview, the port mentioned that while full electrification remains challenging for certain harbor craft duties, the ports are implementing hybrid systems and investing in charging infrastructure. They are also evaluating alternative technologies like fuel cells to increase sustainability and reduce emissions from their tug and ferry fleets. Innovative designs and public-private partnerships are driving these clean air initiatives.

Port of Oakland

The Port of Oakland is aggressively pursuing sustainability through shore power, electrification, and alternative fuels. It is implementing shore power capabilities to allow ships to plug in and cut emissions, with 63 total calls and 46 vessels successfully utilizing shore power as of February 2023. The port aims to further expand shore power usage. It recently approved a $2 million contract for a major clean energy project, including solar generation, battery storage, a fuel cell system, and electrical infrastructure upgrades like a new substation. [Additionally, the port is improving electrical capacity to support widespread electrification of equipment and operations, while also exploring alternative fuel sources as part of its comprehensive drive toward achieving zero-emissions goals.

Port of Richmond

The Port of Richmond is committed to minimizing its negative environmental impacts and has implemented a Clean Air Action Plan (CAAP), which they adopted in 2016. This plan outlines a range of projects and key strategies aimed at reducing air emissions and mitigating associated health risks. Key initiatives include using exhaust treatment devices for ships at berth, exploring the feasibility of shore power infrastructure, and transitioning to cleaner cargo-handling technologies.

Under its strategy from CAAP GB5, it has set a target under strategy GB5 to "reduce its MTC02e emissions below the 2005 baseline by 2030." In line with this, the port has installed solar panels over parking areas. It is now investigating the feasibility of generating 100% of its energy needs from on-site renewable generation.

To reduce reliance on single-occupancy vehicles, the port has expanded public transportation options. This includes a free shuttle service that connects the port with the Bay Area Rapid Transit (BART) system.

Port of Richmond is actively integrating alternatively fueled and hybrid equipment into its fleet. It also prioritizes electric, LNG, CNG, or propane-powered options when replacing older diesel units.

In addition to climate issues, the port collaborates closely with the City of Richmond on various sustainability projects. An example is the joint effort to evaluate and implement treated wastewater reclamation initiatives within the port and adjacent commercial areas. The city has also launched a Climate Action Plan Goals Dashboard to track the city's overall performance in achieving these goals.

Port of San Diego

The Port of San Diego is actively transitioning toward electrification and zero-emission technologies across its maritime operations. It generates around 500,000 kilowatt-hours of renewable energy annually on-site and has facilitated the construction of the United States' first electric tugboat.

Additionally, the port has authorized $14 million for two all-electric mobile harbor cranes to replace diesel units at its Tenth Avenue Marine Terminal. It is expected to be operational by mid-2023. The port is also electrifying its vehicle fleet, recently adding an electric van and truck with 14 more electric vehicles approved for purchase to phase out gas/diesel models. Furthermore, it has developed a comprehensive Zero-Emission Heavy-Duty Truck Transition plan. The goal is to achieve 40% zero-emission truck trips by 2026 and 100% by 2030 as part of reshaping freight transportation through vehicle electrification and alternative fuels.

Port of San Francisco

The port utilizes electric and hybrid passenger vehicles and renewable diesel for its heavy trucks and equipment as part of its sustainability measures. Additionally, the port has backed tenant projects focused on promoting clean transportation, such as biodiesel production and the SF Breeze hydrogen fuel cell ferry research initiative.

Port of Stockton

The Port of Stockton has implemented shore power for ships and installed shore-side electrical power for tugs. This allows vessels to plug in instead of running diesel engines. The port has also replaced older gasoline trucks with new zero-emission electric vehicles for use on the docks. The port secured grant funding for 34 additional zero/low-emission forklifts as part of the Zero- and Near Zero-Emission Freight Facilities (ZANZEFF) program in collaboration with the Ports of Long Beach and Oakland. This demonstrates its comprehensive push toward sustainable cargo-handling equipment across its maritime operations.

Port of West Sacramento

The Port of West Sacramento is working to expand its electric vehicle charging infrastructure, with plans to add eight to 10 new charging stations on the East side of the port area. These new charging stations will be supplemented by solar panels and battery storage systems to provide renewable energy for powering electric vehicles and equipment at the port.

Workstream 3:

ASSESSING THE SUITABILITY OF ALTERNATIVE FUEL OPTIONS FOR COMMERCIAL HARBOR CRAFT IN CALIFORNIA

3 ASSESSING THE SUITABILITY OF ALTERNATIVE FUEL OPTIONS FOR COMMERCIAL HARBOR CRAFT IN CALIFORNIA

3 – 1. INTRODUCTION

Studies have shown that decarbonization potential from alternative specific fuel type is not sufficient, as no fuel option can offer the 100% emission reduction required by the sector by 2050. It is from this perspective that Workstream 5 was commissioned to assess the suitability of alternative fuels options for harbor crafts in California. This section highlights an urgent need for the shipping sector to consider various factors when investing in different alternative fuels for harbor crafts. It should also be noted that, while this section focuses on alternative fuels as good decarbonization potential, this cannot be achieved without accelerated investment in new and retrofit harbor crafts and the building of sustainable new fuel value chains. In addition, there is a need to integrate alternative fuel uptake with other decarbonization strategies such as slow steaming and wind propulsion.

3 – 2. METHODOLOGY

The suitability analysis was conducted through a comparison of fuels and pathways that were identified through the GREET Marine Module and their applicability to the California harbor craft (CHC). These narrow variety of vessels have specific design constraints that are important to consider when gauging the compatibility of a fuel. These constraints include size, cost, route, and region.

Within the smaller harbor crafts, space requirements become a serious issue. If the fuel storage demands are larger than what is currently available, it could be impossible for smaller vessels to accommodate despite the commonality of oversized fuel tanks. These alternatives can require two to twenty-four times the fuel storage to achieve an equivalent amount of energy potentially impacting the normal operations of these vessels. With these large volume increases, fuel weight becomes a non-negligible characteristic of the fuels as well. The margins on these boats for additional weight are limited. Even small changes can negatively affect the stability of the vessel.

Cost is another limiting factor for most of these vessels. These boats and their operators likely do not command as much capital as larger tankers or shipping vessels. Therefore, retrofits or implementations, which have a high capital or operating cost, will be difficult to justify.

Lastly, these vessels have short or pre-planned routes. This allows them to use fuels that may not have the same energy density as current fuels. Since they know their route, or because it can be relatively short, and since they can plan for additional refueling, they can make use of some technologies that larger ships cannot due to energy constraints and scaling issues.

To complete this comparison, a heat map was used, like the sample heat map in Table 12, to show the levels of performance for every fuel. Red indicates low performance and dark green represents high performance for a given metric. These ratings are qualitative in nature and were given based on knowledge gained through literature review.

Table 12: The Ranking Options, Their corresponding Colors, and Meaning as Indicators of Performance

Color Indicators					
Grade or Ranking	1	2	3	4	5
Meaning	Very Poor	Poor	Average	Good	Very Good

The metrics will look to cover the important characteristics of each fuel and are defined below.

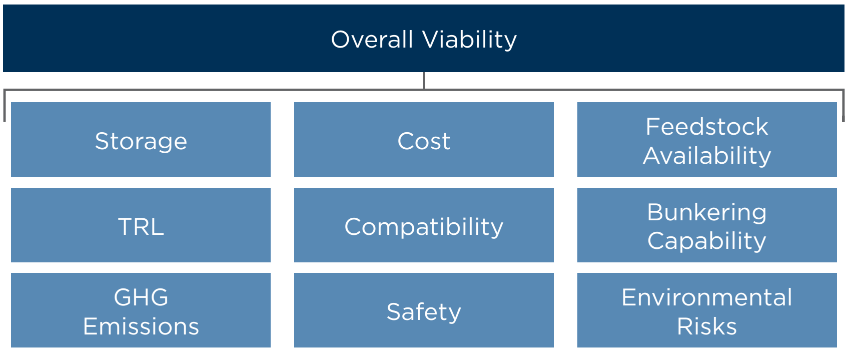


Table 13: Breakdown of Metrics Used for Suitability Analysis

METRIC	DESCRIPTION
Storage	There were a couple of aspects considered in the analysis of the storage qualities of the fuel. First was its volumetric energy density and second was the gravimetric energy density of the fuel. Only when these two metrics are combined can an accurate picture of the storage qualities of a fuel be observed. Storage is a significant issue for these harbor crafts as an increase in weight or tank capacity would result in a decrease in cargo/passengers held and therefore a decrease in revenue. Lastly, some alternative fuels require extreme, energy-intensive conditions to store, which would burden the systems onboard. This was also considered, if necessary.
Cost Competitiveness	This is an evaluation of the total cost to implement the alternative fuel. This includes engine retrofits (if necessary), new tanks, feedstock acquisition, and production process.
Current Feedstock Availability	The term *feedstock* mainly applies to biofuels but has been used here to reference the material needed to produce an alternative fuel. This metric represents the ability to access a fuel and its components. Many alternative fuels currently do not have mature feedstock sources, and as such, are hard to source for most vessels. This can cause some feedstocks to be abundant in theory but difficult or costly to procure.
Technological Readiness	This refers to the current technological readiness level (TRL) of the fuel. The matrix has been split up among the nine levels where a 1 – 2 TRL is a 1 on the matrix, 3 – 4 is a 2, 5 is a 3, 6 – 7 is a 4, and 8 – 9 is a 5. All TRLs were obtained through research on the latest advancements made in the industry. TRLs are the same as NASA definitions.
Compatibility with Current Systems	This metric looks at the compatibility of a fuel with the systems likely found on harbor craft. Many alternative fuels require significant modifications to a vessel before they can be implemented. This section judges the compatibility of these alternative fuels with the engine and fuel storage systems aboard small harbor craft. A fuel considered "drop-in," for example, will score highly in this section.
Current Bunkering Capability	This looked at the ability of the fuel to be bunkered without modifications to the existing infrastructure. Bunkering infrastructure is a major issue for alternative fuels today. Difficulties bunkering these fuels are a big problem for large-scale adoption and must be considered when looking to the future.
GHG Emissions	This section is a comparison of the lifecycle emissions produced in the GREET marine model. However, hydrogen was not considered within the GREET[42] marine model so these numbers were sourced from the GREET Well to Wake (WTW) calculator [3].

---

[42] The GREET Marine Module used can be accessed here: R&D GREET Marine Module (anl.gov).

METRIC	DESCRIPTION
Safety	Safety here will consider the potential risk a fuel poses to crew and passengers aboard the vessel. Some alternative fuels do come with increased risk factors for all passengers onboard. This might become a consideration for a ferry, which transports hundreds of passengers a day. This also would come with increased training costs for owners and operators who must now account for new safety concerns.
Environmental Risks (Spill)	This metric analyzed the potential damage a fuel might inflict on the environment in the case of a spill. Currently, fuel leaks/spills are a major risk to local wildlife. Though they can be uncommon, spills are destructive to the ecosystem and cause long-term damage to the animals affected.

OVERALL VIABILITY

This is an average of the metrics above to give an overall outlook at the applicability of the fuel to CHC in their current technological state (2023).

3 – 3. SUITABILITY OF ALTERNATIVE FUEL OPTIONS FOR COMMERCIAL HARBOR CRAFT

3 – 3.1 BIOCRUDE

Biocrude is a biofuel made using hydrothermal liquefaction (HTL) from a feedstock of manure or sludge. Hydrothermal liquefaction is a thermal depolymerization process used to convert wet biomass and other macromolecules into crude-like oil under moderate temperature (200 –400°C) and high pressure (10 – 25 MPa) [4]. The initial product is not considered a drop-in fuel, but through further upgrading, can be utilized in diesel engines.

Table 14: Biocrude Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Hydrothermal Liquefaction	Manure	3	3	5	4	2	4	5	5	1	4
Hydrothermal Liquefaction	Sludge	3	3	5	4	2	4	5	5	1	4

KEY TAKEAWAYS

PROS	CONS
• Cheap and abundant feedstock • California has one of the largest livestock industries in US • Can provide significant emissions reduction • Can be bunkered using existing infrastructure with small modifications • No additional safety risk	• The process is expensive • Will require more space to achieve the same amount of energy as MGO • Is denser than MGO • Requires additional processing to be used in diesel engines • Highly toxic to aquatic life • Might need to be heated to reduce viscosity before it can be combusted

Table 15: Detailed Description of Biocrude Suitability[8]

METRIC	DESCRIPTION
Storage	Biocrude has a lower energy density than MGO[43], and as such, will require more volume of the fuel to reach the same amount of energy. It is also heavier per unit volume at about 0.97 – 1.04 g/ml [44] [5] and will require larger tanks to reach equivalent energies. However, it will not require additional modification to current infrastructure to store on the ship.
Cost Competitiveness	The cost of biocrude is moderate compared to the biofuels studied. The feedstocks of manure and sludge are inexpensive to procure and abundant. However, hydrothermal liquefaction is expensive and takes a significant amount of energy to complete. This, combined with a need to increase storage tanks and to further process the fuel for it to be used in diesel engines, increases the cost.
Current Feedstock Availability	Manure: California, being one of the nation's largest producers of livestock [1], particularly dairy, gives it a unique access to this feedstock. This gives it the potential to be a cheap resource to tap into. Sludge: California, being one of the nation's most populous states, has an abundance of this feedstock.
Technological Readiness	The TRL of biocrude was assessed to be a 6. There have been studies that have used this fuel in experimental engines [7]. However, there have been no announcements of vessels running on biocrude or of it being produced at any commercial level for marine use.
Compatibility with Current Systems	Biocrude is not currently considered a drop-in fuel, and engine modifications and additional "upgrading" of the fuel itself are considered necessary to use it. It can, however, use current fuel tanks, though they may need to be expanded. Additionally, they may need slight modification due to its high viscosity [8].
Current Bunkering Capability	Like most biofuels, biocrude does not require additional infrastructure to store and can use current systems in place. However, it will likely need some heating to move due to its high viscosity.
GHG Emissions	Feedstock: Manure — Lifetime Emissions (g GHGs/kWh): -175 Feedstock: Sludge — Lifetime Emissions (g GHGs/kWh): 36.3 Depending on the feedstock, biocrude has the potential to be a net-zero-emission fuel.
Safety	Biofuels do not impose an increased safety risk compared to fossil fuels.
Environmental Risks (Spill)	Biocrude is less dense than water and will float on the surface of the water. Due to high viscosities, it can be expected to form a floating slick. However, because it is partially water-soluble, part of this slick will dissipate into the water. Since it is a new fuel, its full toxicity is not well studied, but it is believed to have a similar toxicity to bio-oils, which are highly toxic to aquatic wildlife [5].

GHG Emissions:

Feedstock	Lifetime Emissions (g GHGs/kWh)
Manure	-175
Sludge	36.3

---

[43] Heat value of MGO is assumed to be 45.84 MJ/kg.

[44] MGO density is assumed to be .86 g/ml.

OVERALL VIABILITY OF BIOCRUDE

This fuel, while its feedstocks are abundant and cheap, especially in the California region, is not yet tested in marine engines, and from lab tests, has shown to be incompatible with current engines without further treatment. With more research, biocrude could potentially be a great option for smaller vessels since it has remarkable lifetime emission reductions and is only slightly worse than MGO in its storage capacity.

However, the process of HTL is a costly and energy-intensive process that requires specialized equipment. The severe reaction conditions of the process lead to severe corrosion in this equipment, making large-scale production of this fuel difficult and expensive. This does not include the additional treatment that would be needed for it to be usable in diesel engines. Also, it is likely that there would need to be some modification to the vessel, such as pre-heating in the storage tanks, to be able to move and use this fuel due to its high viscosity. All these aspects increase the potential cost of this fuel. Currently, this fuel is not developed enough for use in CHC, but its significant emissions reductions and cheap feedstocks make it a viable option for the future. If the cost to conduct HTL can be reduced, biocrude could become an economic option for the future.

3 – 3.2 BIODIESEL

Biodiesel is a biofuel made using transesterification from a feedstock of soybeans. Transesterification of the soybean oil is performed by reacting the oil with alcohol, usually methanol, and a catalyst, such as sodium hydroxide. The resulting mixture is centrifuged to remove excess methanol, glycerin, and other impurities. The mixture is then washed with a water acid solution and dried to become methyl ester, otherwise known as biodiesel [9]. Biodiesel has a high volumetric energy density and gravimetric energy density compared to other biofuels. In this way, it is one of the most like traditional diesel.

Table 16: Biodiesel Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Trans-esterification	Soybean	4	5	3	5	5	5	3	5	2	4

PROS	CONS
• Cheap and abundant feedstock • Can provide emissions reduction • Can be bunkered using existing infrastructure • A drop-in fuel • Is similar in density to MGO • Ports are beginning to bunker blends of fuel • Less environmental impact in case of spill	• Feedstock has significant competition • Higher cost to fossil fuels • Slight reduction in energy density to MGO • Feedstock is not the most abundant in the California region • Low shelf life

Table 17: Detailed Description of Biodiesel Suitability

<table>
<tr><th>METRIC</th><th>DESCRIPTION</th></tr>
<tr><td>Storage</td><td>Biodiesel has a lower energy density than MGO, and as such, will require more volume to reach the same amount of energy. It is also slightly heavier per unit volume, at about 0.82 – 0.88 g/ml [5]. Biodiesel will not require additional or modified infrastructure to store on the ship.</td></tr>
<tr><td>Cost Competitiveness</td><td>The cost of biodiesel is low overall compared to other alternative fuels. Its process—transesterification—is inexpensive and well studied. It is also a drop-in fuel, so no retrofit is required. Its physical properties are similar to MGO so storage can remain at a similar level. Lastly, ports are already beginning to bunker blends of biodiesel, reducing overall cost to acquire as its supply lines become more mature.</td></tr>
<tr><td>Current Feedstock Availability</td><td>Within the U.S., due to an expansive agriculture industry, soybeans have a high availability but are also in high demand from other industries [10].</td></tr>
<tr><td>Technological Readiness</td><td>Currently, biodiesel has a TRL of 9 and is commercially available in various blends.</td></tr>
<tr><td>Compatibility with Current Systems</td><td>Biodiesel is a drop-in fuel that can be used with current engines. It can also use current fuel tanks, though they may need to be expanded.</td></tr>
<tr><td>Current Bunkering Capability</td><td>Blends of this fuel are already being bunkered around the U.S.</td></tr>
<tr><td>GHG Emissions</td><td><table><tr><th>Feedstock</th><th>Lifetime Emissions (g GHGs/kWh)</th></tr><tr><td>Soybean</td><td>114</td></tr></table>It does have a preferable lifetime emission profile when compared to MGO; however, it will not meet 2050 requirements. It also has one of the lower performing emissions profiles.</td></tr>
<tr><td>Safety</td><td>Biofuels do not impose an increased safety risk compared to MGO.</td></tr>
<tr><td>Environmental Risks (Spill)</td><td>Biodiesel is less dense than water, so it will float on the water surface and form a nonflammable, nontoxic slick, which can coat wildlife. This is of greatest risk to birds whose coated feathers will lose any insulating properties. It is also biodegradable and will degrade about four times faster than diesel fuels [5].</td></tr>
</table>

OVERALL VIABILITY OF BIODIESEL

Biodiesel is a great alternative to diesel today; however, it is currently about two times more costly to produce than traditional diesel. However, if an owner can tolerate the cost, it is a drop-in fuel with very similar properties to traditional diesel. Therefore, it would require minimal changes to current systems to be used. This greatly increases its cost competitiveness compared to the other fuels analyzed.

Currently, the feedstock for biodiesel is mature and available. However, it does not have great scalability as the production of soybeans could not currently meet the demand if many industries began switching to this fuel. This does not provide as much of an issue for harbor craft since the scale is much smaller than other commercial sectors so it maintains a high rating in this aspect.

This technology has a high readiness level of 9, and blends of this fuel are currently being used commercially. Biodiesel can use the same bunkering infrastructure as diesel and is currently bunkered at ports around the world.

Biodiesel currently has great applicability as an alternative fuel. It is considered a drop-in fuel and is miscible with MGO as well. This makes it incredibly versatile as either a stand-alone fuel or a mix with currently available fossil fuels. It is more expensive than the current options, but when compared to other alternative fuels, it remains comparatively low. However, biodiesel does not provide as significant reduction in GHG emissions as other options, which hurts its future applicability.

Overall, biodiesel is a great option for quick emission reductions without modifying current infrastructure. In the short term, it looks to be a viable option for those looking to switch to alternative fuels.

3 – 3.3 BIO-OIL

Bio-oil is a biofuel made using fast pyrolysis from a feedstock of woody biomass, woody biomass and Pt/TiO2, and woody biomass and ZSM-5. Fast pyrolysis is a process in which biomass is rapidly heated (10 – 200°C/s) to high temperatures (300 – 700°C) in the absence of air, specifically oxygen [11]. After cooling, this creates a dark-brown liquid oil, otherwise known as bio-oil. However, this process results in a product with a high concentration of water and therefore less energy. Because of this, recent studies have used catalysts such as Pt/TiO2 and ZSM-5 to reduce this concentration.

Table 18: Bio-Oil Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Fast Pyrolysis	**Woody Biomass**	**1**	**4**	**5**	**4**	**3**	**1**	**4**	**5**	**1**	**3**
Fast Pyrolysis	**Woody Biomass, Pt/TiO2**	**2**	**4**	**5**	**4**	**4**	**3**	**5**	**5**	**1**	**4**
Fast Pyrolysis	**Woody Biomass, ZSM-5**	**3**	**4**	**5**	**4**	**5**	**3**	**5**	**5**	**1**	**4**

PROS	CONS
• Can provide emissions reduction • Cheap process to produce fuel • No additional safety risk • Abundant feedstock in the region	• Will require stainless steel storage due to corrosion issues • Must be further processed to use in diesel engines • Is extremely damaging to aquatic life if a spill occurs • Large reduction in energy density compared to MGO

Table 19: Detailed Description of Bio-Oil Suitability

METRIC	DESCRIPTION
Storage	Bio-oil has a lower energy density than MGO, and as such, will require more volume to reach the same amount of energy. It is also heavier per unit volume at about 1.1 – 1.3 g/ml [5]. Due to corrosion risks, it will require stainless steel tanks if not already present.
Cost Competitiveness	The cost of bio-oil made through fast pyrolysis is low compared to the fuel analyzed. It is not a drop-in fuel so extra treatment of this fuel is needed before it can be used in diesel engines. Energy density is low and gravimetric density is high leading to the need for significant storage increases and added weight since the bio-oil is about 20% more dense. However, the feedstock is abundant in the California region and the process is one of the cheapest to complete.
Current Feedstock Availability	California has a great amount of woody biomass and has been considering sustainable ways to acquire this feedstock, which aligns with the state's policies. A supply line, however, does not exist and this would need an initial investment to establish.
Technological Readiness	Currently, bio-oil, made from fast pyrolysis of only biomass, has a TRL of 9. It has been used in commercial settings, but using catalytic pyrolysis is only at a 6. This has not yet been performed commercially and is still being studied to optimize the output.
Compatibility with Current Systems	It cannot be used with current engines without significant upgrading. It will also require stainless steel tanks due to the high water content in the fuel, so it will likely corrode normal steel tanks. The tanks will likely need to be expanded to accommodate the lower energy density of the fuel.
Current Bunkering Capability	The storage tanks will need to be stainless steel but do not need any additional modifications to accommodate the bio-oil. However, bio-oil has a tendency to separate so it might have a lower shelf life or may need additional attention while it is bunkered.
GHG Emissions	<table><tr><th>Feedstock</th><th>Lifetime Emissions (g GHGs/kWh)</th></tr><tr><td>Woody Biomass</td><td>71</td></tr><tr><td>Woody Biomass, Pt/TiO2</td><td>39.4</td></tr><tr><td>Woody Biomass, ZSM-5</td><td>2.95</td></tr></table> With the use of sustainable feedstocks, bio-oil does achieve a low lifetime emissions profile.
Safety	Biofuels do not impose an increased safety risk compared to MGO.
Environmental Risks (Spill)	It is denser than water so the fuel will be suspended in the water column as a slick or dispersion.[45] Any wave action will produce globules of dense matter, and over time, the bio-oils will polymerize and increase in density causing these globules to sink. Due to the lignin content, it is expected to remain in the environment for a long time. Bio-oils are considered highly toxic to aquatic life and have long-lasting effects [5].

---

[45] A globule of dense matter

OVERALL VIABILITY OF BIO-OIL

These un-upgraded bio-oils do not provide as much energy per unit volume and are heavier than MGO per unit volume. This is a major problem for these smaller vessels, which do not have the additional space or weight to accommodate significantly larger or heavier tanks. However, it is a highly cost competitive fuel.

Fast pyrolysis is a cheap, quick process, and as such, this fuel is economical to produce. The current feedstock of woody biomass is not commercially available and is not as mature as some other feedstocks; however, there is a large amount available, especially in the California region.

The California government has stated its commitment to developing this resource [12], posing a positive outlook for the future development of this supply chain.

Bio-oil, when it is un-upgraded and the excess oxygen has not been removed, cannot be considered a drop-in fuel. Therefore, it is not compatible with the current systems onboard CHC.

One of the main benefits of biofuels is their ability to be bunkered without updating the current infrastructure. However, bio-oil does have an issue with corrosion due to the excess oxygen in the form of water in the final product of the fuel. This requires that tanks storing bio-oil be, at minimum, stainless steel to prevent corrosion.

Currently, bio-oil has not been proven in marine engines. This fuel also brings many additional problems to small crafts. This is because it is heavy and takes up a significant amount of additional space, which reduces its viability. However, using a catalyst, such as ZSM-5, can greatly increase the inherent quality of the fuel produced. By utilizing this feedstock, you can reduce almost all negative qualities of the fuel. It helps remove the oxygen providing for higher energy content, reduction in the emissions of the fuel, reduction in the weight, and reduction in the corrosive properties of the fuel.

Overall, bio-oil provides small benefits for CHC in its current state. Despite its potential preferable emissions profile, its physical properties and technological readiness level keep it from being a great option for CHC. More research must be done into the catalysts before it can truly be a commercial alternative.

3 – 3.4 FT-DIESEL

FT-Diesel is a biofuel made using the Fischer-Tropsch method from a feedstock of biomass, coal, natural gas, waste CO_2, or electricity. The Fischer-Tropsch process is a catalytic chemical reaction in which carbon monoxide (CO) and hydrogen (H2) in the syngas are converted into hydrocarbons of various molecular weights [13].

Table 20: FT-Diesel Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Fischer-Tropsch	Biomass	5	1	5	2	5	5	5	5	2	4
Fischer-Tropsch	Biomass & Coal	5	2	5	2	5	5	1	5	2	4
Fischer-Tropsch	Biomass & Natural Gas	5	2	5	2	5	5	2	5	2	4
Fischer-Tropsch	Natural Gas	5	2	5	2	5	5	1	5	2	4
Fischer-Tropsch	Waste CO_2 & Electricity	5	1	2	2	5	5	5	5	2	4

PROS	CONS
• Biofuel that is most similar to diesel in performance and properties • Slightly lighter than diesel • Can provide emissions reduction • Can be bunkered using existing infrastructure • A drop-in fuel • No additional safety risk • Less environmental impact in case of spill	• Expensive process to complete and still in experimental phases • Most abundant and mature feedstocks provide worst emissions performance • Feedstock significant competition • Higher cost to fossil fuels • Is similar in density to MGO • Slight reduction in energy density to MGO

Table 21: Detailed Description of FT-diesel Suitability

METRIC	DESCRIPTION
Storage	FT-diesel is one of the most similar biofuels to traditional diesel. It has a similar energy density to MGO and is slightly lighter per unit volume at around 0.77 – 0.785 g/ml. Because its physical properties are so similar to fossil fuels, it does not require any modified infrastructure to store and has similar storage needs. It also provides a higher energy content than other biofuel alternatives.
Cost Competitiveness	The cost of biodiesel is high overall compared to other alternative fuels. The Fischer-Tropsch process is expensive and still in experimental stages when pertaining to marine fuel. Significant investment still needs to be made to bring the fuel into the relevant environment. However, it is a drop-in fuel so no retrofit will be required, and the properties of the fuel are the most similar to those of diesel out of all the biofuels. This means storage tanks can remain at similar levels. However, depending on the feedstock used, the emissions performance is severely lacking. To establish cleaner feedstocks as a viable option, significant additional investment will be necessary.
Current Feedstock Availability	FT-diesel can be produced from a variety of feedstocks, many of which are abundant. However, the ones with the best emissions profile are still immature and costly.
Technological Readiness	Currently, FT-diesel has a TRL of 4. This fuel is still relegated to a laboratory environment and is still being studied to better understand the production process and how it will apply in a marine environment.
Compatibility with Current Systems	It is considered a drop-in fuel, which can be used with current diesel engines. It can use current fuel tanks with little to no expansion necessary to achieve equivalent amounts of energy.
Current Bunkering Capability	The bunkering infrastructure can store this fuel with no modifications.
GHG Emissions	See table below. It varies greatly depending on feedstock. Fossil fuel feedstocks currently produce even more lifetime emissions than diesel, but green sources can provide one of the highest reductions in lifetime emissions.

Feedstock	Lifetime Emissions (g GHGs/kWh)
Biomass	22.1
Biomass & Coal	414
Biomass & Natural Gas	236
Natural Gas	362
Waste CO_2 & Electricity	-246

METRIC	DESCRIPTION
Safety	Biofuels do not impose an increased safety risk compared to MGO.
Environmental Risks (Spill)	More research needs to be done to fully understand the effects that FT-diesel will have on the environment in case of a spill. This is a burgeoning fuel that requires more research to fully understand its impacts [5].

OVERALL VIABILITY OF FT-DIESEL

FT-diesel is a biofuel of higher energy density, almost equivalent to diesel, and most importantly, at a significantly reduced density. Although it does not reach the energy levels contained in traditional diesel, its low density could provide weight reductions. This would make it an enticing alternative for harbor craft. FT-diesel has very similar physical properties to traditional diesel, and therefore, does not require any new infrastructure on the ship to store or combust. However, production of FT-diesel is not mature technology and is expensive to complete. This greatly reduces the cost efficiency as further research must still be done of the fuel to make it commercially available.

There are many feedstocks that can be used to create FT-diesel; however, the price and availability will vary greatly depending on the feedstock chosen. Many of these feedstocks are not yet developed and are expensive to utilize. The only one that is currently viable is natural gas; however, it has a worse emissions profile than current fossil fuels.

Currently, FT-diesel is not an applicable fuel since its process is still new and cannot be used to produce large amounts. This forces a high cost for both production and procurement of the fuel. With further research, FT-diesel could be a top competitor as it one of the highest performing fuels studied in this report. It provides a similar profile to fossil fuels, and when procured from a sustainable source, can provide great emissions reductions.

3 – 3.5 PYROLYSIS OIL

Pyrolysis oil is a biofuel made through pyrolysis from a feedstock of biomass, mainly forest residue. Pyrolysis oil, also sometimes referred to as upgraded bio-oil, is a refined form of bio-oil, which has completely removed the oxygen in the fuel.

Table 22: Pyrolysis Oil Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Pyrolysis	Biomass	3	2	5	2	5	4	5	5	1	4

PROS	CONS
Cheap and abundant feedstock Can provide emissions reduction Can be bunkered using existing infrastructure Close to diesel in energy density A drop-in fuel No additional safety risk Less environmental impact in case of spill	Extremely expensive to produce Feedstock is abundant but the supply line is unestablished Is higher in density than MGO Not well studied yet Possibility for corrosion Toxic to aquatic wildlife

Table 23: Detailed Description of Pyrolysis Suitability

<table>
<tr><th>METRIC</th><th>DESCRIPTION</th></tr>
<tr><td>Storage</td><td>Pyrolysis oil has a slightly lower energy density than MGO depending on how "upgraded" the oil is. It is slightly heavier per unit volume at about 0.96 g/ml. Depending on the degree of oxygen removed, it may still have the corrosive properties of bio-oil and may require stainless steel tanks for long-term storage.</td></tr>
<tr><td>Cost Competitiveness</td><td>The cost of pyrolysis oil is high overall compared to other alternative fuels. Upgrading bio-oil, a removal of the excess water to reduce oxygen content, is an expensive process and needs more research to make it economically viable. Once the fuel is close to or completely deoxygenated, it is considered a drop-in fuel so no retrofit is required. Energy density and gravimetric density are similar to MGO, so extra storage is likely not required. However, tanks will likely need to be made of stainless steel to reduce corrosion risk.</td></tr>
<tr><td>Current Feedstock Availability</td><td>Biomass is an abundant feedstock in California and the U.S. However, it is an unestablished line and needs investment to secure.</td></tr>
<tr><td>Technological Readiness</td><td>Currently, pyrolysis oil has a TRL of 5. The process of upgrading is still being proven in an experimental setting to determine which method produces the most usable bio-oil.</td></tr>
<tr><td>Compatibility with Current Systems</td><td>Upgraded bio-oil is considered a drop-in fuel, which can be used with current engines. However, it still retains some of the corrosive properties so it cannot use current fuel tanks.</td></tr>
<tr><td>Current Bunkering Capability</td><td>Depending on fuel quality, it may require new infrastructure to bunker this fuel. This is due to the potential for corrosion based on how much oxygen still exists in the fuel.</td></tr>
<tr><td>GHG Emissions</td><td><table><tr><th>Feedstock</th><th>Lifetime Emissions (g GHGs/kWh)</th></tr><tr><td>Biomass</td><td>39.7</td></tr></table>It has a preferable lifetime emission profile when compared to MGO.</td></tr>
<tr><td>Safety</td><td>Biofuels do not impose an increased safety risk compared to MGO.</td></tr>
<tr><td>Environmental Risks (Spill)</td><td>Many of the bio-oil precautions apply for upgraded bio-oil as well. It is still denser than water so it will sink. It is likely extremely toxic to aquatic wildlife, similar to bio-oil [5].</td></tr>
</table>

OVERALL VIABILITY OF PYROLYSIS OIL

This form of bio-oil has increased energy density than that produced through fast pyrolysis, but it also comes at a greatly increased cost. The method of production for upgraded bio-oil is currently extremely expensive to operate and has only been proven in lab tests.

There is no commercial process available for production of this fuel; as such, its supply is low and will require a high level of investment before it will be viable for marine use. This goes into its TRL of 5 as it has been validated in the lab but not in a prototype or relevant environment yet.

Theoretically, this is a drop-in fuel and should be able to fit within current engine infrastructure; however, there is not yet a marine engine example running on pyrolysis oil. This compatibility is enticing to investors as it would not require significant changes in bunkering or engine infrastructure. Although like bio-oil, it will require stainless steel tanks to prevent corrosion. However, its corrosive properties are greatly reduced in the upgrading process.

Overall, bio-oil is not currently a viable option for CHC, though it does provide a significant emission reduction. It is costly to produce and unproven in marine environments. If the upgrading process matures through further research, it could become a viable option in the future.

3 – 3.6 RENEWABLE DIESEL

Renewable diesel is a biofuel made from a feedstock of yellow grease (used cooking oil) or yellow grease and heavy fuel oil through hydrotreating used cooking oils or yellow grease. Hydrotreatment is performed by reacting hydrogen with a catalyst at high temperatures and pressure to remove undesirable components from the feedstock, such as oxygen, nitrogen, and sulfur. One benefit of hydrotreated vegetable oils (HVO) is that they do not have the detrimental effects of ester-type biodiesel, such as increased NO_x emissions and storage stability problems [14]. Due to the requirements contained in section 2449.1(f) of the CARB, “amendments to the in-use off-road Diesel-fueled fleets” regulation requiring R99 or R100, the feedstock with heavy fuel oil was not considered for this analysis.

Table 24: Renewable Diesel Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Hydrotreating	Yellow Grease	**4**	**5**	**3**	**5**	**4**	**5**	**4**	**5**	**5**	**5**

PROS	CONS
• Cheap and abundant feedstock • Similar weight per volume as diesel • Can provide emissions reduction • Can be bunkered using existing infrastructure • A drop-in fuel • No additional safety risk • Ports are beginning to bunker blends of fuel • Less environmental impact in case of spill	• Feedstock has significant competition • Higher cost to fossil fuels where it is bunkered • Slight reduction in energy density to MGO • More studies need to be done to determine its full effect in case of a spill

Table 25: Detailed Description of Renewable Diesel Suitability [10]

<table>
<tr><th>METRIC</th><th>DESCRIPTION</th></tr>
<tr><td>Storage</td><td>Renewable diesel has a slightly lower energy density to MGO and is about the same weight per unit volume, about 0.77 – 0.8 g/ml [5]. It does not require additional or modified infrastructure to store on the ship.</td></tr>
<tr><td>Cost Competitiveness</td><td>The cost of renewable diesel is low overall compared to other alternative fuels. Hydrotreating is a well-studied process and is already commercially available, making it more inexpensive to procure. Its drop-in fuel status also requires no retrofit. Energy density and gravimetric density are similar to MGO, so storage can remain at a similar level. Additionally, ports in California are already beginning to bunker blends of renewable diesel, reducing overall cost.</td></tr>
<tr><td>Current Feedstock Availability</td><td>There are significant sources for yellow grease in the U.S., but it has severe competition from other transportation industries. However, California has already established supply chains for this feedstock as its vessels are required to use the fuel. It also accounts for almost all renewable diesel consumption in the U.S.</td></tr>
<tr><td>Technological Readiness</td><td>Currently, biodiesel has a TRL of 9. It is currently a commercial product and is being used in vessels in California.</td></tr>
<tr><td>Compatibility with Current Systems</td><td>A drop-in fuel that can be used with current engines, it can also use current fuel tanks. However, they may need to be expanded to reach an equivalent energy amount to fossil fuels.</td></tr>
<tr><td>Current Bunkering Capability</td><td>It is already being bunkered using the infrastructure in California.</td></tr>
<tr><td>GHG Emissions</td><td><table><tr><th>Feedstock</th><th>Lifetime Emissions (g GHGs/kWh)</th></tr><tr><td>Yellow Grease</td><td>52.6</td></tr></table>It does have a preferable lifetime emission profile when compared to MGO; however, it will not meet 2050 requirements.</td></tr>
<tr><td>Safety</td><td>Biofuels do not impose an increased safety risk compared to MGO.</td></tr>
<tr><td>Environmental Risks (Spill)</td><td>The Spill profile is expected to be similar to diesel forming a clear oily slick on the surface of the water. Renewable diesel does not contain any of the aromatic structures present in petroleum, which makes it less toxic to wildlife. The biodegradation rate is somewhere between biodiesel and petroleum diesel. More studies need to be done to determine the full range of potential effects on the environment [5].</td></tr>
</table>

OVERALL VIABILITY OF RENEWABLE DIESEL

Renewable diesel has very similar properties to traditional diesel. It can be used in diesel engines in concentrations up to 100% with little to no negative effects. This makes it a promising option for those looking to lower emissions in the near future with limited initial investment.

Although the lifetime GHGs emitted through the production and use of renewable diesel is higher than some of the other biofuels studied, it outperforms current diesel products. The main drawbacks for switching to renewable diesel will be the price increase over traditional fuels; however, it will soon be bunkered at California ports. Harbor craft operating in the region will have to switch to either R99 or R100 to meet the new regulations. This will positively affect demand and, as demand increases, likely so will production, lowering the price in the long term.

This fuel will be a good option for vessels further into their lifespan where the cost of a full retrofit could not be recouped in the remaining operation of the vessel. Renewable diesel is a current and mature option, which fits the needs of harbor craft. Similar storage needs, no demand for a retrofit, and the beginning of bunkering this fuel in ports make it a solid alternative for those looking to lower their emissions today.

3 – 3.7 STRAIGHT VEGETABLE OIL

Straight vegetable oil (SVO) is a biofuel made through oilseed oil extraction from a feedstock of soybeans. It is a developed fuel that has been commonly used in road vehicles; however, it does have significant impacts on modern engines over its lifetime.

Table 26: SVO Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Oilseed Oil Extraction	Soybean	**3**	**3**	**3**	**5**	**2**	**4**	**3**	**5**	**5**	**4**

PROS	CONS
• Cheap and abundant feedstock • Can provide emissions reduction • Can be bunkered using existing infrastructure • A drop-in fuel • No additional safety risk • Less environmental impact in case of spill	• Feedstock suffers significant competition • Denser than diesel • Reduction in energy density to MGO • Will harm engines overtime, even at 1% concentrations, bringing increased maintenance costs • Low shelf life

Table 27: Detailed Description of SVO Suitability

METRIC	DESCRIPTION
Storage	SVO has a lower energy density than MGO. It is heavier per unit volume at about 0.91 – 0.95 g/ml [5]. It does not require additional or modified infrastructure to store on the ship. It will need more storage to reach the same amount of energy and will add a significant amount of weight since it is denser than MGO.
Cost Competitiveness	The cost of SVO is moderate overall compared to other alternative fuels. Oilseed oil extraction is inexpensive and well studied. It is a drop-in fuel, so no retrofit is required. However, SVO and its high viscosity will cause damage to engines over time. It will also increase maintenance costs and decrease the life span of the engine and its supporting components. Storage will also need to be increased due to the low energy content in SVO.
Current Feedstock Availability	Within the U.S., due to expansive agriculture industry, soybeans have a high availability. However, there is significant competition for the resource. It is not currently being used in marine applications so new supply lines would need to be created.
Technological Readiness	Currently, SVO has a TRL of 9. There have been tests using SVO in ships, although it is currently more widespread for road vehicles.
Compatibility with Current Systems	It is a drop-in fuel, which can be used with current engines. It can use current fuel tanks but they may need to be expanded.

<table>
<tr><th>METRIC</th><th>DESCRIPTION</th></tr>
<tr><td>Current Bunkering Capability</td><td>The current bunkering infrastructure is capable of handling SVO, although additional heating may be needed to move the fuel. Also, due to a shorter shelf life, it will require more management.</td></tr>
<tr><td>GHG Emissions</td><td><table><tr><th>Feedstock</th><th>Lifetime Emissions (g GHGs/kWh)</th></tr><tr><td>Soybean</td><td>114</td></tr></table>It does have a preferable lifetime emission profile when compared to MGO; however, it will not meet 2050 requirements.</td></tr>
<tr><td>Safety</td><td>Biofuels do not impose an increased safety risk compared to MGO.</td></tr>
<tr><td>Environmental Risks (Spill)</td><td>Since it is less dense than water, it will float on the surface forming a thick slick, which will not spread as far as diesel. This is due to its high viscosity, which is heavily influenced by temperatures and can easily increase depending on the temperature of the surrounding environment. This fuel is biodegradable and will degrade even faster than biodiesel. It is also considered relatively nontoxic [5].</td></tr>
</table>

OVERALL VIABILITY OF SVO

SVO is a fuel that is heavily studied and applicable to harbor craft today. There has been a vast amount of testing with SVO in various diesel engines, which has proven its ability to be used by modern diesel engines.

However, it is a fuel of lower energy density when compared to other biofuels and is slightly heavier per unit volume than MGO. It would require larger tanks to store the same amount of energy without affecting operations. Also, due to its higher viscosity, it would likely need to be preheated for it to flow and combust efficiently.

This high viscosity also leads to other problems with the engine. This property can lead to incomplete combustion, coking of the fuel injectors, and ring carbonization. Even when mixed with other fuels, studies show that a 1% concentration of SVO causes premature wear on fuel pumps and injectors [15]. This will lead to increased maintenance costs on engines that use SVO fuel. Additional research will be needed to make this fuel more compatible with current ICE technology.

Overall, SVO can be a short-term solution fuel since it does not require any retrofit to use. However, the use of this fuel can cause significant damage to the engines when switched to it and would inherently bring with it additional maintenance costs and a lower engine lifespan. This fuel in its current technological state cannot be used long term in modern diesel engines. It does not have a large enough feedstock to support the shipping industry as there exists significant demand from other industries for this feedstock. This fuel might be an alternative for a small number of ships that are looking to immediately reduce emissions and are not worried about the potential harm and additional maintenance cost that it will induce on their engine.

3 – 3.8 AMMONIA

Ammonia is a liquid fuel made through either steam methane reforming or hydrolysis and the Haber-Bosch process. Each process aligns with a specific feedstock with the steam methane reforming and Haber process being conducted using natural gas. On the other hand, hydrolysis and the Haber-Bosch process are performed with water and electricity. Based on the feedstock used, the cost of ammonia can vary significantly. This is also reflected in its emission profile.

Table 28: Ammonia Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Steam & Methane Reforming & Haber-Bosch Process	Natural Gas	1	1	5	3	1	3	1	1	1	2
Hydrolysis & Haber-Bosch Process	Water & Electricity	1	1	1	3	1	3	5	1	1	2

PROS	CONS
• Natural gas is an abundant feedstock • Can provide emissions reduction • Can be used as a hydrogen carrier • Some gas carriers, which already carry ammonia, can be used as bunker vessels	• Feedstock suffers significant competition • Technology is not mature • Engines are still in experimental phases • Requires a large increase in fuel tank size • Tanks require low temperatures and high pressure to store efficiently • Ammonia is toxic to humans and can be dangerous if it leaks • Investment would need to be made to bunker this fuel

Table 29: Detailed Description of Ammonia Suitability

METRIC	DESCRIPTION
Storage	Ammonia has a lower energy density than MGO, and as such, will require more volume to reach the same amount of energy. It is a gas and therefore its density is only around $0.8*10^{-6}$ g/ml [5]. Ammonia would require significantly larger fuel tanks—about 24 times the tank volume—to generate the same energy as HFO. These fuel tanks would also need to be kept at around 18 bar to keep the gas compressed or at -33.6°C and 1 bar to keep it a liquid, which is an energy drain, especially on smaller vessels.
Cost Competitiveness	The cost of ammonia is high overall compared to other alternative fuels. The tanks on these vessels would need to be massively increased, refrigerated, and pressurized to hold ammonia. A retrofit would be required to burn ammonia, and no ammonia engines currently exist on the market, which makes this a very high initial investment. Also, more ammonia is needed to reach the same energy levels as MGO, and ammonia is already more expensive to procure since there is not an established supply for marine use.
Current Feedstock Availability	Ammonia is already produced at a large scale from hydrocarbon fuels. There is a large demand for ammonia, and the supply is there for smaller vessels, but competition for this resource from other industries inhibits procurement.
Technological Readiness	Currently, ammonia has a TRL of 5. Many are racing to produce the first working prototype for an ammonia vessel. As of writing this report, there is no active ship running on ammonia fuel.
Compatibility with Current Systems	Ammonia has no compatibility with the current systems. Engine and storage retrofit or modifications would be required.

METRIC	DESCRIPTION
Current Bunkering Capability	There is currently little bunkering capability for ammonia. We do have the ability to store commercial amounts of ammonia, but investment would need to be made for these stores at ports. Some gas carriers could be converted to bunkering vessels of this fuel.
GHG Emissions	<table><tr><th>Feedstock</th><th>Lifetime Emissions (g GHGs/kWh)</th></tr><tr><td>Natural Gas</td><td>561</td></tr><tr><td>Water & Electricity</td><td>39</td></tr></table> Ammonia has many problems when it is produced from “grey” sources or fossil-fuel-powered ammonia synthesis and Haber process. Using this process, its lifetime emissions surpass traditional fuels. However, when produced from “green” sources, or electricity-driven methods like hydrolysis and Haber process, it can be made carbon neutral. There is a small risk of fugitive emissions being released into the atmosphere, which are more potent than CO_2. This needs to be considered when designing these systems.
Safety	Ammonia poses many new safety risks to passengers and crew. There can be an explosion and fire risk when handling certain concentrations of ammonia. Ammonia is also toxic to humans, and in large concentrations, can kill.
Environmental Risks (Spill)	Ammonia gas is highly toxic to humans and marine life; a shipborne release could have dire consequences for both the ship crew and any nearby population. Spilled NH3 gas will rise quickly into the atmosphere and dissipate; however, the NH3 that contacts the water will react with the water and form a hot and toxic NH4OH layer. The NH4OH, ammonium hydroxide, will form a layer on the water and threaten marine life in the spill zone [5].

OVERALL VIABILITY OF AMMONIA

Ammonia poses many potential problems for harbor craft adoption. It requires low temperatures and significant pressure to remain in a liquid state, which provides for a higher energy density in the stored fuel. Even with these benefits to energy density, it does not come close to what is currently provided by MGO, making storage a major issue for implementation. This also factors into the total cost.

Ammonia use requires new tanks, which require more resources than before, an engine retrofit as diesel engines cannot burn ammonia, and high production costs. These reasons take away from the cost competitiveness of ammonia and place it as a financially unviable option for most operators. Currently, the feedstocks or supply lines for ammonia are mature as it is commonly used in other industries; however, this also brings significant competition to procurement. Since it is such a widely utilized resource, its cost is not likely to go down for some time until the production can meet the current demand.

In its current state, this fuel is not applicable to CHC. The prohibitive cost, complexity, and potential health risk for passengers all bode negatively for ammonia as a potential fuel for harbor craft.

3 – 3.9 METHANOL

Methanol is a liquid fuel made through methanol synthesis of natural gas or through the gasification of biomass and subsequent methanol synthesis. Gasification can also be accomplished with a feedstock of coal. Since methanol can be synthesized from a variety of feedstocks, it is a more versatile fuel to procure. However, like other alternative fuels, it suffers from significant competition as other fields use methanol in various applications. However, many ports around the world have already begun to bunker methanol and have established a space for marine use of the fuel.

Table 30: Methanol Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Gasification & Methanol Synthesis	Black Liquor	2	3	3	5	3	4	3	5	2	3
Gasification & Methanol Synthesis	Coal	2	3	5	5	3	4	1	5	2	3
Gasification & Methanol Synthesis	Forest Residue	2	3	5	5	3	4	5	5	2	4
Methanol Synthesis	Natural Gas	2	3	5	5	3	4	2	5	2	3
Methanol Synthesis	Renewable Natural Gas	2	2	1	5	3	4	4	5	2	3
Methanol Synthesis	Waste CO_2 & Electricity	2	2	1	5	3	4	5	5	2	3
Methanol Synthesis	Waste Industrial Gas	2	2	1	5	3	4	5	5	2	3

PROS	CONS
• Diverse and abundant feedstocks to choose from • Can provide significant emissions reduction depending on feedstock • Less dense than MGO • Methanol tanks are inexpensive • Can be bunkered using existing infrastructure • Less environmental impact in case of spill	• Feedstocks have significant competition • Higher cost to fossil fuels • Would require a retrofit to use • Tanks would need to be about 2.5x larger to achieve same energy content • Methanol has additional safety risks for crew and passengers

Table 31: Detailed Description of Methanol Suitability [16] [17]

<table>
<tr><th>METRIC</th><th>DESCRIPTION</th></tr>
<tr><td>Storage</td><td>Methanol has a lower energy content than MGO, and as such, will require more fuel to reach the same amount of energy—about 2.5 times. It is lighter per unit volume at about 0.792 g/ml [5]. Much larger tanks will be required, but methanol tanks are relatively inexpensive. Methanol can be corrosive, but not for carbon steel, aluminum, or stainless steel, which makes this less of an issue for marine storage.</td></tr>
<tr><td>Cost Competitiveness</td><td>The cost of methanol ranges from moderate to high overall compared to other alternative fuels. Methanol production is already practiced on a commercial level and is available as a fuel. However, it is not a drop-in fuel so retrofit is required; however, methanol engines are commercially available. Storage tanks would need to be increased to accommodate the reduction in energy density. Ports are beginning to bunker methanol, which will reduce overall cost.</td></tr>
<tr><td>Current Feedstock Availability</td><td>Methanol can be produced from a variety of feedstocks. Its feedstocks are abundant, but methanol does suffer demand from many different industries. California has secured methanol supply to its ports from a few different firms.</td></tr>
<tr><td>Technological Readiness</td><td>Currently, methanol has a TRL of 9. Methanol is available commercially as a marine fuel and can currently be adopted.</td></tr>
<tr><td>Compatibility with Current Systems</td><td>Methanol requires an engine retrofit as diesel engines cannot run on methanol, but it can be stored using current fuel tanks. However, they may need to be expanded to fit energy needs.</td></tr>
<tr><td>Current Bunkering Capability</td><td>Methanol will soon be bunkered in California, and should be able to use current bunkering infrastructure.</td></tr>
<tr><td>GHG Emissions</td><td>
<table>
<tr><th>Feedstock</th><th>Lifetime Emissions (g GHGs/kWh)</th></tr>
<tr><td>Black Liquor</td><td>141</td></tr>
<tr><td>Coal</td><td>573</td></tr>
<tr><td>Forest Residue</td><td>46.8</td></tr>
<tr><td>Natural Gas</td><td>340</td></tr>
<tr><td>Renewable Natural Gas</td><td>100</td></tr>
<tr><td>Waste CO_2 & Electricity</td><td>-237</td></tr>
<tr><td>Waste Industrial Gas</td><td>34.4</td></tr>
</table>

It does have a preferable lifetime emission profile when compared to MGO; however, depending on the feedstock chosen, it can have worse lifetime emissions than fossil fuels. Methanol that is produced using fossil fuels, which make up the largest percentage of methanol produced today, have worse lifetime emission profiles when compared to diesel. However, there are pathways using renewable sources, which have the potential to reach carbon-neutral levels. These paths would require significant investment and would greatly increase fuel cost if chosen.</td></tr>
<tr><td>Safety</td><td>Methanol comes with some additional fire risks if it gets spilled. Since it burns with an invisible flame, extra precautions need to be taken. Methanol is also heavier than air and will spread along the ground. This will require additional ventilation in confined areas and additional detection in protection-leak areas.</td></tr>
<tr><td>Environmental Risks (Spill)</td><td>Methanol will rapidly spread out and dissolve into the water. It will also dissipate before cleanup can begin. However, studies show no long-term impact on aquatic life, but it can poison those that come into direct contact with it [5].</td></tr>
</table>

OVERALL VIABILITY OF METHANOL

Overall, methanol provides an option for high emission reductions at a reduced cost when compared to other alternatives. Since it can be implemented with minor changes to current infrastructure, has cheaper production costs, and as many ports begin to bunker the fuel, it has a more favorable cost. Currently, at the Port of Rotterdam, the fuel sits at about 340 $/mt [18], which is about half of what MGO costs. However, this price varies widely. The extra fuel, which must be purchased due to the lower energy density of methanol, must also be taken into account. However, this investment into methanol infrastructure will likely drive down the cost over time.

Despite the favorability of the cost currently shown in Amsterdam, methanol can vary widely. Additionally, its potential emissions benefits can be completely negated depending on the feedstock used to produce it. Of all the fuels analyzed, methanol has one of the highest ranges in its lifetime emissions profile. For example, when using a feedstock of coal, it creates the highest amount of GHGs in any fuel studied. If this is changed to waste CO_2 and electricity, it is one of the highest performers in this study. It should be noted that the cost of production is inversely proportional to the lifetime emissions.

Those looking to make the change to methanol will also need to add ventilation to the vessel and increase safety training to include the precautions needed for handling methanol. They will also need to increase storage or change routes to account for the decrease in available energy. Additionally, they will need to retrofit the engine because current diesel engines cannot burn methanol; however, these engines are commercially available and proven in the field.

Methanol is viable for those looking for a mid-term solution or looking to retrofit newer vessels to make use of the fuel. With infrastructure and production investments, the fuel could be an option for harbor craft with short, predetermined paths as the switch to methanol will come with either larger tanks or a reduction in total energy storage capacity for a vessel.

3 – 3.10 HYDROGEN (LCE)

Hydrogen is a liquid fuel made through steam methane reformation from fossil fuels and natural gas, or electrolysis from water and renewable natural gas. Its unique properties necessitate intense storage conditions, which make it difficult for harbor craft to utilize.

Table 32: Hydrogen (ICE) Suitability

Process	Feedstock	Storage	Cost	Feedstock Availability	TRL	Compatibility	Bunkering Capability	GHG Emissions	Safety	Enviro. Risk	Overall Viability
Steam Methane Reforming	Fossil Fuel or Natural Gas	1	1	5	4	1	1	1	4	5	3
Steam Methane Reforming w/ Carbon Capture	Fossil Fuel or Natural Gas	1	1	1	4	1	1	5	4	5	3
Hydrolysis w/ renewable energy	Water & Renewable Natural Gas	1	1	1	4	1	1	5	4	5	3

PROS	CONS
• Cheap and abundant feedstocks • Can provide the highest potential emissions reduction • Can potentially provide weight reductions • Less environmental impact in case of spill	• Extremely high capital cost to perform retrofit or new build • Engines are new and expensive to produce • Will have a higher cost to refuel for many years to come • Requires extreme storage conditions • No current bunkering capabilities • Tanks are large and have rounded ends, making them space inefficient • Hydrogen produced from gray sources, which are the most economical, will provide little to no lifetime emission reduction • Infrastructure would need extra management due to hydrogen embrittlement

Table 33: Detailed Description of Hydrogen Suitability

METRIC	DESCRIPTION
Storage	Hydrogen has a lower volumetric energy density than MGO and will require more volume to reach the same amount of energy. It is much lighter per unit volume at about 0.093*10^{-6} g/ml [5]. The tanks will need to be very large to hold an equivalent amount of energy, but due to the high gravimetric energy density of hydrogen, even at the larger tank size, this will amount to a weight reduction due to how light the fuel is. Since the density of hydrogen is so low to store efficiently, it requires cryogenic temperatures of -253°C to remain in a liquid state or pressures of 300 – 700 bar to remain compressed. These extreme storage conditions are infeasible on small vessels that do not have the space or available energy to maintain these conditions. Tanks will also require a space-inefficient shape to support the extreme pressures.
Cost Competitiveness	The cost of hydrogen is high compared to other alternative fuels. Gray hydrogen procurement may come at a reduced cost, but blue and green hydrogen costs are prohibitive. Currently, the fuel can be as much as five times more expensive from gray sources and 16 times as much from green sources [19]. It is not a drop-in fuel so retrofit is required, and currently, these retrofits and new builds are extremely costly to complete. Additionally, a hydrogen engine is not yet commercially available. Storage would need to be greatly increased and reinforced to prevent potential hydrogen embrittlement. Lastly, bunkering of the fuel is extremely expensive, energy intensive, and not yet available, further increasing the cost for refueling.
Current Feedstock Availability	Gray hydrogen from fossil fuel sources is available but hard to store and does not have an established supply chain for maritime purposes. However, California has already developed hydrogen refueling stations for road vehicles and could use the knowledge gained to support bunkering development and procurement. Green and blue hydrogen will still require significant investment before supply lines are established, and currently are highly expensive to procure. Until these sources mature, it will remain a premium.
Technological Readiness	Currently, hydrogen has a TRL of 7. There are a few dual fuel hydrogen ships that are currently operating. However, these technologies have not reached commercial availability.

<table>
<tr><th>METRIC</th><th>DESCRIPTION</th></tr>
<tr><td>Compatibility with Current Systems</td><td>Hydrogen has almost no compatibility with current systems. It will require a retrofit, as diesel engines cannot use hydrogen fuel and the current fuel tanks will need to be expanded. All infrastructure would need reinforcement due to potential hydrogen embrittlement.</td></tr>
<tr><td>Current Bunkering Capability</td><td>There is no current bunkering capability for hydrogen. However, it can potentially be stored on ships that carry ammonia, using ammonia as a carrier. California has also made a $1.2 billion federal grant to create a hydrogen hub. Hydrogen can be sourced, but at a premium.</td></tr>
<tr><td>GHG Emissions[46]</td><td>
<table>
<tr><th>Feedstock</th><th>Lifetime Emissions (g GHGs/kWh)</th></tr>
<tr><td>Fossil fuels or natural gas</td><td>335</td></tr>
<tr><td>Fossil fuels or natural gas w/ Carbon Capture</td><td>155</td></tr>
<tr><td>Water and renewable natural gas</td><td>0</td></tr>
</table>
It does have a preferable lifetime emission profile when compared to MGO. Hydrogen is one of the clearest paths to the 2050 goal that the IMO has set. When procured from green or blue sources, hydrogen can provide the best emissions performance over its lifetime. However, most hydrogen today is produced through gray sources since it is less energy intensive. However, this process is still expensive and provides little benefit to lifetime emissions when compared to fossil fuels.</td></tr>
<tr><td>Safety</td><td>Hydrogen is relatively safe to handle and nontoxic. It is extremely flammable and burns with a nearly invisible flame making special flame detectors required. In the case of a spill, there is an extreme risk of explosion and a small risk of suffocation.</td></tr>
<tr><td>Environmental Risks (Spill)</td><td>Hydrogen poses very little risk to the surrounding environment and a spill will chill the surrounding water on contact. Since it is so light and its boiling point is so low, it will dissipate fast and rise [5].</td></tr>
</table>

OVERALL VIABILITY OF HYDROGEN (ICE)

When looking at the compatibility of liquid hydrogen fuel with CHC, there are some key factors to consider. The greatest limiting factor for this alternative fuel is the size of the vessels since harbor craft are smaller and hydrogen is the least energy-dense fuel. The requirement of large cylindrical hydrogen tanks, which would occupy an overwhelming portion of the available space, is an issue that has not been solved. Despite the potential for weight reduction with this fuel, the geometry and size of these tanks will likely outweigh any benefit gained. This will result in a vessel having to refuel more often. However, if their trips are short and destinations are pre-planned, as is the case for most ferries, this might not be an issue.

Generator load could become a problem when many of the ship's resources will have to be delegated to hydrogen storage. Keeping a tank at cryogenic levels and under that amount of pressure would be difficult for most smaller vessels.

Another key constraint is the increased capital cost to create or retrofit a hydrogen vessel. These systems are incredibly expensive to install and currently have only been accomplished under the cooperation of multiple large organizations. Between the hydrogen engine, completely updating the storage systems, reinforcing all infrastructure to prevent hydrogen embrittlement[47], and procuring the fuel from preferable feedstocks, the cost of utilizing hydrogen to effectively lower emissions is far above any other fuel studied.

---

[46] Values for Hydrogen received using the GREET WTW Calculator which can be found here: Tools (anl.gov)

[47] Hydrogen Embrittlement – Due to the small size of the hydrogen molecule, it can permeate the walls of a typical fuel tank, weakening the structure and eventually cracking the tank.

One idea to alleviate some of these potential challenges with hydrogen is to transport hydrogen in a carrier substance such as ammonia, methanol, or LOHCs. However, since hydrogen must now also be removed from the carriers to use the fuel, it increases the energy input and decreases the efficiency of the fuel. These challenges need further research before hydrogen can be widely bunkered for marine use.

Although it is not currently a viable option for harbor craft, hydrogen does promise one of the highest potentials in an alternative fuel. It looks to be the clearest path ahead for reaching net-zero emissions and has very little potential to affect wildlife in the case of a spill or leak, making it one of the most environmentally friendly fuels. It also provides the most energy per kilograms of fuel. If the fuel storage issue can be resolved, hydrogen will quickly become the most sought-after alternative fuels.

3 – 4. CONCLUSIONS, RECOMMENDATIONS, AND KEY TAKEAWAYS

1. LNG was not considered in this study due to its incompatibility with CHC. Based on the metrics used, it did not prove feasible for smaller vessels to utilize.
2. It should be noted that these conclusions are based on current knowledge and can change with advancements in technology. These are predictions for future fuels that are being rapidly researched and developed.
3. From the metrics studied and reports seen, there were four options that seemed to stand out as current options for harbor craft to consider: biodiesel, renewable diesel, bio-oil, and SVO.
   a. These fuels are the best current options available and provide the most immediate solutions for ship owners.
   b. Biodiesel and renewable diesel are options that can be utilized in 2024 and provide significant emission reductions.
   c. Bio-oil using catalytic pyrolysis will require some further research, but the process has been commonly used in the petroleum industry and can be assumed that an optimized solution can be realistically obtained.
4. There were also three fuels that seemed to underperform in the metrics studied. Those fuels are hydrogen (ICE), ammonia, methanol, and FT-diesel.
   a. These fuels have a too-high capital investment to be profitable for those looking to switch or are too underdeveloped to know if they will be viable soon.
   b. Hopefully with advancements in the processes used to produce these fuels, they can become viable options in the future.
5. Biocrude, though not listed in the top four, is a strong contender due to California’s large population and dairy industry [6]. These feedstocks are incredibly abundant and some of the cheapest per ton. They provide great emissions reductions through offsetting the GHGs produced during combustion. Breakthroughs in optimizing hydrothermal liquefaction could push this fuel to a frontrunner position.

FURTHER INSIGHTS

The California maritime landscape includes a diverse array of 238 vessel types. Each serves unique functional roles and has varied operational characteristics. Offshore tugs, totaling 63, are essential for towing large vessels and handling offshore operations. These tugs are characterized by high power demands due to the heavy loads they manage and the long distances they cover. They often require robust and reliable fuel sources, making them ideal candidates for LNG and renewable diesel, which provide the necessary energy density and reliability. The long-duty cycles of these vessels necessitate fuels that offer high energy efficiency and reduced emissions.

Harbor tugs, numbering 66, mainly operate within port limits, assisting with docking and maneuvering larger ships. These vessels have shorter duty cycles and operate within confined areas, leading to frequent start-stop operations. The power demands, while still significant, are lower than those of offshore tugs. Given their operational profile, harbor tugs can benefit from cleaner fuels, such as biodiesel and hydrogen. Hydrogen, particularly in fuel cell technology, can provide a zero-emission solution suitable for the localized operations of harbor tugs, reducing the environmental impact within busy port areas.

The 19 articulated tugs operate as part of tug-barge combinations, providing versatile and efficient transportation solutions. They are involved in both short and long-haul operations, leading to varied duty cycles. The adaptability of articulated tugs makes them suitable for a range of alternative fuels, including LNG and methanol. These can offer lower emissions while meeting the power requirements of both short- and long-distance travel.

Ferry vessels, which make up 19% of the fleet, are designed for transporting passengers and vehicles over relatively short distances. Ferries have regular and predictable duty cycles with frequent stops and starts. This makes them excellent candidates for electric propulsion systems powered by hydrogen fuel cells or batteries. The adoption of such technologies can significantly reduce emissions in coastal and urban areas where ferries operate. Crew supply vessels, accounting for 13% of the fleet, are crucial for transporting personnel and equipment to and from offshore platforms. These vessels typically have moderate power demands and operate over short to medium distances. The operational profile of crew supply vessels supports cleaner fuels such as biodiesel, renewable diesel, and hydrogen. The adoption of alternative fuels can enhance the sustainability of offshore operations. Workboats and pilot vessels, though fewer, play vital roles in maintenance, inspection, and navigation assistance.

These vessels have varied power demands and duty cycles, often operating in coastal and harbor areas. The flexibility in their operations allows for a wide range of alternative fuels, including LNG, biodiesel, and hydrogen. The choice of fuel for these vessels can be directly linked to their specific operational needs and the availability of fueling infrastructure within ports. The diverse fleet in California requires a mix of fuel types and technologies to meet their specific functional roles and operational characteristics. The transition to cleaner fuels, such as LNG, biodiesel, hydrogen, and methanol, will depend on factors like power demands, duty cycles, and the development of appropriate fueling infrastructure. Ports will play a crucial role in supporting this transition by providing the necessary facilities for bunkering and refueling alternative fuels, thereby enhancing the sustainability and efficiency of maritime operations.

Workstream 4:

ASSESSING THE SUITABILITY OF POWER OPTIONS FOR COMMERCIAL HARBOR CRAFT IN CALIFORNIA

ABS

4 ASSESSING THE SUITABILITY OF POWER OPTIONS FOR COMMERCIAL HARBOR CRAFT IN CALIFORNIA

4 – 1. SUMMARY

This report discusses the power and energy storage options for Commercial Harbor Craft (CHC) in California's ports and the regulations to reduce emissions from CHC. The report evaluates the suitability of power and energy storage options to reduce the environmental impact of CHC. It also provides insights to decision makers on the key factors to consider for the adoption of zero-emission options. The report focuses on various lithium-ion battery types, fuel cells, shore power, solar photovoltaic (PV), wind, hybrid systems, and other non-fossil fuel power and energy storage options for implementation in CHC.

The research posits that there is no one-size-fits-all answer for alternative power options for CHC. Instead, it is a stacked mix of appropriate power and energy storage options depending on the vessel type, size, operation profile, and other factors like cost. The advantages and challenges associated with each power and energy storage option are discussed in detail. Each option is ranked in a matrix using a six-category evaluation method. Except for the "other" power option category, which turned out to be an outlier, the options studied ranked close to each other, overall. This ranking can be an effective comparison tool for readers to analyze how the various options stack up against each other in different scenarios.

4 – 2. INTRODUCTION

CHC play a vital role in the transportation of goods, materials, and passengers in California's ports. However, they are also major sources of air pollution, contributing significantly to the greenhouse gas (GHG) emissions.

According to the California Air Resources Board (CARB) on 2020, CHC emit approximately 6,500 tons of NO_x, 200 tons of particulate matter (PM), and 570,000 metric tons of GHG emissions annually. To address this issue, CARB has adopted the Commercial Harbor Craft Regulations (CHCR) to reduce emissions from CHC by 8% by 2035 [20].In this document, we will evaluate the suitability of power options to reduce the environmental impact of CHC.

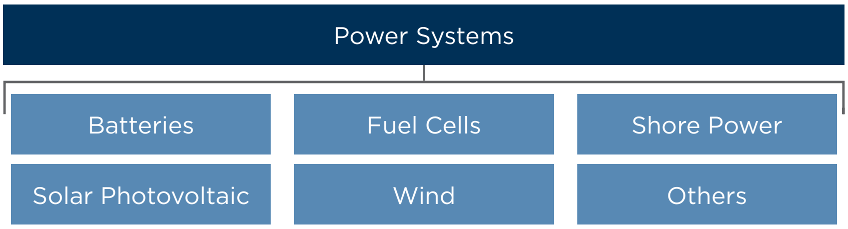
The types of harbor craft to be examined in this report include tug/tow boats, ferries, crew and supply boats, workboats, and pilot vessels. Barges, dredges, excursion boats, research vessels, fishing boats, Coast Guard/Military, and oceangoing vessels will not be part of this study.

To determine the most practical and feasible options for reducing emissions and improving energy efficiency, all aspects of the energy options for CHC will be evaluated based on their current and future benefits and barriers.

This report provides a rough guide to the design of space for the adoption of zero-emission technology on maritime vessels. Rather than determining definitive limits, it aims to identify areas with higher or lower potential for adoption. By selecting representative vessel types and comparing their power and energy requirements, the study offers vessel designers a simple method to estimate the suitability of power option technology to reduce GHG emission for a variety of CHC.

4 – 3. OVERVIEW OF POWER OPTIONS

Figure 28: Power Options Studied



4 – 3.1 BATTERIES

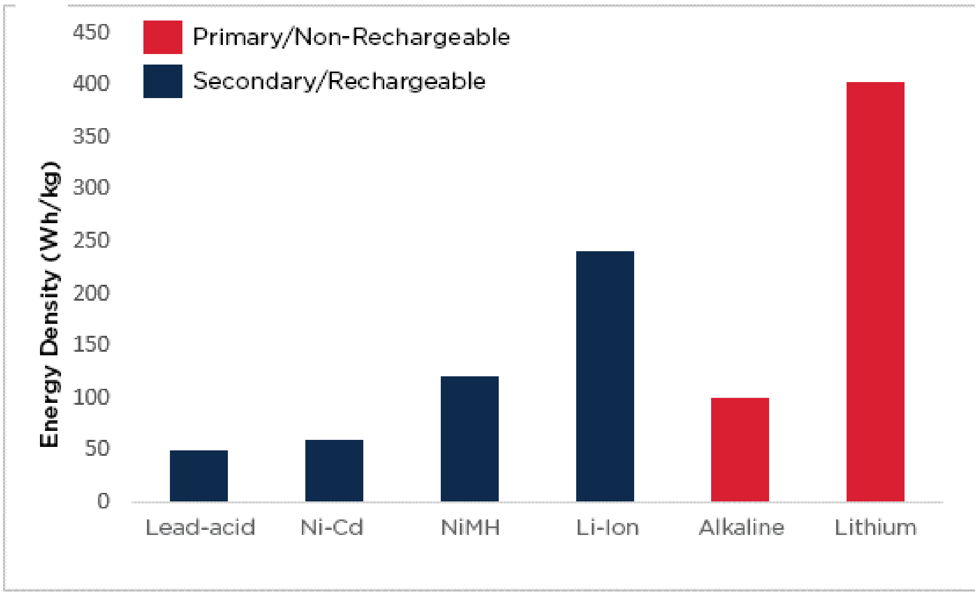
A battery is an electrochemical device that consists of two electrodes that are isolated by a separator and soaked in electrolyte to promote the movement of ions. It stores chemical energy and releases electrical energy [21].

Primary batteries, also known as disposable batteries, are batteries that are designed for one-time use and cannot be recharged. These batteries are typically used in low-drain devices such as remote controls, flashlights, and smoke detectors. Primary batteries are available in a variety of chemistries, including alkaline, lithium, zinc-carbon, and zinc-chloride.

Secondary batteries, also known as rechargeable batteries, are batteries that can be recharged multiple times after they have been discharged. These batteries are typically used in high-drain devices. Secondary batteries are available in a variety of chemistries, including lithium-ion, nickel-cadmium, nickel-metal-hydride, and lead-acid.

Rechargeable batteries are more expensive than primary batteries, but they offer the advantage of being able to be used multiple times. This makes them more cost-effective over the long term [21].

Figure 29: Specific Energy Comparison of Secondary and Primary Batteries [22]



This document focuses on lithium-ion battery types. These include lithium-ion cobalt oxide, lithium-ion manganese oxide, lithium-ion nickel manganese cobalt oxide, and lithium-ion nickel cobalt aluminum oxide, lithium-ion iron phosphate, and lithium-ion titanate [21].

Those types of batteries are used for electric propulsion systems due to their high energy density and reduced costs. The use of electric motors can reduce GHG emissions, and it eliminates exhaust emissions.

Battery-powered electric engines are currently the most practical method for small CHC with short-range requirements. Battery-electric CHCs have zero emissions, low noise levels, and are ideal for short-range operations. Battery technology for large CHC or those with longer routes is still under development and may not be suitable.

Table 34: Characteristics of Commonly Used Rechargeable Batteries [23]

Specifications	Lead-Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific Energy (Wh/k)	30 – 50	45 – 80	60 – 120	150 – 250	100 – 150	90 – 120
Internal Resistance	Very Low	Very Low	Low	Moderate	Low	Very Low
Cycle Life	200 – 300	1,000	300 – 500	500 – 1,000	500 – 1000	1,000 – 2,000
Charge Time	8 – 16h	1 – 2h	2 – 4h	2 – 4h	1 – 2h	1-2h
Overcharge Tolerance	High	Moderate	Low	Low		
Self-Discharge/ Month (Room Temperature)	5%	20%	30%	Less 5%		
Cell Voltage (Nominal)	2V	1.2V	1.2V	3.6V	3.7	3.2 – 3.3V
Charge Cutoff Voltage (V/Cell)	2.4 float 2.25		Full charge detection by voltage signature	4.2V		3.6V
Discharge Cutoff Voltage (V/Cell, 1C)	1.75V		1.00V	2.5 – 3.00V		2.50V
Peak Load Current	5C	20C	5C	2C	>30C	>30C
Best Result	0.2C	1C	0.5C	<1C	<10C	<10C
Charge Temperature	-20 – 50°C		0 – 45°C	0 – 45°C		
Discharge Temperature	-20 – 50°C		0 – 65°C	-20 to 60°C		
Maintenance Requirements	3 – 6 months		Full discharge every 90 days when in full use	Maintenance free		
Safety Requirement	Thermally stable		Thermally stable, fuse protection	Protection circuit mandatory		
In Use Since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic Efficiency	~90%		~70% slow charge ~ 90% fast charge	99%		

Figure 30: Effect of Lithium-Ion Chemistries on Battery Performance [24]

	1	2	3	4	5
Lithium Cobalt Oxide (LiCoO2) - LCO		Life Span Safety Specific Power	Cost Performance		Specific Energy
Lithium Manganese Oxide (LiMn2O4) - LMO			Life Span Performance	Cost Safety Specific Energy Specific Power	
Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2) - NMC				Cost Life Span Performance Safety Specific Power	Specific Energy
Lithium Iron Phosphate (LiFePO4) - LFP		Specific Energy		Cost Performance	Life Span Safety Specific Power
Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2) - NCA		Cost	Safety	Life Span Performance Specific Power	Specific Energy
Lithium Titanate (Li2TiO3) - LTO		Cost Specific Energy	Specific Power		Life Span Performance Safety

Table 35: Detailed Characteristics of Current Lithium-Ion Battery Chemistries [25]

Type Composition	Lithium Cobalt Oxide: LiCoO2 Cathode (~60% Co), Graphite Anode	Lithium Manganese Oxide: LiMn2O4 Cathode Graphite Anode	Lithium Nickel Manganese Cobalt Oxide: LiNiMnCoO2, Cathode, Graphite Anode	Lithium Iron Phosphate: LiFePO4 Cathode, Graphite Anode	Lithium Nickel Cobalt Aluminum Oxide: LiNiCoAlO2 Cathode (~9% Co), Graphite Anode	Lithium Titanate: Cathode Lithium Manganese Oxide or NMC; Li2TiO3 (Titanate) Anode
Year of Invention	1991	1996	2008	1996	1999	2008
Nominal Voltage	3.60V	3.70V (3.80V)	3.60V, 3.70V	3.20, 3.30V	3.60V	2.40V
Operating Voltage/Cell	3.0 – 4.2V	3.0 – 4.2V	3.0 – 4.2V, or higher	2.5 – 3.65V/cell	3.0 – 4.2V/cell	1.8 – 2.85V/cell

Type Composition	Lithium Cobalt Oxide: LiCoO2 Cathode (~60% Co), Graphite Anode	Lithium Manganese Oxide: LiMn2O4 Cathode Graphite Anode	Lithium Nickel Manganese Cobalt Oxide: LiNiMnCoO2, Cathode, Graphite Anode	Lithium Iron Phosphate: LiFePO4 Cathode, Graphite Anode	Lithium Nickel Cobalt Aluminum Oxide: LiNiCoAlO2 Cathode (~9% Co), Graphite Anode	Lithium Titanate: Cathode Lithium Manganese Oxide or NMC; Li2TiO3 (Titanate) Anode
Specific Energy (Capacity)	150 – 240 W-h/kg	100 – 150 W-h/kg	150 – 220 W-h/kg	90 – 120 W-h/kg	200 – 300 W-h/kg	50 – 80 W-h/kg
Charge (C-Rate)	0.7 – 1C, charge current above 1C shortens battery life	0.7 – 1C, 3C maximum	0.7 – 1C, charge current above 1C shortens battery life	1C typical, 3h charge time typical	0.7C, 3h charge typical, fast charge possible with some cells	1C typical; 5C maximum
Charging Cut-Off Voltage	4.2V	4.2V	4.2V	3.65V	4.2V	2.85V
Discharge (C-Rate)	1C; 2.50V cut-off, discharge current above 1C shortens battery life	1C; 10C possible with some cells, 30C	1.2V	3.6V	3.7	3.2 – 3.3V
Discharging Cut-Off Voltage	pulse (5s)	1C; 2C possible on some cells	1C, 25C on some cells; 40A pulse (2s)	1C typical; high discharge rate shortens battery life	10C possible, 30C	3.6V
Cycle Life[48]	5s pulse		1.00V	2.5 – 3.00V		2.50V
Thermal Runaway	2.50V	2.50V	2.50V	2.50V (lower than 2V causes damage)	3.00V	1.8V
Cost 2022 per Cell	See Figure 5		~$101 per kWh [26]	~$70 per kWh (30% cheaper than NMC) [27]	~$101 per kWh (Similar to NMC)	$600 – $770 per kWh $70,000 for containerized solutions [28]
Applications	Mobile phones, tablets, laptops, cameras	Power tools, medical devices, electric powertrains	E-bikes, medical devices, EVs, industrial	Portable and stationary needing high load currents and endurance	Medical devices, industrial, electric powertrain (Tesla)	UPS, electric powertrain, solar-powered street lighting
Comments	• Very high specific energy • Limited specific power • Cobalt is expensive • Market share has stabilized	• High power but less capacity • Safer than Li-cobalt • Commonly mixed with NMC to improve performance • Less relevant now; limited growth potential	• Provides high capacity and high power • Serves as Hybrid Cell • Market share is increasing • Leading system; dominant cathode chemistry	• Flat voltage discharge curve but low capacity • One of safest Li-ions • Elevated self-discharge • Used primarily for energy storage • Moderate growth	• Shares similarities with Li-cobalt	• Long life, fast charge • Good temperature tolerance, -30 – 60C, but low specific energy and expensive • Among the safest Li-ion batteries • Ability to ultra-fast charge

---

[48] Related to depth of discharge, load, temperature

Lithium-ion batteries are currently the leading battery technology in maritime applications. They have been shown to be useful for electrical energy storage and electricity distribution on vessels. However, the high safety risks and energy limitations surrounding Li-ion batteries have sparked interest in other battery technologies, both existing and being researched now, that could be used as alternatives.

A few of these technologies are metal-air batteries, redox flow batteries, and solid-state batteries. These potential alternatives to Li-ion batteries are in different stages of research and development but may make battery systems more practical and common in maritime use in the future.

Table 36: Battery Technology Data [29]

Battery Type		Voltage (V)	Specific Energy (W-h/kg)	Energy Density (Wh/L)	Cycle Life	Power Density (mW/cm2)
Lithium-Ion Batteries		3.7	265	670	High	**
Solid-State Batteries		3.6	350	**	Medium	**
Metal-Air Batteries	**Lithium-Air Batteries**	2.96	3,463*	2,004*	Low	**
	Zinc-Air Batteries	1.65	1,085*	1,670*	Low	**479**
	Aluminum-Air Batteries	2.71	2,791*	**	Low	**
Redox Flow Batteries	**Vanadium Redox Flow Batteries**	1.25	20	15-25	High	**
	Iron-Chromium Flow Batteries	0.94	**	**	High	**70 – 100**

* Indicates theoretical value.

** Indicates value unable to be found in research.

4 – 3.2 FUEL CELLS

A fuel cell is a device that continuously converts an oxidizing fuel (hydrogen, methane, etc.) into electricity and water through an electrochemical reaction [30]. Fuel cell systems are becoming increasingly popular for CHCs because they have high energy density and produce zero emissions. This makes them an attractive alternative to conventional fuel-powered engines.

The main difference among fuel cell types is the electrolyte. Therefore, fuel cells are generally classified by the type of electrolyte utilized. Some main types of fuel cells available today include Proton Exchange Membrane (PEM), alkaline, phosphoric acid, molten carbonate, and solid oxide fuel cells. PEM fuel cells are the most common type of fuel cell used for marine applications due to their high efficiency, fast start-up time, and low operating temperature.

The most common fuel source for fuel cells is hydrogen, which can be produced from a variety of sources. Sources include natural gas, biogas, and renewable energy, such as wind and solar power. Hydrogen can also be produced from water through the process of electrolysis, using electricity generated from renewable sources. The electrical energy produced by the fuel cell can be used to power electric motors that drive propellers or other onboard electrical systems.

Fuel cells have the potential to provide a clean and efficient power source for CHC. Fuel cell CHC have longer ranges than battery-electric CHC and can be refueled quickly. While there are challenges that must be addressed, continued research and development of fuel cell technology can help to overcome these challenges and make fuel cells a viable option for CHC in the future.

Table 37: Fuel Cell Type [30]

Type		**Alkaline (AFC)**	**PEM**	**Phosphoric Acid (PAFC)**	**Molten Carbonate (MCFC)**	**Solid Oxide (SOFC)**
Typical Fuels		H_2	H_2	H_2, LNG and methanol	H_2, methanol and hydrocarbons	H_2, methanol and hydrocarbons
Electrochemical Reactions	**Anode**	$2H_2$+4OH- $4H_2O$+4e-	$2H_2$ 4H+ + 4e-		$2H_2$ + $2CO_2$-3 $2H_2O$ + $2CO_2$ + 4e-	$2H_2$+O_2- $2H_2O$ + 4e-
	Cathode	O_2+$2H_2O$+4e- 4OH-	4H+ + 4e-+O_2 $2H_2O$		O_2 + $2CO_2$+ 4e- $2CO_2$-3	O_2 + 4e- $2O_2$-
	Mobile Ion	OH-	H+	H+	$CO_3{}^{2+}$	O_2-
Operating Temperature		100 – 250°C	30 – 120°C	150 – 220°C	600 – 700°C	650 – 1,000°C
Power Capacity		<500 kW	<120 kW	100 – 400 kW	120 kW – 10 MW	<10 MW
Efficiency	**Electric**	50 – 60%	50 – 60%	40 – 55%	50 – 55%	50 – 60%
	Overall	_	_	80%	85%	85%
Relative Cost		Low	Low	Medium	High	High
Lifetime		Medium	Medium	Good	Good	Medium
Size		Small	Small	Large	Large	Medium
Applications and Notes		Used in space vehicles (e.g., Apollo, Shuttle)	Vehicles and mobile applications, and for lower power Combine Heat Power (CHP) systems	Large numbers of 200-kW CHP systems in use	Suitable for medium- to large-scale CHP systems, up to MW capacity	Suitable for all sizes of CHP (Combine Heat Power) systems, 2 kW to multi-MW

4 – 3.3 HYBRID ELECTRIC POWER SYSTEMS

Hybrid electric power systems (HEPS) combine internal combustion engine-driven generators and/or shaft generators/motors driven by main engines with an ESS. The ESS consists of batteries, supercapacitors, fuel cells, or other technologies to form the power generation and propulsion system of the vessel. The architecture of a hybrid system can be designed specifically for the requirements of each vessel. This optimizes the use of each component for maximum efficiency. The combination of two or more new technologies when conventional generation is not installed on board also constitutes a HEPS [24].

One aspect of HEPS is a hybrid power train. Hybrid power trains are becoming more popular with various types of vessels. The term “hybrid” can refer to many different power systems.

Energy storage for hybrid systems also allows a vessel to maximize the benefit from other power sources such as wind, solar, shaft regeneration, shore power from the electrical grid, and fuel cells. Hybrid power trains are ideal for medium-range operations and can operate in zero-emission electric mode when the battery is charged. Hybrid propulsion systems are designed to improve the fuel efficiency of vessels that have varying power demands, such as fishing boats, tug, workboats, and RoPax ferries [31].

A hybrid power train can be configured as “series hybrid” or “parallel hybrid” [32] [33].

4 - 3.3.1 Series Hybrid

A series hybrid is similar to a diesel-electric propulsion (DEP) system but includes energy storage. In this configuration, the propellers are powered entirely by electric motors while diesel generators provide propulsion and auxiliary power. The diesel generator, shore power, or other sources, such as wind, solar, or shaft regeneration, can charge the battery bank. The batteries are charged during low power demand and discharged during high power demand. This allows the diesel engines to operate near their optimal efficiency point under most conditions instead of having to follow load changes and operate at sub-optimal fuel efficiencies.

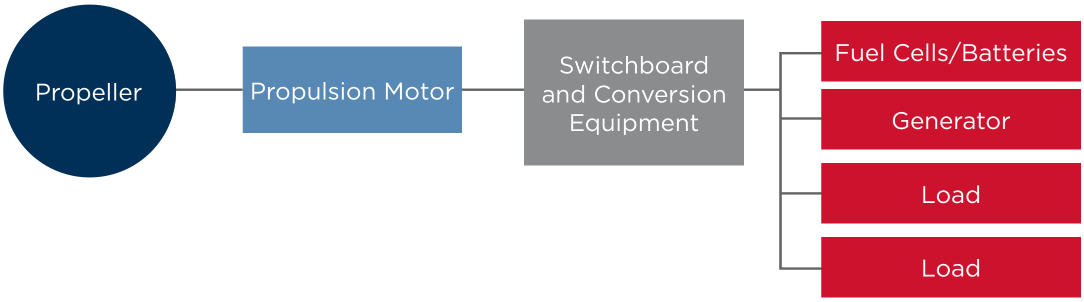
4 - 3.3.2 Parallel Hybrid

A parallel hybrid system combines a traditional propulsion system with a small diesel-electric system. This configuration is suitable for applications with a wide range of power demands for propulsion or auxiliary loads and multiple operating modes with varying power demands. Harbor-assist and escort tugs are ideal for a parallel hybrid configuration.

These vessels require high-power diesel engines to provide the necessary thrust to control large oceangoing vessels. However, peak power is only needed for a small portion of the operating time of the vessel. A parallel hybrid system allows the vessel to operate on battery power when transiting or loitering, producing little to no emissions and low noise. When peak power is needed, the main engines and electric motors can work together to provide additional power. This configuration also enables the possibility of reducing the size of the main engine. This is due to the supplementary power contributed by the electric motor.

Efficiency can be gained by operating all diesel engines at their optimal efficiency point. Additionally, fuel can be saved by charging the batteries from shore or an alternative power source. In addition, wet stacking diesel engines can be avoided, thus increasing their longevity. In some cases, a parallel hybrid system without energy storage is used to lower costs. Such a system can still provide emissions reduction and energy savings, and the batteries can be installed in the future.

Figure 31: Hybrid Configuration: Electric Motor with Generator Power & Energy Storage [34]



4 – 3.4 SHORE POWER

Shore power has two main types: onshore power supply (OPS) and shore-side battery charging (SBC) [35]. OPS, also known as cold ironing, supplies electrical power directly to ships at berth from a shore-side source. This replaces the onboard electricity generation from auxiliary generators. SBC charges the onboard Battery Energy Storage Systems (BESS) using a connection standard suitable for the specific BESS onboard. Both OPS and SBC can help to improve air quality in ports and reduce the environmental impact of shipping.

The scale of propulsion power and energy consumption presents challenges for shore charging systems. For example, a small ferry can use 200 kWh of energy in one hour during normal operations, while a larger car ferry or small vessel can require 10 times that amount and require multiple megawatts of power.

Battery installations large enough to store energy for a day or week of ship operation are currently impractical. As a result, electric marine vessels typically charge between short voyages. This constraint creates challenges for shore electrical systems, which must recharge vessel batteries within the timeframe the operational requirements of the ship allow. While electric road vehicles can recharge over several hours, battery-electric ships need to be recharged in as little as 10 to 20 minutes. This results in charger ratings ranging from one to two orders of magnitude higher than electric vehicles and presents several safety and interface challenges.

4 – 3.5 SOLAR PV

Solar PV technology converts sunlight into electricity by using photovoltaic cells made of semiconductor materials like silicon [36]. When sunlight strikes the surface of the solar cell, it excites electrons and creates an electric current. The electric current can then be used to power electrical loads onboard the vessel. Solar power can be used to charge batteries and power electric motors, making it a clean and renewable energy option for CHCs.

Solar PV technology offers the benefit of being a completely clean and renewable source of energy, and in many cases can easily be integrated into a vessel's existing battery system. There are even vessels already using solar systems onboard with hybrid systems [37] [38]. However, there can be some additional requirements and barriers to their use.

Depending on the energy management system of the CHC, additional supporting systems might be necessary for optimal use. There are also limitations on solar energy, mainly that peak power is only generated in direct sunlight. It also fluctuates with other factors, such as the incident angle of the light, cleanliness of the panels, or cloud coverage.

Solar panel installations are also expensive, but their price is expected to drop over time. However, there is no anticipation of significant improvements in efficiency or space consumption [39]. Due to these limitations, it is rare for vessels to use solar energy as a sole energy source, but some do exist that rely completely on solar panels for their power [40]. In the short term, it will likely be most effective to use solar panels as supplementary renewable power in hybrid systems.

4 – 3.6 WIND ENERGY

Wind is used to produce electricity by converting the kinetic energy of air in motion into electricity. In conventional wind turbines, wind rotates the rotor blades, which converts kinetic energy into rotational energy. The rotational energy is conveyed through a shaft to the generator, which in turn produces electrical energy. Wind can also be utilized through several different methods to generate propulsion for vessels.

4 – 3.6.1 Wind Turbine

Wind turbines are commonly used in onshore applications, with offshore wind plants also used as a means of power generation. Wind turbines follow a conventional means of generating energy, where wind spins the large rotor blades of the turbine, which drive a generator. This allows for emission-free power generation that is dependent only on the wind. In both onshore and offshore areas with persistent driving winds, this is a great option with minimal environmental effects.

Several groups are working on the development of offshore charging stations located near offshore wind installations. The goal is to use the offshore power generation source and potentially reduce vessel congestion and air pollution in ports. Some venture companies are planning to develop charging stations at offshore wind farms and test a pilot installation [41].

Wind turbines installed directly on vessels could be advantageous for them as an additional source of power generation. However, the additional drag from the turbine may offset any potential benefit for that energy capture. If the turbines could be operated while the ship is idle to charge the battery system, it could be beneficial. The turbines could then be stowed away to reduce drag while the ship is in motion.

Limitations on wind turbine generation are similar to those of solar generation, namely that they are inconsistent because they depend on weather factors for power. In conditions where no wind is blowing, the wind turbines will not produce energy. They also require some additional equipment to manipulate the variable AC generator output to either a consistent AC output, or a converter to change AC to DC power. However, this should be easily integrated into the power system of a vessel. They could easily be used onshore for generating shore power, since wind plants are already implemented in onshore grids.

4 – 3.6.2 Kite Sails

Kite sails are large wind-catching sails released into the air and held in place by long tethers. Kite sails can be used for either propulsion or, through careful manipulation of the sail, direct power generation. The method for generating power requires large and complex systems, so for the CHC application, the direct propulsion from kite sails would likely be more beneficial. However, if the kite sails are used onshore for shore power, that option could also be viable.

The method of propulsion from kite sails has been implemented by some industrial companies [42]. When there are favorable winds, the sail is released and allowed to pull the vessel along. When the winds die down, the sail is retracted. There is a flight control system that causes the sail to move in a figure-eight pattern, which increases the force with which the sail pulls [42]. Using kite sails for power is a bit more complicated but there is a technical method that has been developed for it [43]. The sail is outfitted with an autopilot system and then released into the air attached to a winch. The wind pulls the sail out, unwinding the winch and generating power as it does. Once the tether is fully extended, the autopilot moves the sail into a position with minimal drag and winds the tether back in with less energy required than was generated while it was unwinding. This process can be repeated for as long as there are winds to keep the sail in the air [43].

4 – 3.6.3 Rigid Wingsails

Rigid wingsails work similarly to plane wings. However, for vessel applications, they are placed vertically so the thrust produced is not upwards, but horizontal. They are outfitted with control systems that adjust the sails to a position that best catches the wind for optimal propulsion assistance. Rigid wingsails are not typically used for electricity generation, although in some cases, solar panels are mounted to them for additional power [44]. These can supplement existing propulsion systems and reduce fuel consumption, or battery consumption if equipped to a hybrid or all-electric vessel. CHCs that are not concerned with having large wingsail structures could utilize them as an additional means of propulsion.

Some wingsails have even been developed that can collapse. This removes the potential downside of having the large structures at all times on the vessel.

Rotor sails are another type of rigid wingsail. However, rather than being shaped like vertical airplane wings, these are cylindrical stacks equipped with Flettner rotors that generate thrust as wind blows around them via the Magnus effect. Some companies claim this is around 10 times more efficient than a conventional sail, since more lift is produced from a smaller area [45]. Depending on the vessel, this could be a good way to supplement propulsion when winds are favorable. Method of rigid sail implementation will reduce fuel consumption through the propulsion they generate. It may be the case that, due to their smaller size, Flettner rotors could be more useful for CHCs, but that remains to be seen.

4 – 3.6.4 Flexible Sails

Flexible sails function like rigid wingsails, using wind to produce thrust. However, instead of being rigid, they are made of woven fabrics that move with the wind. This cannot generate electricity, but using sails for propulsion has been around for centuries. In modern CHC, this could be a viable method for reducing propulsion energy costs. Depending on the application, wind power captured in flexible sails for propulsion could even be the sole means of propulsion, greatly reducing emissions. For CHC that require a lot of engine power, like tugs, flexible sails could only be an option as an auxiliary propulsion method. However, for others that do not need large amounts of engine power, it could be a sole propulsion method.

There are few developing technologies for flexible sails, as it is a technology that has been used in shipping for many years. Some companies are implementing sailing propulsion on modern vessels to reduce fuel consumption [46]. The outlook of this method of propulsion seems unlikely to change in the near future, unless some vessels do adopt it to be an auxiliary means of propulsion.

4 – 3.7 OTHER POWER SOURCES

4 – 3.7.1 Supercapacitors Energy Storage (ScES)

Supercapacitors are energy storage devices that can store and discharge large amounts of energy quickly. However, marine propulsion systems need continuous power delivery, which may not align with supercapacitor characteristics.

Supercapacitors are currently being explored as a potential power source for CHC, particularly for short bursts of high-power operations.

Supercapacitors are durable power management solutions. They can be used alone or in combination with batteries to improve performance, extend operating life, reduce size and weight, and control emissions [47].

Compared to traditional batteries, supercapacitors have several advantages. They have a high power density, do not have thermal runaway characteristics, and can operate over a wide temperature range. These features make them well-suited for use in the marine environment, where conditions can be harsh and unpredictable [48]. Supercapacitors can be used for engine starting, high peak power drive cycles, and other applications in marine vessels [49].

4 – 3.7.2 Wave Energy and Wave-Assisted Propulsion

Thrust-generating bow foils have been in development for over a century. A bow foil is made up of a pair of horizontal hydrofoil wings that generate thrust by converting the movement of water over their surface. The thrust is generated by a combination of the wave and the resulting pitching of the vessel. A variation of the bow foil was demonstrated on the Suntory Mermaid II, a 9.5-meter vessel with two hydrofoils fixed between its catamaran hulls. Retractable bow foils have also been developed by some companies. Their aim is to optimize the use of wave propulsion by retracting in overly calm or stormy waters and extending for additional propulsion in better sea conditions [50]. This gives the advantage of bow foils in favorable conditions while avoiding unnecessary drag in poor conditions. This gives fuel savings for suitable ships in the range of 5 to 15%. Bow foils also result in smoother rides, which can be desirable for many vessels. This could be easily applied to CHC, increasing their fuel efficiency by taking advantage of wave energy.

While wave motion can be used to generate thrust, it can also be used as a means of generating power. One solution uses water columns built into the ship's hull. The oscillation of water as waves move up and down is used to compress air, which in turn is either stored or used immediately for energy generation [51].Other methods harvest the wave energy directly through hydraulic pumps, converting it to electricity, which drives the ship's propulsion motor [52].

This could be promising as a means of generating renewable energy since the vessel will naturally be crashing down onto the waves as it travels. This can capture some of the energy in those impacts. Using waves to generate power onboard is still a developing technology. If it is found to be efficient, then it could greatly reduce energy needs from other sources. If the systems are easily implementable, then this could be fitted to CHC as an additional means of power generation.

4 - 3.7.3 Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) systems store energy in a magnetic field created by the flow of direct current in a superconducting coil that has been cooled to a temperature below its superconducting critical temperature [53]. A typical SMES system consists of a superconducting coil, a power conditioning system, and a cryogenically cooled refrigerator. Once charged, the current in the superconducting coil does not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back into the network by discharging the coil.

The power conditioning system uses an inverter/rectifier to convert AC power to DC or vice versa, with an energy loss of about 2 to 3% in each direction. SMES systems are highly efficient, with a round-trip efficiency greater than 95%. They lose the least amount of electricity in the energy storage process compared to other methods [54].

Overall, while these novel power options are promising, they are still in the experimental or development stages and are not yet widely used in the maritime industry. It will take some time to determine their feasibility, safety, and regulatory requirements before they can be adopted on a large scale.

4 – 4. EVALUATION OF POWER OPTIONS

This section presents an analysis of each power option based on criteria such as emissions reduction potential, cost, availability, and operational feasibility. This comparison of power options is to determine the most promising alternatives for CHC.

4 – 4.1 ALL-ELECTRIC VESSEL USING BESS

Lithium-ion batteries have demonstrated their effectiveness and reliability in powering electric vehicles. Vehicles include smaller vehicles like cars and buses, as well as larger vessels, such as electric ferries and smaller electric boats. Several companies and organizations have successfully implemented lithium-ion battery systems in these marine applications. Technology readiness level (TRL) is a method for estimating the maturity of technologies during the acquisition phase of a program. TRLs allow for consistent and uniform discussions of technical maturity across different types of technology. A TRL of 8 for the lithium-ion battery technology for an all-electric vessel is relatively high. This indicates that the technology is being ready for commercial use.

Battery (all-electric) vessels have rapidly matured and are now deployed globally in large numbers. For instance, many hybrid vessels under construction that can operate propulsion on 100% battery power are classed by ABS and carried the notation “ESS-LiBATTERY.” However, the charging infrastructure must be carefully planned to meet the operational needs of fully electric vessels. If charging is not available at one or more routine docking points, the amount of onboard storage required may be dictated by the charging infrastructure.

4 - 4.1.1 Advantages of BESS

- Reduced Emissions: Lithium-ion batteries for marine applications do not produce direct emissions during operation since they do not burn fuel. It is worth noting that the environmental impact of lithium-ion batteries is generally considered to be lower than that of conventional power sources such as fossil fuels. This is because lithium-ion batteries do not produce direct emissions during operation. However, the full life cycle of lithium-ion batteries should be considered to understand their environmental impact.

Table 38: Emissions for BESS with Primary Propulsion Option

Source of Charging	Life Cycle Emissions (g CO_2e/MJ)[1]	% reduction from MGO[2]	Emissions Score
Grid Electricity	54.8	41%	3
Renewable Source	0	100%	5
1 - Energy Intensity Ratio (EIR) adjusted for primary power option 2 - 0.1% sulfur Marine Gas Oil (MGO); 92.6 g CO_2e/MJ			

- **Lower Operating Costs:** Although batteries are initially more expensive than traditional fuel-powered engines, they have lower operating costs. Batteries have fewer moving parts, which means they require less maintenance. Additionally, they do not require expensive fuel to operate.

- **Improved Performance:** Batteries can provide a consistent and reliable source of power, which can lead to improved vessel performance.

- **Regulatory Compliance:** There are several regulations and standards for the use of lithium-ion batteries in marine applications. They are intended to ensure the safety and performance of these batteries in this unique environment. Some of the most important regulations and standards for the use of lithium-ion batteries in marine applications are the following:
  - **International Electrotechnical Commission (IEC) Standards:** The IEC has developed a set of standards for the design and testing of lithium-ion batteries for marine applications. These standards cover topics such as safety, performance, and environmental requirements.
  - **Class societies:** ABS has developed a set of rules for the use of lithium-ion batteries in marine applications. These rules cover topics such as battery design, installation, and testing [21].
  - **United States Coast Guard (USCG) Regulations:** The USCG has developed regulations for the use of lithium-ion batteries on vessels operating in US waters. These regulations cover topics such as fire safety, ventilation requirements, and emergency response procedures [55, 56].

4 - 4.1.2 Challenges with BESS

- **Indirect Emissions:** The manufacturing and disposal processes associated with lithium-ion batteries can produce indirect emissions that can impact the environment. The manufacturing process of lithium-ion batteries involves the extraction, processing, and transportation of raw materials such as lithium, cobalt, nickel, and other metals. The production of these metals can result in greenhouse gas emissions, air pollution, and water pollution. According to a study conducted by the Swedish Environmental Research Institute, the production of a typical lithium-ion battery with a capacity of 20 kWh can result in GHG emissions of between 61 and 106 kg CO_2 equivalent per kWh of capacity. This means that the total GHG emissions produced during the fabrication process of a 20-kWh lithium-ion battery can range from 1.22 to 2.12 metric tons of CO_2 equivalent [57]. Additionally, the transportation of raw materials and finished products can also result in emissions from fossil fuel-powered vehicles. The disposal of lithium-ion batteries at the end of their life cycle can also have environmental impacts. If not properly disposed of, lithium-ion batteries can release toxic substances such as heavy metals, which can contaminate soil, water, and air. The recycling process for lithium-ion batteries can also be energy-intensive and produce emissions if not done properly. Overall, while lithium-ion batteries for marine applications do not produce direct emissions during operation, their indirect emissions from the manufacturing and disposal processes should be considered to understand their full environmental impact.

- **Safety:** Lithium-ion batteries can pose safety risks due to their chemical composition and the potential for thermal runaway. Thermal runaway is a chain reaction that can occur if a lithium-ion battery overheats, causing it to release heat and potentially ignite nearby materials. This can happen if the battery is damaged, overcharged, or exposed to high temperatures. The heat generated can cause a fire or explosion, which can be dangerous and difficult to control.

- **Complex Monitoring System:** Li-ion systems require complex monitoring systems to keep them within the proper operating range for temperature and voltage.

- **Limited Range:** Batteries have a limited range compared to traditional fuel-powered engines. This can be a problem for CHC that need to travel long distances or operate for extended periods.

- **Limited Charging Infrastructure:** Charging infrastructure for batteries is still in the early stages of development. This means that vessels may need to return to shore more frequently for charging, which can limit their operating range.

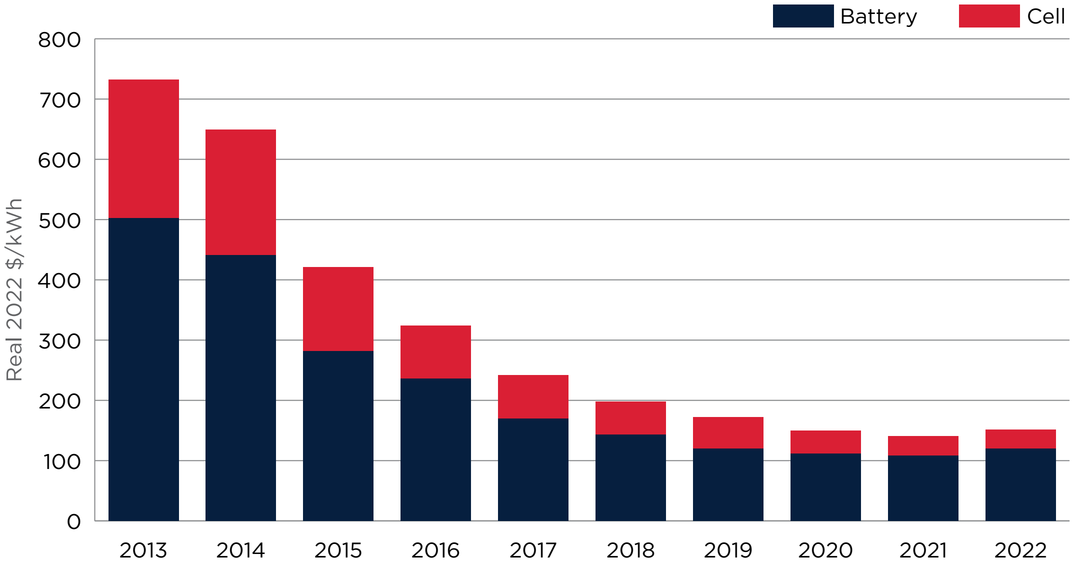
- **High Initial Costs:** Batteries are currently more expensive than traditional fuel-powered engines. This can be a barrier to entry for some vessel owners who may not have the financial resources to invest in a new power system. (See Table 39.)

Table 39: Total Cost of Ownership (TCO) Results for BESS

	TCO (2021 $/dwt-nm)	Score
MGO Baseline	~$0.02	–
BESS Charged by Grid Electricity (Current)	$0.058	3
BESS Charged by 100% Renewable Electricity	$0.064	3

As of 2022, the estimated average cost to produce 1 kWh of energy from lithium-ion batteries per module is around $151 (See Figure 5). Decarbonizing the entire fleet of tugboats will necessitate retrofitting as the lifespan of a tugboat can surpass 30 years. This poses challenges for technologies such as electric-powered tugs. A major drawback to battery-driven electric tugs is that it is hard/not possible to retrofit on existing vessels. Additionally, currently, batteries are mainly suited for smaller tugs with light and short harbor duties. Requiring new tugboats to meet decarbonization targets will put significant cost pressure on operators, especially in a very cost-sensitive market like tugboat services.

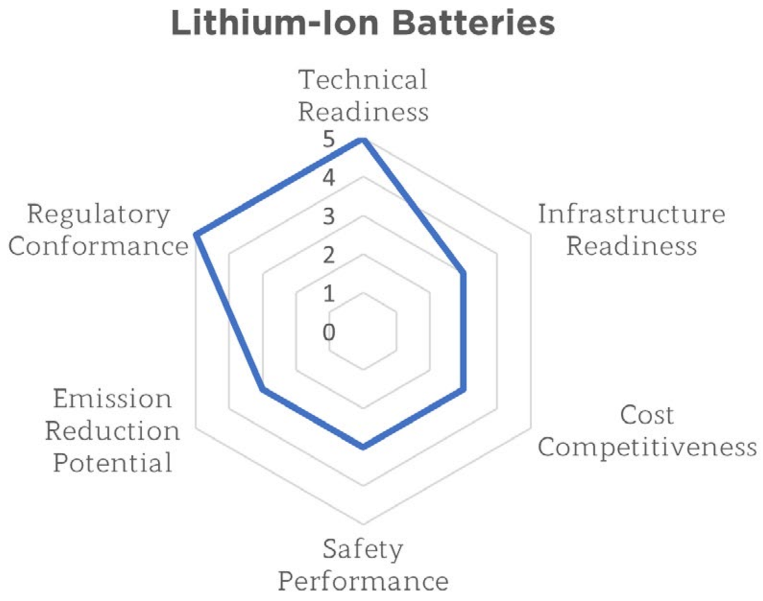
Figure 32: Volume-Weighted Average Lithium-Ion Battery Pack and Cell Price Split, 2013 – 2022 [58]



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Battery	502	441	282	236	170	143	120	112	108	120
Cell	230	208	139	88	72	55	52	38	33	31

DASHBOARD — TECHNOLOGY EVALUATION OF BESS

All-Electric Vessels Using BESS		Tugs		Ferries		Crew, Supply & Work Boats		Pilot Vessels	
Power Plant	**(MW)**	<3	>3	<1	1< >6	<1	>1	<1	>1
Load Profile	**Continuous**	✓	✓	✓	✓	✓	✓	✓	✓
Integration	**Newbuilt**	✓		✓		✓		✓	
	Retrofit	○		○		○		○	
Technical Readiness	**TRL 8**								
Technology Evaluation Summary	• Existing battery technologies are ideal for newly constructed vessels with specific arrangement and electrical systems. LFP and NMC emerge as the most promising options. • The charging infrastructure plays a pivotal role in determining the battery size. • When shore power relies on renewable energy sources, it significantly contributes to overall emissions reduction. • Fast shore power charging is essential, even though it may impact battery lifespan.								



✓ Good compatibility

○ Poor compatibility

4 – 4.2 FUEL CELL

Today, fuel cell technology for CHC is at a TRL of 7 or 8, with several projects underway to demonstrate the feasibility and viability of the technology. However, widespread deployment of fuel cell technology in CHC will require further development, testing, and validation to increase the TRL of the technology to levels that would be needed for large-scale commercial adoption.

Over the next 10 years, significant progress is expected in the development of fuel cell technology for CHC. This will include improvements in fuel cell efficiency, durability, and cost, as well as advances in the design and integration of fuel cell systems into CHC. By 2030, it is anticipated that fuel cell technology for CHC will have reached a TRL of 9, with several commercial-scale demonstrations and pilot projects successfully completed.

4 – 4.2.1 Advantages of Fuel Cells

- High Efficiency: (Greater thermal efficiency [41 – 53%]) One advantage of fuel cells is their high efficiency, which can exceed 50% in some cases. This means that more than half of the energy in the fuel can be converted into electrical energy. This is compared to less than 40% for conventional internal combustion engines. This high efficiency results in lower fuel consumption and emissions, which can lead to cost savings and environmental benefits.

- Low Emissions: Specific types of fuel cells emit only water and heat as byproducts, making them a clean and sustainable power option for marine applications. They produce no harmful pollutants, such as NO_x or PM.

Table 40: Emissions for Fuel Cell with Primary Propulsion Option

Source of Hydrogen for Fuel Cell	Life Cycle Emissions (g CO_2e/MJ)[1]	% reduction from MGO[2]	Emissions Score
Natural Gas	113.3	-22%	1
Natural Gas and Carbon Capture and Storage CCS	96.3	-4%	1
Grid Electricity	199.5	-115%	1
Renewable Source	1.3	99%	5
1 – EIR adjusted for primary power option 2 – 0.1% sulfur MGO; 92.6 g CO_2e/MJ			

- Reliable and Require Less Maintenance: They have less vibrations that could cause resonance (fractures in structures). Also, fuel cells have fewer moving parts and require less maintenance than conventional engines. This leads to increased reliability and reduced downtime.

- Scalability: Fuel cells can be scaled to meet the power requirements of different types of vessels, from small boats to large ships.

- Regulatory Framework: The regulatory framework should mature rapidly with the number of projects in the pipeline.
  - IMO and flag states have developed regulations specific to fuel cell power systems. For example, IMO's interim guidelines for the safety of ships using fuel cell power installations, MSC.1/Circ.1647, can serve as guidance.
  - Guides from multiple class societies have been developed for hydrogen-fueled vessels.

4 - 4.2.2 Challenges with Fuel Cells

- **High Cost of Fuel Cell Systems:** Generally, fuel cells for CHC are still considered to be relatively expensive compared to other power sources, such as diesel engines or batteries. Hydrogen as a fuel is estimated to be 3 to 7 times the price of MGO on a mass basis, based on gray hydrogen as the source. On an energy basis, this range is closer to 1 to 2.5 times the price of MGO depending on the size and type of the fuel cell system [59]. However, it is worth noting that the cost of fuel cells is expected to decrease over time as technology improves and becomes more widely adopted. In addition, the cost of hydrogen fuel is also expected to decrease as production methods become more efficient and the hydrogen infrastructure becomes more widespread.

Table 41: TCO Results for BESS, Baseline

	TCO (2021 $/dwt-nm)	Score
MGO Baseline	~$0.02	–
Fuel Cell Powered by Hydrogen Produced by Fossil Fuel and/or Grid Electricity	$0.066 – 0.080	3
Fuel Cell Powered by Hydrogen Produced by Green Energies	$0.084	2

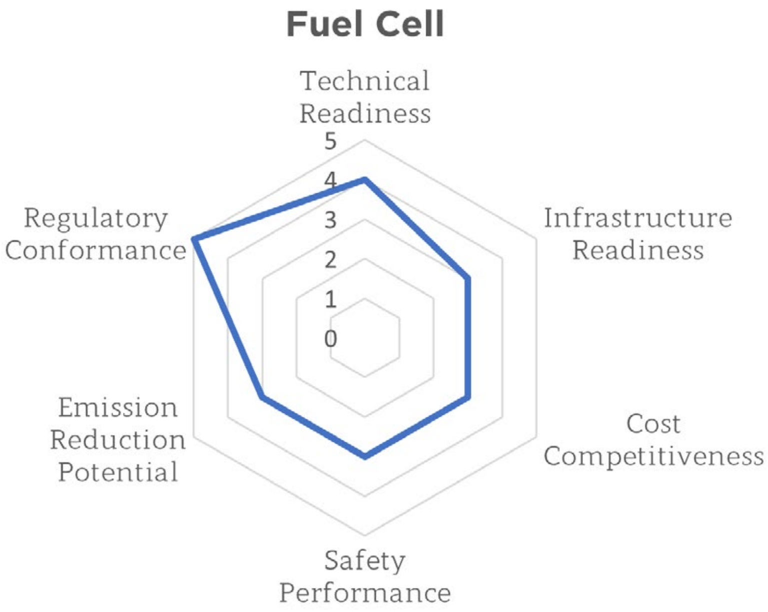
- **Fuel Storage and Transportation:** One of the challenges of using fuel cells for marine applications is the storage and delivery of fuels like hydrogen. Hydrogen is a highly flammable gas and needs to be handled with care. It can be stored onboard in compressed or liquid form, but both methods require specialized equipment and safety precautions.

- **Refueling Infrastructure:** Availability of refueling infrastructure is limited, which can make it difficult to refuel fuel cell-powered vessels in some areas.

- **Power Density:** While fuel cells have high efficiency, they have a lower power density than combustion engines, which can limit their use in high-power marine applications.

DASHBOARD — TECHNOLOGY EVALUATION OF FUEL CELL SYSTEMS

All-Electric Vessels Using Fuel Cell		Tugs		Ferries		Crew, Supply & Work Boats		Pilot Vessels	
Power Plant	**(MW)**	<3	>3	<1	1< >6	<1	>1	<1	>1
Load Profile	**Continuous**	✓	✓	✓	✓	✓	✓	✓	✓
Integration	**Newbuilt**	✓		✓		✓		✓	
	Retrofit	✗		✗		✗		✗	
Technical Readiness	**TRL 7 – 8**								
Technology Evaluation Summary	• Fuel cells exhibit high efficiency, leading to lower fuel consumption and reduced emissions. This makes them an attractive option for greener maritime operations. • Fuel cells can be scaled to meet the power demands of various vessel sizes. Whether it is a small boat or a large ship, fuel cells offer flexibility. • One challenge is the limited availability of refueling infrastructure for hydrogen. Establishing a reliable supply chain is essential. • Retrofitting vessels with fuel cell systems is complex due to the integration with existing ship systems, ensuring safe fuel storage, and addressing infrastructure upgrades. This includes gas handling and cooling mechanisms.								



✓ Good compatibility

✗ Very poor compatibility

4 – 4.3 HYBRID ELECTRIC PROPULSION SYSTEMS

There are many configurations available that enable hybrid operation of vessels, with demonstrations planned or already in operation. For example, SEACOR MAYA (the case study in section 4-5 of this report) is a proof of concept of how hybrid configurations can be practical in reducing greenhouse gas emissions for harbor craft. The TRL of hybrid power systems for marine applications is quite advanced. Many commercial projects are planned that will bring hybrid mechanical/electrical technology to full commercial readiness in the coming years. For instance, the successful adaptation, quick execution, and enhanced fuel efficiency achieved by the SEACOR MAYA has set a precedent for potential upgrades on other vessels. This includes the SEACOR AZTECA, SEACOR WARRIOR, and SEACOR VIKING. This showcases the scalability of such retrofitting projects.

ADVANTAGES OF HEPS

The advantages offered by HEPS are summarized as follows:

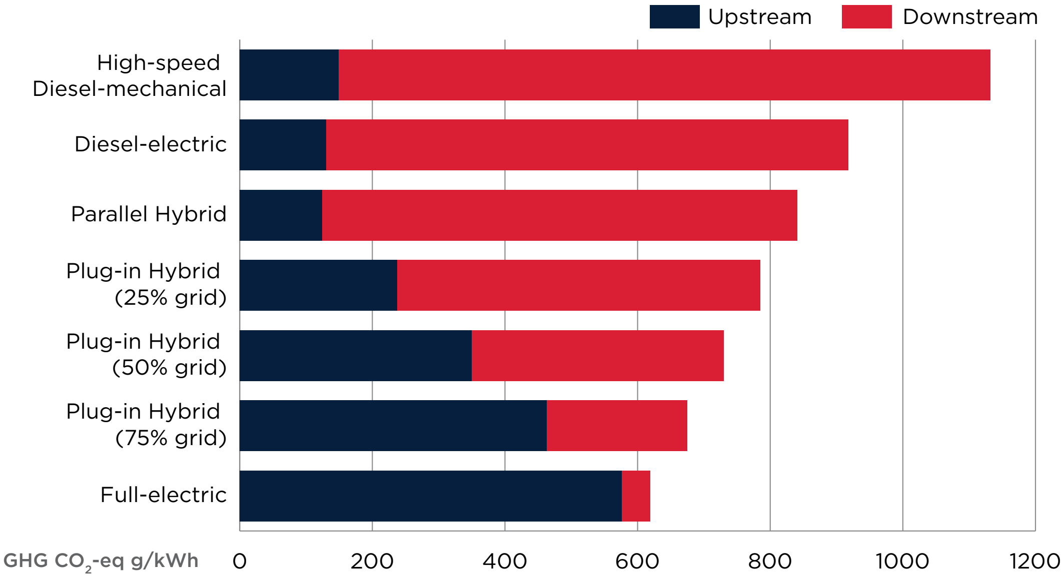
- **Integrate multiple energy generation and storage technologies, thereby increasing operational flexibility, reliability, and safety:** HEPS provide opportunities to utilize different energy storage and generation technologies. Lithium-ion batteries, supercapacitors, flywheel energy storage, fuel cells, solar, and wind can be used to supplement, or in some instances, replace traditional gen-sets during a vessel's different operational scenarios. Scenarios include at sea, during maneuvering, and docking. This diversity of available electric power sources helps improve operational flexibility and reliability. It allows for a minimum number of generators to be run, where previously, multiple generators were operated with less-than-ideal loading. The use of the appropriate energy storage system can decrease generator use with the energy storage providing ride-through power to prevent a blackout until the time it takes for the stand-by generator to come online. Energy storage technologies can serve a similar function in vessels during dynamic positioning operations. Other uses of energy storage are load leveling, such as crane systems.

- **Optimize generator capacities and appropriately meet power consumption needs:** The inclusion of alternate energy generation and storage technologies in the vessel electrical plant allows for a minimum number of generators to be run. This offers the opportunity to optimize the number and the operating point of generators for different operating scenarios. Maintenance costs can be cut by reducing running hours on equipment. Another way to cut maintenance costs is by operating generators at or close to the point of maximum efficiency, as alternate sources are available to supply the required power needs of occasional and starting loads instead of a lightly loaded generator. This optimization leads to less air pollution and environmental impact. This is an important aspect when vessels operate in environmentally sensitive or coastal areas.

- **Minimize environmental impact:** As discussed above, the integration of multiple energy storage and energy-generation technologies can result in a vessel's reduced environmental impact. Many port states and individual ports have designated areas along their coasts as emission control areas. The utilization of HEPS can greatly assist with reaching these goals.

Figure 33 illustrates the GHG reduction potential by electrifying Singapore Harbor Craft using high-speed diesel-mechanical as the baseline. The various types of electrified marine vessels considered in the study are diesel-electric, parallel hybrid, plug-in hybrid (25% grid), plug-in hybrid (50% grid), plug-in hybrid (75% grid), and full-electric. The well to tank emissions (upstream) were calculated separately from the tank to wake emissions (downstream). The total amount of GHG emissions decreases steadily with increased electrification, thus building the case for the electrification of harbor craft as the primary strategy for decarbonization. It is worth noting that the amount of downstream GHG emissions decreases more noticeably with increased levels of electrification. It shows a sharp decrease from 212 g/kWh CO_2 to 43 g/kWh CO_2 emissions reduction for plug-in hybrid with 75% grid power compared to full-electric. 31% reduction in GHG emissions is considered the threshold for a significant reduction in GHG emissions from the baseline. In the plug-in hybrid power configurations, the batteries are charged via a shore power connection. The plug-in hybrid (50% grid) power configuration shows a total emissions reduction of over 34% from the baseline, whereas the diesel-electric, parallel hybrid and plug-in hybrid (25% grid) configurations do not. Hence, the results indicate that to achieve significant reduction in GHG emissions, the battery in a hybrid power configuration needs to be sized to at least 50% of the vessel power demand [60].

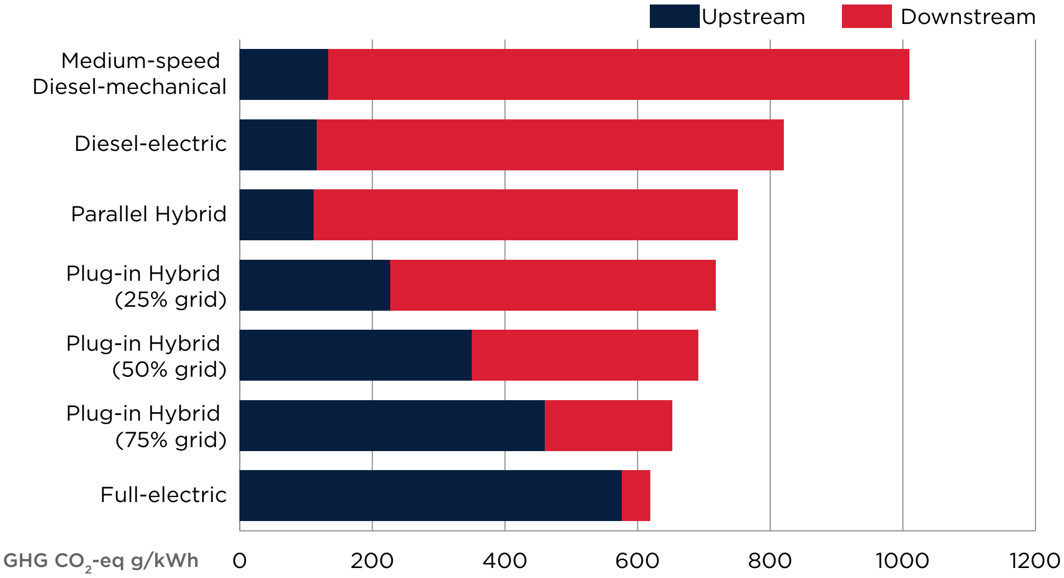
Figure 33: GHG Emissions Reduction Potentials for Different Power Configurations with a High Speed Diesel-Mechanical Configuration as the Baseline [60]



	High-speed Diesel-mechanical	Diesel-electric	Parallel Hybrid	Plug-in Hybrid (25% grid)	Plug-in Hybrid (50% grid)	Plug-in Hybrid (75% grid)	Full-electric
Upstream	149	130	124	237	350	463	576
Downstream	983	788	717	548	380	212	43
Total	1132	918	841	785	730	675	619

- The trends are similar for medium-speed diesel-mechanical propulsion as the baseline. The total GHG emissions are reduced with increased levels of electrification.

Figure 34: GHG Emissions Reduction Potentials for Different Power Configurations with a Medium-Speed Diesel-Mechanical Configuration as the Baseline [60]

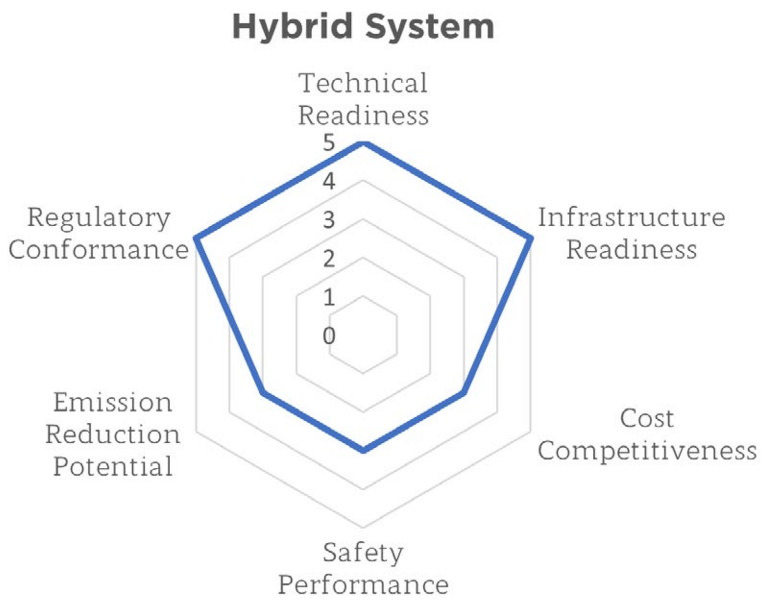


	Medium-speed Diesel-mechanical	Diesel-electric	Parallel Hybrid	Plug-in Hybrid (25% grid)	Plug-in Hybrid (50% grid)	Plug-in Hybrid (75% grid)	Full-electric
Upstream	133	116	111	227	350	460	576
Downstream	877	704	640	491	341	192	43
Total	1010	820	751	718	691	652	619

- **Regulatory Framework:** ABS has published an advisory on HEPS related to hybrid installation that can operate propulsion using hybrid mechanical/electrical power technology [9].

DASHBOARD — TECHNOLOGY EVALUATION OF HYBRID ELECTRIC PROPULSION SYSTEMS

Hybrid Electric Propulsion Systems		**Tugs**		**Ferries**		**Crew, Supply & Work Boats**		**Pilot Vessels**	
Power Plant	**(MW)**	<3	>3	<1	1< >6	<1	>1	<1	>1
Load Profile	**Continuous**	✓	✓	✓	✓	✓	✓	✓	✓
	Intermittent	✓	✓	✓	✓	✓	✓	✓	✓
Integration	**Newbuilt**	✓		✓		✓		✓	
	Retrofit	✓		✓		✓		✓	
Technical Readiness	**TRL 8 – 9**								
Technology Evaluation Summary	• Hybrid systems in marine applications combine various energy-generation methods (such as conventional engines, fuel cells, or renewables) with energy storage systems (typically batteries). This integration enhances operational flexibility, reliability, and safety. • The use of hybrid systems minimizes environmental harm. By optimizing energy usage and reducing reliance on fossil fuels, ships can significantly lower emissions and contribute to a cleaner marine environment.								



✓ Good compatibility

4 – 4.4 SHORE POWER

BENEFITS OF SHORE POWER

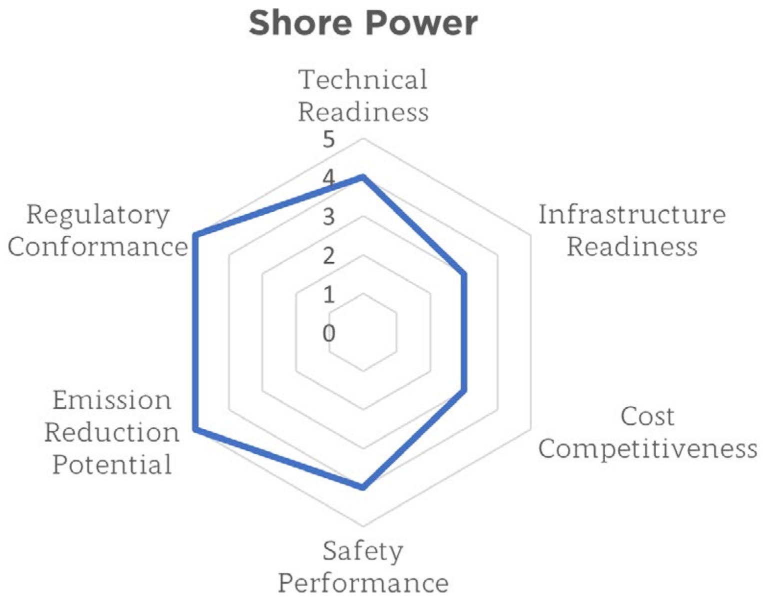
- **Reduced Emissions:** Shore power can be powered by grid power from an electric utility company or an external remote generator. These generators may be powered by diesel or renewable energy sources, such as wind or solar. If renewable energy sources are used, shore power can provide a clean source of power without emitting pollutants or greenhouse gases.
- **Lower Operating Costs:** Shore power has the potential to be less expensive than running engines or generators in the future. It can also reduce maintenance costs by reducing the wear and tear on the vessel's engines and generators.
- **Improved Safety:** Shore power eliminates the need for fuel on board the vessel, which can reduce the risk of fire or explosion. It also eliminates the need to handle and store fuel on board, which can be a safety hazard.

CHALLENGES WITH SHORE POWER

- **Limited Availability:** Shore power infrastructure is still in the early stages of development in many areas. This means that vessels may not be able to connect to shore power in all ports or marinas, which can limit their ability to use shore power as a power option.
- **Compatibility:** Shore power systems may not be compatible with all types of vessels or electrical systems. This can limit the number of vessels that can use shore power as a power option.
- **Capital Investment:** Retrofitting vessels to use shore power can require a significant capital investment. This may be a barrier to entry for some vessel owners who may not have the financial resources to make this investment.

DASHBOARD — TECHNOLOGY EVALUATION OF SHORE POWER

Shore Power		**Tugs**		**Ferries**		**Crew, Supply & Work Boats**		**Pilot Vessels**	
Power Plant	**(MW)**	<3	>3	<1	1< >6	<1	>1	<1	>1
Integration	**Newbuilt**	✓		✓		✓		✓	
	Retrofit	○		○		○		○	
Technical Readiness	**TRL 8 – 9**								
Technology Evaluation Summary	• Shore power installations are very expensive and require upgrades to the port and grid infrastructure. • Shore power can effectively reduce the emission of CO_2, PM, NO_x, and other toxins from traditional diesel engines, which are otherwise used by ships for power when at ports. • It is crucial that ports involve the utility companies from the initial planning stage to ensure that shore power systems can be supplied without interruptions and the infrastructure is designed to consider future power demand. • Standardization of shore power requirements for many types of vessels with Low Voltage (LV) and High Voltage (HV) systems is still in progress. Also, the standardization bodies have only recently started focusing on the shore power charging standards for vessels with DC power systems.								



✓ Good compatibility

○ Poor compatibility

4 – 4.5 WIND AND SOLAR POWER

ADVANTAGES OF RENEWABLE ENERGY SOURCES

There are several advantages of using renewable energy sources as a power option for CHC, such as wind and solar PV technologies, including the following:

- **Reduced Emissions:** Wind and solar PV technologies generate electricity without producing any greenhouse gas emissions, air pollutants, or noise. This can help reduce the environmental impact of CHC operations and contribute to a cleaner and healthier environment.
- **Reduced Fuel Consumption:** By using solar PV and wind technologies, CHC can reduce their reliance on fossil fuels and save on fuel costs. This can also help reduce the risk of spills and leaks associated with fuel storage and handling.
- **Technology Maturity:** Wind and solar power generation have reached 12% of global power and are growing at a rate of 15 – 20% per year [61]. In addition, the new technologies are designed to withstand harsh conditions of the sea environment.
- **Good Power Density:** Some types of PV cells can give relatively good power-to-size ratio (e.g., efficiencies within ranges of 135 to 170 watts/m2). CHC are strategically positioned to harness this renewable energy resource by utilizing electricity generated to charge onboard energy storage systems. [24].
- **Good Life Spans:** Some types of PV cells have a good life span (e.g., mono-crystalline type being advertised for 25 years).

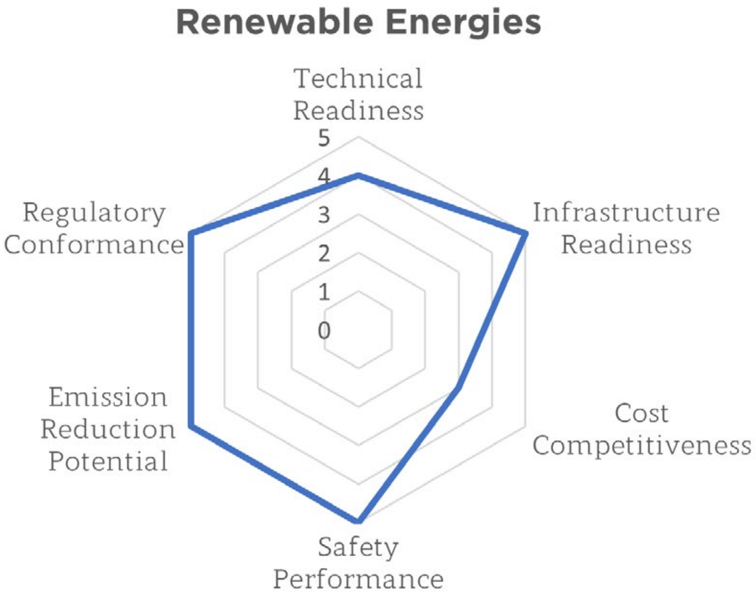
CHALLENGES WITH RENEWABLE ENERGY SOURCES

Despite the many advantages of these technologies, there are also several challenges that need to be addressed, including the following:

- **Initial Cost:** The initial investment required for installing wind turbines or solar PV systems to generate power for CHC can be substantial. This high, upfront cost may pose challenges when evaluating the feasibility and justification of such an investment.
- **Space Limitations:** Wind farms and solar PV panels require a certain amount of space to be installed, which can be a challenge on CHC that have limited deck space.
- **Battery Storage:** Wind and solar PV systems require a battery storage system to store excess energy generated during the day for use at night or during periods of low sunlight. This can add to the cost and complexity of the system.

DASHBOARD — TECHNOLOGY EVALUATION OF RENEWABLE ENERGY

Renewable Energy		**Tugs**		**Ferries**		**Crew, Supply & Work Boats**		**Pilot Vessels**	
Power Plant	**(MW)**	<3	>3	<1	1< >6	<1	>1	<1	>1
Integration	**Newbuilt**	○		○		○		○	
	Retrofit	✘		✘		✘		✘	
Technical Readiness	**TRL**	**7 – 9 for land-based and offshore installations** **4 – 6 for onboard installations**							
Technology Evaluation Summary	• CHC are strategically positioned to harness this renewable energy resource by utilizing electricity generated to charge onboard energy storage systems. • Existing vessels may be retrofitted with solar panels, but finding adequate space may be challenging on many vessel arrangements.								



○ Poor compatibility

✘ Very poor compatibility

4 – 4.6 ScES

Supercapacitors are ideal for applications that require quick delivery of energy to a load, such as pulsed power applications. In these applications, capacitors are charged as quickly as possible and can deliver the stored energy in a high-power pulse. Charging times can range from seconds to minutes, while discharge times can be as short as microseconds or nanoseconds.

Supercapacitors are also suitable for bidirectional energy exchange applications. As such, they can deliver stored energy when needed and absorb excess or regenerative energy when available. They can also be used to deliver stored energy to an electrical network when normal power sources are unavailable. Although they do not store as much energy as batteries, they can provide enough energy to ride through a temporary power interruption until another power source comes online.

Supercapacitor technology is still maturing (same TRL as the lithium-ion battery). However, it is already considered a viable energy storage solution that can be confidently deployed in the right application. Supercapacitors are a leading choice for applications that require a fast rate of charge or discharge or a high cycle life. They have excellent performance capabilities. They can also manage peak and average power demands of power grids or act as backups for primary energy supplies. Supercapacitors can also be combined with batteries to protect them from extreme peak loads. This extends battery life and takes advantage of their higher energy storage capacity [24].

ADVANTAGES OF ScES

- **Excellent Cycle Life:** Capacitors for energy storage can be cycled millions of times.
- **High Specific Power:** The low internal resistance of a capacitor enables high discharge current.
- **Fast Charging and Discharging Rate:** Capacitors for energy storage can be charged and discharged within a few minutes for LIC or even seconds for EDLC.
- **Easy Charging Without Overcharge Protection:** Capacitors are not subject to overcharge/over discharge due to stabilized ion reactions and fractional milliohms of internal resistance. It is not necessary for capacitors to have an end-of-charge termination mechanism.
- **Safety:** Supercapacitors have a risk of thermal runaway because of their carbon-based cathode material with minimal bound oxygen. In addition, a pressure-relief valve on each capacitor will reduce the internal pressure due to internal short circuit.
- **Outstanding Low-Temperature Charge and Discharge Performance:** The operating temperature range of an EDLC is from -40°C to 65°C. The operating temperature range of an LIC is from –20°C to 70°C.
- **Reduced Load Variations:** When capacitors are used as energy buffers, they can reduce load variations due to sudden external disturbances.
- **Improved System Stability:** When capacitors are used as energy buffers, it increases the average loading with fewer running generators.
- **More Fuel-Efficient Operations:** When capacitors are used as energy buffers, it allows for more fuel-efficient operation of available generators resulting in lower fuel consumption and maintenance.

CHALLENGES WITH ScES

- **Low Energy Density:** Supercapacitors have a lower energy density of approximately 5 W-h/kg compared to lithium-ion batteries.
- **High Self-Discharge Rate:** Supercapacitors have a higher self-discharge rate than lithium-ion batteries. Self-discharge is a phenomenon whereby the open-circuit voltage on the terminal of a charged capacitor/battery drops after a set period without being connected to a load. Self-discharge can lead to a capacitor having a less-than-full charge when connected to a network.

- **LV Per Capacitor:** Capacitors have an LV per basic element (typically 2.7V for EDLC). This requires multiple capacitors to be connected in series to meet the system voltage requirement (e.g., a typical crane operation needs about 900V).
- **Limitation of Stored Energy:** The linear discharge voltage of supercapacitors prevents the use of the full stored energy.

4 – 5. GHG EMISSIONS REDUCTION OF THE CALIFORNIA CHC FLEET THROUGH HYBRID TECHNOLOGIES

Hybrid power arrangements on CHC are known to reduce emissions by 15 to 30%. CARB defines zero-emission capable hybrid vessels as vessels that utilize power sources capable of providing a minimum of 30% of vessel power required for main propulsion and auxiliary power operation with zero tailpipe emissions when averaged over a calendar year. CARB has set a compliance date of December 31, 2025 for Zero Emission and Advanced Technologies (ZEAT) for new, newly acquired, and in-use short-run ferries [62].

Figure 21 from Workstream 1 of this report illustrates estimated CO_2 emissions from main and auxiliary engines in conventional CHC within the California fleet fitted with diesel main propulsion engines and diesel generators. If the existing California CHC fleet of ferries is retrofitted to meet the CARB ZEAT regulation by 2025, the state of California can expect at least 30% reduction in GHG emissions from ferries. In the future, if the ZEAT regulation were expanded to all CHC types included in this study and the entire CHC fleet of tugboats, pilot boats, ferries, work boats, and crew/supply boats is retrofitted with hybrid arrangements, even more significant GHG emissions reduction and fuel savings will be realized. Table 42 shows the potential reduction in GHG emissions that can be achieved by implementing hybrid technologies across the California CHC fleet, based on the assumption that these hybrid technologies will reduce GHG emissions by at least 30% to meet the ZEAT regulation.

Table 42: Estimated CO_2 Emissions Reductions of California CHC Fleet through Hybridization

Engine Type	Main Engines (g CO_2/vessel /hour)	Auxiliary Engines (g CO_2/vessel /hour)
Crew/Supply Boats	214,680	56,707
Ferries	361,915	49,435
Pilot Boats	14,728	4,192
Workboats	89,562	13,025
Articulated Tugs	358,046	9,199
Harbor Tugs	262,810	36,199
Offshore Tugs	444,981	31,578
Total	1,746,722	200,334
Hybrid Meeting ZEAT Regulation	1,222,706	140,234
Savings	524,017	60,100

A specific example of how hybridization of a CHC lead to significant fuel savings and emissions reduction is the integration of a lithium-ion battery system into the SEACOR MAYA's power system.

The hybrid configuration of this vessel optimizes generator loading by operating the generators within their optimal load factor. This is typically between 75% and 80% of their maximum continuous rating. When power demands increase, the batteries supply energy for peak shaving. During lower demand periods, the generators recharge the batteries. This approach ensures that the generators consistently operate near their sweet spot for efficiency. It also avoids light loading of the diesel engines.

The integration of the lithium-Ion battery system aboard the SEACOR MAYA led to reduction of the average fuel consumption by 20%. As a result of this performance, SEACOR adapted three more vessels for service with plans to adapt an additional six.

This vessel is an example of how hybrid configurations can be practical in reducing greenhouse gas emissions for harbor craft. The successful implementation of this technology on the SEACOR MAYA can pave the way for similar upgrades on other CHC operating in California, such as tugboats and workboats.

Figure 35: Dynamically Positioned Diesel-Electric Vessel, OSV SEACOR MAYA

4 – 6. CONCLUSION

From the research findings presented in this report, it is evident that there is no one-size-fits-all solution to reducing emissions from CHC. The suitability of each power option depends on different factors. Factors include the size of the vessel, the distance traveled, the operating profile, cost, and the availability of infrastructure. A combination of different power options and technology stacking may be necessary to achieve the emission reduction targets set by CARB. This is evidenced by the high ranking assigned to the hybrid power option.

The key findings listed below have been derived from the research:

1. The regulatory environment is ready for the implementation of most alternative CHC power options (see Table 78 in the appendix) such as hybrid, as evidenced by the high ranking assigned to regulatory conformance for each power option besides those contained in the “other” option.
2. Shore power, solar PV, and wind power are the most mature alternative options to provide sustainable power for CHC, when evaluated by technical readiness, infrastructure readiness, cost competitiveness, safety performance, emissions reduction potential, and regulatory compliance.
3. The main challenge with the alterative power options studied is cost competitiveness.
4. It is expected that the costs of these alternative power options will be reduced as the technologies advance, manufacturing processes are optimized, and adoption increases.

Workstream 5:

PROJECTION OF THE SUITABILITY OF FUEL OPTIONS

5 PROJECTION OF THE SUITABILITY OF FUEL OPTIONS

5 – 1. INTRODUCTION

This section focuses on the alternative fuel options considered in Workstream 3. The projection was divided into short (until 2030), medium (to 2040) and long term (to 2050). These forecasts consider a range of factors, including:

- Storage
- Cost competitiveness
- Feedstock availability
- Technological readiness
- Compatibility with current systems
- Bunkering capability
- Greenhouse Gas (GHG) emissions
- Safety
- Environmental risks
- Current applicability
- Overall viability

They outline the expected evolution of alternative marine fuels in California's harbor craft sector, which indicates a shift toward cleaner fuels and technologies. This transition is propelled by regulatory mandates, environmental objectives, and market incentives. Studies, such as those performed by CARB, complement this transition influencing initiatives like the Low Carbon Fuel Standard and its amendments, which will be pivotal in shaping the future fuel landscape within California [63]. The influence of initiatives like the Low Carbon Fuel Standard (LCFS) and its amendments will be pivotal in shaping the future fuel landscape. It will foster investment in sustainable transportation fuels and advance California's broader climate goals [64]. These projections offer a comprehensive evaluation of the potential of each alternative marine fuel and power option in California over the next three decades.

5 – 2. OVERVIEW OF THE FORECAST AND POLICY CONSIDERATIONS FOR CALIFORNIA HARBOR CRAFT

In current trends and regulations, engine upgrades have been a prominent strategy since the introduction of the Commercial Harbor Craft (CHC) regulation in 2008 [65]. This initiative, reinforced by subsequent amendments in 2010, has incentivized vessel owners to replace older engines with newer, cleaner alternatives. The objective is to curtail emissions of air pollutants and GHGs. This reflects a concerted effort toward environmental stewardship within California's maritime sector.

The 2022 Amendments to the CHC regulation signal a notable expansion of its scope, now encompassing a broader range of vessel types. These amendments mandate the adoption of cleaner upgrades and newer technology across the maritime sector. They reflect a steadfast commitment to emissions reduction and environmental protection. This underscores a continued focus on fostering sustainability and minimizing the industry's environmental impact.

The LCFS, instituted in 2009, serves as a pivotal policy framework in California's efforts to mitigate carbon emissions. Designed to be technology-neutral, the LCFS establishes a performance standard aimed at reducing the life-cycle carbon intensity (CI) of transportation fuels across the state. This policy sets ambitious targets for CI reduction. It contains a specific goal for achieving a 20% decrease in CI between the 2010 baseline and 2030, which emphases a long-term commitment to sustainability and environmental stewardship.

To achieve its objectives, the LCFS implements annual CI benchmarks that progressively decline over time. These benchmarks provide a roadmap for reducing emissions intensity, incentivizing the production and adoption of lower-CI fuels within California's transportation sector. By setting clear targets and milestones, the LCFS fosters innovation and investment in cleaner fuel technologies, driving the transition toward a more sustainable energy landscape.

Operating as a market-based mechanism, the LCFS creates a dynamic framework where deficits in meeting CI targets can be offset through the acquisition of credits. These credits are generated through the production and blending of lower-CI fuels. They encourage market participants to invest in and promote the use of alternative, environmentally friendly fuel sources. Through this mechanism, the LCFS stimulates competition and innovation in the fuel sector while facilitating the state's broader goals of reducing greenhouse gas emissions and combating climate change.

In the short term (through 2030), the forecast for alternative marine fuels anticipates a continuation of the trend toward adopting cleaner engine technologies. This response is driven by regulatory requirements, resulting in further reductions in emissions of air pollutants and GHGs. Additionally, there is expected to be an uptick in the use of biofuels and other low-CI fuels to meet the targets that California's LCFS set. It will foster incentives for producers to invest in alternative fuel production [66].

Looking toward the midterm (spanning to 2040), there is a projected expansion in the utilization of alternative marine fuels. This includes biofuels, renewable diesel, and potentially, hydrogen and ammonia as technology and infrastructure mature. Furthermore, there will be a greater integration of LCFS-compliant fuels into the maritime sector. Integration will be bolstered by evolving regulations and market dynamics that incentivize sustainability and emissions reduction.

Looking ahead to 2050, the forecast anticipates the full integration of alternative marine fuels into California's harbor craft fleet. Low-CI fuels are expected to power most vessels to effectively achieve emissions reduction targets. This period will also witness the emergence of innovative fuel technologies and infrastructure, driven by ongoing efforts to decarbonize the maritime industry and address climate change on a broader scale.

Based on the above overviews and individual fuel pathways with their respective feedstock, the following subsections provide a deep dive analysis of these projections.

In this workstream's analysis of projections or forecasts, color codes and ranking serve to provide clarity. These indicators denote the level of suitability or desirability for each parameter. In terms of viability, green represents the best scenario and red indicates the worst. The varying shades between red and green offer a quick visual reference for evaluating the performance of each parameter. The overall viability at the bottom of each table represents those possible projections and the resultant aggregate of all parameters considered in this study.

Table 43: Ranking Options and their Corresponding Colors and Meaning as Indicators of Performance

Color Indicators					
Grade or Ranking	**1**	**2**	**3**	**4**	**5**
Meaning	Very Poor	Poor	Average	Good	Very Good

5 – 2.1 BIOCRUDE PROJECTION FOR 2030, 2040, AND 2050

This subsection focuses on the projections and forecasts for biocrude as a marine fuel in California's CHC for 2030, 2040, and 2050. It considers the availability of feedstocks, as well as cattle shed wastes like dung, urine, and slurry from biogas plants, among others. It particularly considers manure and sludge, which are abundant in the state as a result of activated waste biomass resulting from biological treatments. California's thriving agricultural industry generates significant quantities of manure, while wastewater treatment plants produce substantial volumes of sludge. These organic waste materials serve as valuable feedstocks for biocrude production.

They offer a sustainable solution to both waste management and fuel production challenges. By converting these waste streams into biocrude through processes such as hydrothermal liquefaction or pyrolysis, California can harness a locally available and renewable resource to meet its energy needs while reducing environmental impacts [67].

The viability of biocrude as a marine fuel for the three decades is presented in Table 44. The color codes indicate the level of viability: green represents the most viable scenario, yellow indicates moderate viability, and orange signals lower viability.

Table 44: Overall Viability of Biocrude as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**3**	**4**	**5**
Cost Competitiveness	**2**	**3**	**4**
Feedstock Availability	**5**	**5**	**5**
Technological Readiness	**3**	**4**	**5**
Compatibility with Current Systems	**3**	**4**	**5**
Bunkering Capability	**2**	**3**	**4**
GHG Emissions	**4**	**5**	**5**
Safety	**3**	**4**	**5**
Environmental Risks (Spill)	**3**	**4**	**5**
Current Applicability	**2**	**3**	**4**
Overall Viability	**3**	**4**	**5**

As illustrated in the above table, in the short term (by 2030), the projection for biocrude suggests steady growth in production and adoption. Growth will be driven by advancements in conversion technologies and increasing recognition of the environmental benefits of the fuel. With supportive policies and incentives that promote the utilization of renewable fuels, biocrude production facilities are expected to proliferate across the state. The facilities will capitalize on the abundant feedstock sources available. Furthermore, partnerships between agricultural operations, wastewater treatment facilities, and biorefineries are likely to emerge. These will facilitate the efficient supply chain management of feedstocks and biocrude production. This collaborative approach, combined with regulatory mandates that aim to reduce emissions from marine vessels, positions biocrude as an alternative sustainable fuel option for California's harbor craft sector by 2030 [66].

Furthermore, for midterm spanning to 2040, and the long-term stretching to 2050, the projection for biocrude becomes increasingly optimistic as technology advancements and infrastructure investments further drive market penetration. By midcentury, biocrude may play a significant role in decarbonizing the maritime sector. This is because biocrude has lower carbon and hydrogen when compared with conventional marine fuel. The state's commitment to sustainability, coupled with the scalability and cost-effectiveness of biocrude production, positions it as a key component of California's energy transition strategy.

Moreover, ongoing research and development efforts focused on optimizing feedstock utilization and refining conversion processes are anticipated. They will enhance the efficiency and environmental performance of biocrude production. With a favorable regulatory environment and growing consumer demand for renewable fuels, biocrude emerges as a mainstay of California's efforts to achieve carbon neutrality and combat climate change in the coming decades [66].

5 – 2.2 BIODIESEL PROJECTION FOR 2030, 2040, AND 2050

To forecast the potential of biodiesel as a marine fuel in California for 2030, 2040, and 2050, it is important to assess the availability of feedstocks, primarily soybean, and other local considerations. Soybean cultivation in California is limited compared to other states. However, the state boasts a diverse agricultural landscape that produces various oilseed crops suitable for biodiesel production. This brings the chance to supply soybeans to California for continual biodiesel production. Additionally, California is a significant importer of soybean oil, which serves as a key feedstock for biodiesel production. With a growing emphasis on sustainability and renewable energy, the demand for biodiesel is expected to rise. Demand will drive investments in feedstock cultivation, supply chains, and biodiesel production facilities across the state. Furthermore, advancements in agricultural practices and crop diversification initiatives may lead to increased availability of feedstocks for biodiesel production. This will further bolster the chance of biodiesel as a marine fuel in California.

Table 45: Overall Viability of Biodiesel as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**4**	**5**	**5**
Cost Competitiveness	**2**	**3**	**4**
Feedstock Availability	**4**	**4**	**5**
Technological Readiness	**4**	**4**	**5**
Compatibility with Current Systems	**4**	**4**	**5**
Bunkering Capability	**2**	**3**	**4**
GHG Emissions	**4**	**5**	**5**
Safety	**3**	**4**	**5**
Environmental Risks (Spill)	**3**	**4**	**5**
Current Applicability	**2**	**3**	**4**
Overall Viability	**3**	**4**	**5**

By 2030, the projection for biodiesel indicates continued growth in production and utilization, supported by favorable regulatory policies and market dynamics. The state's LCFS incentivizes the use of low-CI fuels, providing a robust framework for the adoption of biodiesel in the maritime sector. With ongoing efforts to promote renewable energy and reduce GHG emissions, biodiesel production facilities are expected to expand. They will utilize locally sourced feedstocks and imported soybean oil to meet growing demand. Collaborations between agricultural producers, biodiesel manufacturers, and marine fuel suppliers may facilitate the development of efficient supply chains. This will ensure a reliable and sustainable source of biodiesel for California's harbor craft fleet. By 2030, biodiesel is poised to become a mainstream marine fuel in California. Biodiesel will offer significant emissions reductions and contribute to the state's broader climate objectives [68]. Aside from soybean oil, biodiesel could be produced from waste oils and fats that may be collected in the local region, especially from Central and Southern California metro areas. For example, the largest biodiesel plant in Bakersfield, California usually source their feedstock from restaurants, industrial kitchens, food processors, and rendering facilities [69] [70]. These resources management and circular approaches demonstrate the continuous availability of raw materials for biodiesel production across the state for the coming decades and for boosting local economies.

Moving on from the year 2040 and down to 2050, the projection for biodiesel remains positive as technological advancements and infrastructure investments further drive market penetration. By midcentury, biodiesel is expected to play a pivotal role in decarbonizing the maritime sector, with widespread adoption across California's harbor craft fleet. Continued advancements in feedstock cultivation, biodiesel production processes, and distribution networks are anticipated to enhance the efficiency and competitiveness of biodiesel as a marine fuel. Moreover, innovations in crop genetics and agricultural practices may lead to increased yields and improved feedstock availability. This will further strengthen the position of biodiesel in California's energy landscape. With a supportive regulatory framework and growing public awareness of environmental issues, biodiesel emerges as a key component of California's transition to a sustainable and low-carbon maritime sector. Biodiesel will contribute to the state's long-term climate goals and environmental sustainability [69].

5 – 2.3 BIO-OIL PROJECTION FOR 2030, 2040, AND 2050

Analyzing the projection for bio-oil as a marine fuel in California for 2030, 2040, and 2050 requires evaluating the availability of feedstocks. This includes woody biomass and other California peculiar considerations. Because California has an abundance of forestry resources, woody biomass is an easily accessible feedstock for the manufacture of bio-oil [71]. California produces more than 29 million bone dry tons (BDT) of woody feedstock annually from its farms, orchards, and woods, which shows the potential of the feedstock [12]. Additionally, advancements in biomass conversion technologies, such as gasification, pyrolysis, and hydrothermal liquefaction, offer efficient methods for converting woody biomass into bio-oil. With California's commitment to sustainability and renewable energy, bio-oil is poised to play a significant role in the state's energy transition. Moreover, ongoing research and development efforts focused on improving biomass conversion processes and optimizing feedstock utilization are anticipated. It will further enhance the feasibility and viability of bio-oil as a marine fuel in California [72], [73].

In the short term (by 2030), the projection for bio-oil will be driven by advancements in biomass conversion technologies and increasing recognition of the environmental benefits of fuel. With supportive policies and incentives promoting the use of renewable fuels, bio-oil production facilities utilizing woody biomass feedstocks are expected to proliferate across the state. Collaborations between forestry industry stakeholders, bio-oil manufacturers, and marine fuel suppliers may facilitate the development of efficient supply chains. This will ensure a reliable source of bio-oil for California's harbor craft fleet. By the end of 2030, bio-oil is expected to emerge as a competitive marine fuel option if pilot and demonstration plants are scaled up to full production, as indicated in [72] and [73].

Table 46: Overall Viability of Bio-Oil as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**3**	**3**	**4**
Cost Competitiveness	**3**	**3**	**4**
Feedstock Availability	**5**	**5**	**5**
Technological Readiness	**3**	**3**	**4**
Compatibility with Current Systems	**3**	**4**	**5**
Bunkering Capability	**2**	**3**	**4**
GHG Emissions	**3**	**3**	**4**
Safety	**3**	**4**	**5**
Environmental Risks (Spill)	**3**	**3**	**5**
Current Applicability	**2**	**3**	**4**
Overall Viability	**3**	**3**	**4**

On average, the projection for bio-oil becomes increasingly optimistic. This is due to technology advancements and infrastructure investments further driving market penetration from 2040 to 2050, coupled with available woody biomass from earlier years. By midcentury, bio-oil may be widely adopted across California's maritime sector, with a growing proportion of the harbor craft fleet powered by bio-oil-derived fuels. Continued research and innovation in biomass conversion technologies are expected to improve the efficiency and environmental performance of bio-oil production. This will make it one of the preferred choices for marine fuel applications. Moreover, strategic investments in biomass feedstock cultivation and procurement are likely to enhance feedstock availability and supply chain resilience. This will ensure the long-term sustainability of bio-oil as a marine fuel in California. According to [12], annual market research shows that there are a variety of innovative, sustainable, and value-aligned options to use forest and agricultural woody feedstocks in California [12]. However, for these approaches to scale to the point where they can use the amount of feedstock that becomes available, California will need to implement new policy interventions that promote market expansion at a rapid and scaled rate. With supportive regulatory frameworks and growing public demand for renewable energy solutions, and by the year 2050, bio-oil would be one of the key enablers of California's transition to a sustainable and low-carbon maritime sector. This is provided the reliance on natural gas and crude oil is reduced. Bio-oil will contribute to the state's efforts to combat climate change and promote environmental stewardship.

5 – 2.4 FT-DIESEL PROJECTION FOR 2030, 2040, AND 2050

FT-diesel, derived from Fischer-Tropsch (FT) synthesis (reactor), offers a versatile and efficient pathway for producing liquid fuels from various feedstocks, which already exist in some refineries and gas processing facilities in California. The FT process is a series of chemical processes that turns syngas, a mixture of carbon monoxide and hydrogen, into liquid hydrocarbons. The projection for FT-diesel as a marine fuel in California for 2030, 2040, and 2050 necessitates a thorough assessment of the availability feedstock. This includes biomass, coal, natural gas, waste CO_2, and green electricity. In California, the availability of renewable feedstock like biomass, including agricultural residues and forestry waste, presents a promising feedstock option for FT-diesel production. Additionally, the state's abundant natural gas resources offer another viable feedstock pathway, particularly when coupled with carbon capture and utilization technologies to mitigate GHG emissions. Moreover, the integration of waste CO_2 and electricity from renewable sources into FT-diesel production processes can further enhance the sustainability profile of the fuel. This aligns with California's broader goals of reducing carbon emissions and promoting renewable energy adoption.

Table 47: Overall Viability of FT-Diesel as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**4**	**4**	**5**
Cost Competitiveness	**3**	**3**	**4**
Feedstock Availability	**5**	**5**	**5**
Technological Readiness	**4**	**5**	**5**
Compatibility with Current Systems	**4**	**4**	**5**
Bunkering Capability	**2**	**3**	**4**
GHG Emissions	**3**	**4**	**4**
Safety	**3**	**4**	**5**
Environmental Risks (Spill)	**4**	**4**	**5**
Current Applicability	**4**	**5**	**5**
Overall Viability	**4**	**4**	**5**

For the near future (by 2030), the FT-diesel production may depend on the significant advancements in production technology and feedstock utilization, driving increased adoption of the fuel in California's maritime sector. Biomass-to-liquid (BTL) facilities utilizing agricultural residues and forestry waste as feedstocks are expected to come online. This is provided the outcome of Forest Biomass to Carbon-Negative Biofuels Pilot Program are put in place with the support by government incentives and private investments. Furthermore, partnerships between biomass producers, energy companies, and marine fuel suppliers may facilitate the development of integrated supply chains. This will ensure a reliable source of FT-diesel for harbor craft operations. The utilization of natural gas and waste CO_2 in FT-diesel production processes is also expected to gain traction with time. Also, pilot projects and demonstration plants that showcase the feasibility and environmental benefits of these pathways, based on the two-dozen active biomass-to-energy plants in operation, are an important indicator. This is available on the California Biomass Energy Alliance website. By 2030, FT-diesel is poised to become a competitive and sustainable marine fuel option in California. It will offer significant emissions reductions and contribute to the state's transition to a low-carbon economy [63].

Looking ahead to 2040 and down to 2050, the projection for FT-diesel becomes increasingly optimistic as technology advancements and regulatory support further drive market penetration. With the abundance of natural gas in California, opportunities to utilize CO_2 from other industries, as well as advancement in hydrogen supply for syngas production, FT-diesel technology stands as a promising one [74]. By midcentury and with increased capacity for renewable diesel production, FT-diesel is expected to be an important alternative fuel. Continued investments in carbon capture and utilization technologies, coupled with advancements in biomass conversion processes, are anticipated to enhance the efficiency and sustainability of FT-diesel production. Moreover, the integration of renewable energy sources into FT-diesel production processes, such as wind and solar electricity, may further reduce the carbon footprint of fuel. This will position it as a solution for California's carbon neutrality goals. With supportive policy frameworks and growing public awareness of environmental issues, FT-diesel emerges as a cornerstone of California's efforts to decarbonize the maritime sector and combat climate change in the long term.

5 – 2.5 PYROLYSIS OIL PROJECTION FOR 2030, 2040, AND 2050

Pyrolysis oil as a marine fuel in California for 2030, 2040, and 2050 involves considering the availability of feedstocks, primarily biomass, and others. The availability of biomass, which includes agricultural wastes, forestry waste, and specific energy crops, should not be an issue. California's agriculture industry also produces substantial quantities, which makes it a suitable feedstock source for pyrolysis oil manufacturing. Advancements in pyrolysis technology offer efficient methods for converting biomass into bio-oil, a liquid fuel suitable for marine applications. With California's commitment to renewable energy and sustainability, pyrolysis oil emerges as a viable option for decarbonizing the maritime sector while utilizing locally available feedstocks. In previous years, the existence of pyrolysis operations in El Segundo, Merced, Anderson, and Loyalton, with products like biogas, biohydrogen, biochar, and wood vinegar, make it a promising one for marine fuel production [75].

For the short term (by 2030), the projection for pyrolysis oil anticipates moderate growth in production and adoption. It is driven by advancements in pyrolysis technology and increasing demand for renewable marine fuels. Pilot projects and demonstration plants that utilize biomass feedstocks are expected to highlight the feasibility and environmental benefits of pyrolysis oil as a marine fuel. Partnerships between biomass producers, pyrolysis technology developers, and marine fuel suppliers may facilitate the development of integrated supply chain. This will ensure a reliable source of pyrolysis oil for California's harbor craft fleet. In a similar pattern as bio-oil, by the year 2030, pyrolysis oil is also poised to become a niche player in the marine fuel market. It will offer emissions reductions and contribute to California's broader sustainability goals [72], [73].

Table 48: Overall Viability of Pyrolysis Oil as a Marine Fuel in California

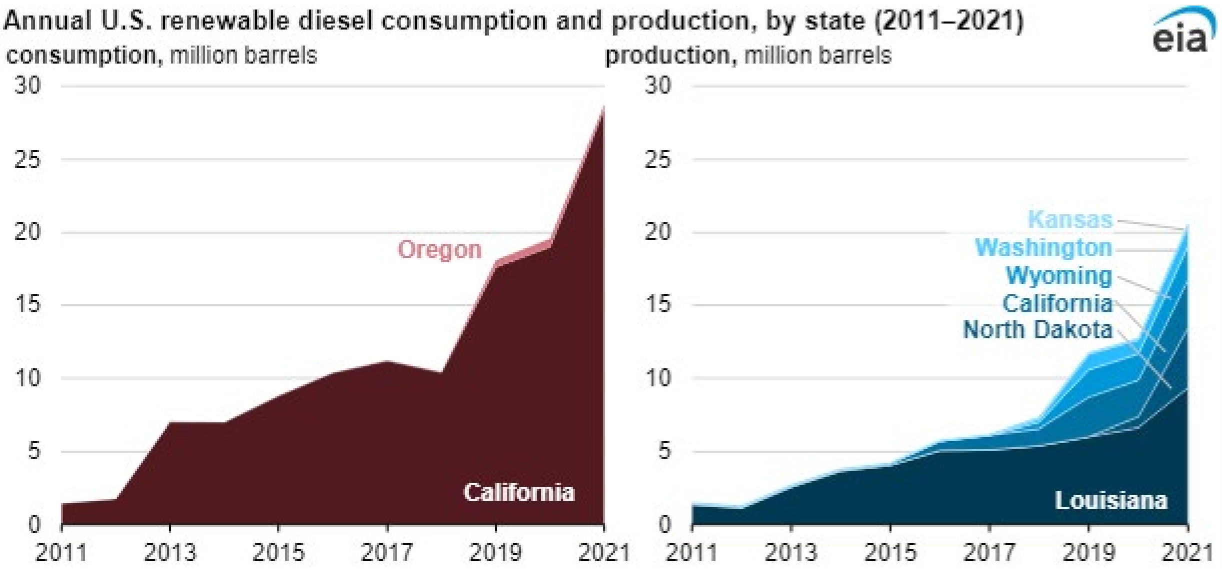
Parameters	2030	2040	2050
Storage	**3**	**4**	**4**
Cost Competitiveness	**5**	**5**	**5**
Feedstock Availability	**5**	**5**	**5**
Technological Readiness	**3**	**4**	**5**
Compatibility with Current Systems	**3**	**4**	**5**
Bunkering Capability	**2**	**3**	**4**
GHG Emissions	**3**	**3**	**4**
Safety	**3**	**4**	**5**
Environmental Risks (Spill)	**3**	**4**	**5**
Current Applicability	**4**	**4**	**5**
Overall Viability	**3**	**4**	**4**

The outlook for pyrolysis oil from 2040 and 2050 grows more positive as governmental backing and technological improvements increase. By midcentury, pyrolysis oil is expected to be a significant marine fuel in California, with widespread adoption across the harbor craft fleet. It is projected that sustained investments in pyrolysis technology and feedstock acquisition would improve the productivity and scalability of pyrolysis oil production. It will be positioned as a competitive substitute for traditional marine fuels. Another economic advantage and prospect for the pyrolysis process could be the possibility of producing pyroligneous acid, carbon black, charcoal, activated carbon, and torrefied wood. It could also produce renewable natural gas, FT-diesel, gas fermentation and gasification, bio-oil, and bioethanol. Pyrolysis oil demand is likely to rise in response to regulations that aim to reduce ship emissions and promote the use of renewable energy sources. Thanks to favorable regulatory frameworks and growing public awareness of environmental issues, pyrolysis oil is one of the alternative fuels to be considered in California's transformation to a low-carbon maritime industry with the state's long-term sustainability goals.

5 – 2.6 RENEWABLE DIESEL PROJECTION FOR 2030, 2040, AND 2050

Although the majority of renewable diesel used in the U.S. is not produced in California, the state is home to almost all of it. In 2021, the amount of renewable diesel consumed in California exceeded eight times its production. Rather, the majority of California's renewable diesel was imported, primarily from Singapore, or produced in other states [76]. The projection for renewable diesel as a marine fuel in California for 2030, 2040, and 2050 involves evaluating market dynamics, feedstock availability, and other local industrial considerations. California's renewable diesel industry relies on various feedstocks, including yellow grease and other oils. They are sourced from industries such as food processing, rendering, and petroleum refining. These feedstocks serve as valuable inputs for renewable diesel production. They offer a sustainable alternative to conventional diesel fuels. Following the implementation of California's LCFS in 2011, the state's consumption of renewable fuel increased significantly. The amount consumed increased from 1 million barrels a year to 28 million barrels annually between 2011 and 2021. That was far more than the initial rate. As renewable diesel becomes more economically competitive with biodiesel, California is the only state that specifically gives a rebate to customers who purchase renewable diesel [76]. This will increase the use of renewable diesel in California, offer significant emissions reductions, and contribute to the state's broader sustainability goals [76].

Figure 36: Shows that California Uses Almost All the Renewable Diesel Produced in the U.S.



The consumption of renewable diesel as an alternative to fossil diesel has been on the rise since 2011. This is because transportation fuels used in the state are mixed with biofuels to lower their carbon intensities. So by 2030, the projection for renewable diesel anticipates steady growth in production and adoption. This will be driven by growing market demands and increased regulatory pressures to reduce emissions from marine vessels. Renewable diesel production facilities that utilize yellow grease and other oil as feedstocks are expected to expand, supported by government incentives and mandates promoting the use of low-carbon fuels. Collaborations between feedstock suppliers, renewable diesel producers, and marine fuel distributors may facilitate the development of integrated supply chains. This will ensure a reliable source of renewable diesel for California's harbor craft fleet. By 2030, renewable diesel is poised to continue to be a mainstream marine fuel.

Table 49: Overall Viability of Renewable Diesel as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	4	5	5
Cost Competitiveness	4	5	5
Feedstock Availability	4	5	5
Technological Readiness	5	5	5
Compatibility with Current Systems	4	4	5
Bunkering Capability	4	4	4
GHG Emissions	3	4	4
Safety	4	4	5
Environmental Risks (Spill)	4	5	5
Current Applicability	4	5	5
Overall Viability	4	5	5

Since 2021, there are exclusive arrangements in place for several of the other states' plants to send all the renewable fuel they produce to wholesalers in California. Therefore, the projection for 2040 and 2050 is more optimistic. This is because the existing renewable diesel businesses are well advanced with further market expansion as demand requires. By midcentury, renewable diesel is expected to be a dominant marine fuel in California, with widespread adoption across the harbor craft fleet. Considering the demands, continuous increase in investments in renewable diesel production capacity and feedstock procurement are anticipated to enhance the scalability and competitiveness as a marine fuel.

Furthermore, the switch to renewable diesel is going to happen faster. This is due to regulations meant to lower emissions from maritime harbor craft and encourage the use of renewable energy. Renewable diesel emerges as a critical enabler of California's transition to a low-carbon and sustainable maritime sector. It supports the state's efforts to combat climate change and encourage environmental stewardship.

5 – 2.7 STRAIGHT VEGETABLE OIL PROJECTION FOR 2030, 2040, AND 2050

Straight vegetable oil (SVO), particularly soybean oil, can be used as a direct replacement for marine diesel fuel. Soybean oil can be processed and utilized without any chemical modifications. This makes it a straightforward alternative marine fuel option. It is important to note that biodiesel is different from raw vegetable oil. If raw vegetable oil is sold for or used to power a diesel-powered highway vehicle in California, it is subject to the same diesel fuel tax as biodiesel or petroleum-based diesel fuel. This includes raw virgin oil (SVO), which is fresh and uncooked, and waste vegetable oil (WVO), which is used cooking oil, grease, fryer oil, and tallow fats [77] [78].

Evaluating the projection for SVO as a marine fuel in California for 2030, 2040, and 2050 requires assessing the availability of feedstocks, primarily soybean oil, and some other aspects to consider. With advancements in oil extraction technology and increasing emphasis on renewable energy, SVO emerges as a potential solution for decarbonizing the maritime sector while utilizing locally available feedstocks. However, it is essential to consider the supply of soybean oil between various industries, such as food processing and biodiesel production. This is because this may impact its availability and price for marine fuel applications.

Table 50: Overall Viability of SVO as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**4**	**5**	**5**
Cost Competitiveness	**3**	**5**	**5**
Feedstock Availability	**4**	**4**	**4**
Technological Readiness	**5**	**5**	**5**
Compatibility with Current Systems	**5**	**5**	**5**
Bunkering Capability	**4**	**5**	**5**
GHG Emissions	**4**	**4**	**4**
Safety	**4**	**4**	**5**
Environmental Risks (Spill)	**4**	**4**	**5**
Current Applicability	**4**	**5**	**5**
Overall Viability	**4**	**5**	**5**

By year 2030, the projection for SVO indicates modest growth in production and adoption, driven by early adopters seeking to reduce emissions from marine vessels. Pilot projects and demonstration initiatives that utilize soybean oil as a marine fuel are expected to indicate the feasibility and environmental benefits of SVO. However, challenges related to feedstock availability and competition with other industries may limit the scalability of SVO as a marine fuel in the near term. Collaboration between soybean growers, oil processors, and marine fuel suppliers may help address supply chain issues. Additionally, it may help ensure a reliable source of SVO for California's harbor craft fleet. By 2030, SVO is expected to remain a niche player in the marine fuel market. It will offer emissions reductions and contribute to the state's sustainability goals.

The outlook for SVO may be promising in 2040 and 2050 as governmental support and technological improvements fuel global growth. With several dynamic efforts among the producers and users, coupled with adequate awareness, SVO may be one of the well-used marine fuels in California by the middle of the 20th century, as its use among port vessels grows. It is anticipated that sustained investments in oilseed farming and processing facilities will improve the availability and competitiveness of SVO as a maritime fuel. Further incentives for the use of SVO may come from regulatory obligations intended to lower emissions from marine vessels and encourage the development of renewable energy. With supportive policy frameworks and growing public awareness of environmental issues, SVO emerges as a viable option for decarbonizing California's maritime sector and aligning with the state's long-term sustainability objectives [68].

5 – 2.8 AMMONIA PROJECTION FOR 2030, 2040, AND 2050

Ammonia production relies primarily on natural gas as a feedstock, which is abundant in California. This makes it a viable option for ammonia synthesis. Additionally, advancements in electrolysis technology enable the production of green ammonia using water and renewable electricity. This aligns with California's commitment to renewable energy and sustainability.

Because the chemical or fuel contains no carbon atoms, it does not emit carbon dioxide when utilized as fuel. Ammonia is very energy-dense compared to other choices, such as liquid hydrogen or battery power. It therefore takes up significantly less room on board. Ammonia is currently an extensively traded commodity. This means the global infrastructure required to produce, store, and transport it is already in place, including at over 130 ports around the world.

However, it is essential to consider the potential competition for natural gas between various industries. It is also important to consider the need for robust infrastructure to support ammonia production and distribution for marine fuel applications. Ammonia is quickly laying the technical foundation required for its broad use as a marine fuel. While the suggested deadlines for some green shipping corridors may appear ambitious, the demonstration work is still ongoing. All stakeholders in the value chain are determined to meet these goals [79].

Table 51: Overall Viability of Ammonia as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**4**	**5**	**5**
Cost Competitiveness	**4**	**5**	**5**
Feedstock Availability	**4**	**5**	**5**
Technological Readiness	**5**	**5**	**5**
Compatibility with Current Systems	**5**	**5**	**5**
Bunkering Capability	**4**	**5**	**5**
GHG Emissions	**4**	**5**	**5**

Parameters	2030	2040	2050
Safety	**4**	**5**	**5**
Environmental Risks (Spill)	**4**	**5**	**5**
Current Applicability	**5**	**5**	**5**
Overall Viability	**4**	**5**	**5**

By 2030, the projection for ammonia as a marine fuel suggests cautious optimism. This is driven by early-stage investments in green ammonia production and pilot projects that highlight its viability. Pilot-scale green ammonia production facilities that utilize electrolysis technology is expected to come online. Production will be supported by government grants and incentives that aim to promote renewable energy adoption. However, challenges related to infrastructure development and cost competitiveness may limit the widespread adoption of ammonia as a marine fuel in the near term. Collaboration between energy companies, technology developers, and marine fuel suppliers may help address these challenges and pave the way for ammonia's integration into California's harbor craft fleet. By 2030, ammonia is expected to emerge as a niche player in the marine fuel market. It will offer emissions reductions and contribute to the state's broader sustainability goals [79].

For 2040 and 2050, the projection for ammonia becomes more optimistic as technology advancements and regulatory support drive market expansion. By midcentury, ammonia is anticipated to be a significant marine fuel in California with increasing adoption across the harbor craft fleet. Continued investments in green ammonia production capacity and infrastructure are expected to enhance the availability and competitiveness of ammonia as a marine fuel [80]. Moreover, regulatory mandates that aim to reduce emissions from marine vessels and promote renewable energy adoption may provide further incentives for the use of green ammonia. With supportive policy frameworks and growing public awareness of environmental issues, ammonia emerges as a key enabler of California's transition to a low-carbon maritime sector. It will contribute to the state's efforts to combat climate change and promote environmental stewardship.

5 – 2.9 LNG PROJECTION FOR 2030, 2040, AND 2050

California's abundant natural gas reserves position it as a key supplier for LNG production, making it a readily available and cost-effective marine fuel option. With advancements in liquefaction technology and infrastructure development, LNG emerges as a viable solution for reducing emissions from marine vessels while utilizing locally available feedstocks. Additionally, LNG offers significant environmental benefits. These include lower emissions of sulfur oxides (SO_x), NO_x, and particulate matter compared to conventional marine fuels. This is in alignment with California's stringent environmental regulations and sustainability goals.

By 2030, the projection for LNG as a marine fuel suggests continued growth and adoption. It is driven by regulatory mandates and market incentives that aim to reduce emissions from marine vessels. Investments in LNG bunkering infrastructure and terminal facilities are expected to increase. This will facilitate the availability and accessibility of LNG for California's harbor craft fleet. Moreover, collaborations between energy companies, port authorities, and marine fuel suppliers may help accelerate the transition to LNG as a marine fuel. However, challenges related to infrastructure development may hinder the widespread adoption of LNG in the near term. Challenges include the need for additional bunkering facilities and vessel retrofits.

Table 52: Overall Viability of LNG as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**4**	**4**	**5**
Cost Competitiveness	**4**	**4**	**5**
Feedstock Availability	**5**	**5**	**5**
Technological Readiness	**4**	**5**	**5**
Compatibility with Current Systems	**4**	**5**	**5**
Bunkering Capability	**4**	**4**	**5**
GHG Emissions	**4**	**4**	**4**
Safety	**4**	**4**	**5**
Environmental Risks (Spill)	**4**	**4**	**5**
Current Applicability	**4**	**5**	**5**
Overall Viability	**4**	**4**	**5**

For mid and long term (2040 and 2050), the projection for LNG becomes increasingly optimistic as technology advancements and regulatory support drive further market expansion. By midcentury, LNG is expected to be a dominant marine fuel in California, with widespread adoption across the harbor craft fleet. Continued investments in LNG infrastructure and vessel technology are anticipated to enhance the efficiency and competitiveness of LNG as a marine fuel. Moreover, regulatory mandates that aim to reduce greenhouse gas emissions from marine vessels are likely to further incentivize the use of LNG. With supportive policy frameworks and growing public awareness of environmental issues, LNG emerges as a key enabler of California's transition to a low-carbon maritime sector. It will contribute to the state's efforts to combat climate change and promote environmental stewardship.

5 – 2.10 METHANOL PROJECTION FOR 2030, 2040, AND 2050

Methanol production relies on various feedstocks, including natural gas, coal, forest residue, and renewable sources, such as black liquor and renewable natural gas. California's diverse resource base positions it favorably for methanol production, with abundant supplies of natural gas and biomass residues. Methanol is widely accessible, abundant, and entirely renewable. Methanol is easily obtained anywhere in the world, and more than 70 million tons are generated annually. Natural gas is the primary feedstock used in the manufacturing of methanol, which may be adapted with carbon capture technology. But as it may be made from a range of renewable feedstocks or as an electro-fuel, methanol might be entirely renewable. Because of this, it is the perfect fuel for a sustainable future when all transportation is done using renewable resources.

Additionally, advancements in methanol synthesis technology, such as electrochemical and BTL processes, offer promising pathways for sustainable methanol production. However, it is essential to consider the environmental and social impacts associated with different feedstock sources. This includes the need for robust infrastructure to support methanol production and distribution for marine fuel applications.

Table 53: Overall Viability of Methanol as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**5**	**5**	**4**
Cost Competitiveness	**4**	**4**	**5**
Feedstock Availability	**5**	**5**	**5**
Technological Readiness	**5**	**5**	**5**
Compatibility with Current Systems	**5**	**5**	**5**
Bunkering Capability	**4**	**4**	**5**
GHG Emissions	**4**	**5**	**5**
Safety	**4**	**4**	**5**
Environmental Risks (Spill)	**4**	**5**	**5**
Current Applicability	**5**	**5**	**5**
Overall Viability	**5**	**5**	**5**

From 2030, the projection for methanol as a marine fuel suggests high growth in production and adoption. This is driven by regulatory mandates and market incentives that aim to reduce emissions from marine vessels. Pilot projects and demonstration initiatives that utilize methanol as a marine fuel are expected to highlight the feasibility and environmental benefits of methanol. Moreover, collaborations between energy companies, technology developers, and marine fuel suppliers may help address supply chain challenges and ensure a reliable source of methanol for California's harbor craft fleet.

From 2040 until 2050, the projection for methanol becomes more promising as technology advancements and regulatory support drive further market expansion. By midcentury, methanol is anticipated to be a significant marine fuel in California, with increasing adoption across the harbor craft fleet. Continued investments in methanol production capacity and infrastructure are expected to enhance the availability and competitiveness of methanol as a marine fuel. With supportive policy frameworks and growing public awareness of environmental issues, methanol emerges as a key enabler of California's transition to a low-carbon maritime sector. It will contribute to the state's efforts to combat climate change and promote environmental protection.

5 – 2.11 HYDROGEN PROJECTION FOR 2030, 2040, AND 2050

Hydrogen production pathways include steam methane reforming (SMR) using fossil fuels or natural gas, electrolysis using water and renewable electricity, and biomass gasification. California's abundance of natural gas reserves and renewable energy resources position it as a potential hub for hydrogen production. However, the choice of feedstock and production method has significant implications for the environmental footprint and sustainability of hydrogen as a marine fuel. While SMR provides a cost-effective pathway for hydrogen production, electrolysis using renewable electricity offers a carbon-neutral alternative. It aligns with California's commitment to renewable energy and decarbonization. Moreover, collaborations between energy companies, technology developers, and marine fuel suppliers may help accelerate the transition to hydrogen as a marine fuel. It is supported by government policies, grants, and incentives that aim to promote renewable energy adoption. The transition of the shipping sector to a net-zero emissions path by 2050 requires total emissions to remain stable until 2025, and then begin to decline in 2030.

Table 54: Overall Viability of Hydrogen as a Marine Fuel in California

Parameters	2030	2040	2050
Storage	**4**	**4**	**4**
Cost Competitiveness	**3**	**4**	**5**
Feedstock Availability	**5**	**5**	**5**
Technological Readiness	**5**	**5**	**5**
Compatibility with Current Systems	**4**	**5**	**5**
Bunkering Capability	**4**	**4**	**5**
GHG Emissions	**4**	**5**	**5**
Safety	**4**	**4**	**5**
Environmental Risks (Spill)	**4**	**5**	**5**
Current Applicability	**5**	**5**	**5**
Overall Viability	**4**	**5**	**5**

By the year 2030, the projection for hydrogen as a marine fuel suggests cautious optimism. It is driven by early-stage investments in electrolysis technology and pilot projects that indicate the feasibility and environmental benefits of hydrogen. Pilot-scale hydrogen production facilities that utilize electrolysis and renewable electricity are expected to come online. Additionally, hydrogen refueling stations shall be common for different transportation modes with the support of government grants and incentives that aim to promote renewable energy adoption for decarbonization strategies. However, challenges related to infrastructure development and cost competitiveness may limit the widespread adoption of hydrogen in the near term. Nonetheless, hydrogen is expected to be accepted by the marine fuel market by 2030. It will offer emissions reductions and contribute to the state's broader sustainability objectives by the California Energy Commission (CEC).

Future project from 2040 to 2050, the hydrogen economy would be increasingly optimistic as technology advancements and regulatory support drive further market expansion. By midcentury, hydrogen is anticipated to be a significant marine fuel in California, with increasing adoption across the harbor craft fleet. Hydrogen storage equipment shall be able to supply fuel cells in harbor crafts. Continued investments in hydrogen production capacity and infrastructure are expected to enhance the availability and competitiveness of hydrogen as a marine fuel. Moreover, regulatory mandates that aim to reduce GHG emissions from marine vessels and promote renewable energy adoption are likely to further incentivize the use of hydrogen. With supportive policy frameworks and growing awareness of safety and environmental issues, hydrogen emerges as a key fuel of California's transition to a low-carbon maritime sector. The introduction of infrastructure for alternative fuels will be a priority from 2040 to 2050. This will enable the use of non-toxic alternative fuels in the maritime sector and will require new fuel delivery infrastructure, like bunkering.

5 – 3. CONCLUSIONS, RECOMMENDATIONS, AND KEY TAKEAWAYS

1. The production of these alternative fuels and power options in California is projected to see moderate growth. It is driven by increasing investments fueled by growing demand for low-carbon transportation fuels and supportive state policies and regulatory frameworks, such as the LCFS.
2. Continued investment in research, innovation, collaboration between industry stakeholders, policymakers, regulatory agencies, and technology providers will be essential. It is necessary in order to overcome challenges related to safety, infrastructure, and feedstock availability and market incentives for renewable fuel adoption.

3. The diverse feedstock options to produce sustainable transportation fuels are favorable to the market dynamics such that other industrial sectors and local economies would be empowered for regional growth.

4. By 2030, biocrude, biodiesel, bio-oil, FT-diesel, pyrolysis oil, renewable diesel, and SVO are expected to continue their growth trajectory. Additionally, they are expected to become significant contributors to California's efforts to decarbonize the maritime sector and reduce GHG emissions.

5. By 2040, LNG infrastructure is anticipated to expand further. Increased bunkering capabilities and supply chain resilience will drive broader adoption among shipowners and operators. However, uncertainties surrounding future regulations and market dynamics could impact LNG's long-term viability beyond 2050.

6. By 2030, ammonia and methanol production and their bunkering infrastructure are projected to mature. Increased supply chain efficiencies and expanded distribution networks facilitate broader adoption across the maritime sector. As renewable ammonia and methanol production becomes more prevalent and their production costs decline, both fuels could become leading renewable fuel options by 2050.

7. As renewable hydrogen production becomes more widespread and economies of scale improve, hydrogen is poised to emerge as one of the zero-emission marine fuels by 2050. It will offer significant emissions reduction benefits and contribute to California's transition toward a carbon-neutral economy.

8. The International Maritime Organization's (IMO) initial GHG strategy aims to reduce the CI of international shipping by at least 40% by 2030 and 70% by 2050, compared to 2008 levels. In the short term, biofuels will dominate by 2030 due to their current usability and lower costs. They will provide an immediate solution for harbor craft fleet, with methanol being suitable for ferries, crew, and pilot vessels due to their lower energy requirements. By 2040, many biofuels will no longer suffice in meeting emission reduction targets. However, biocrude will remain viable due to its significant emission reductions. By 2050, ammonia and hydrogen are expected to become the primary fuels, as they produce no CO_2 upon combustion. This represents the optimal path for the industry to achieve net-zero emissions. See Table 55 for a summary of the overall viability for the 11 alternative fuels options. See Figure 2 for their projection analysis with respect to the IMO GHG Strategy.

Table 55: Overall Viability for Alternative Fuels Options and their Projection Analysis

Summary of Alternative Fuels` Overall Viability	**2030**	**2040**	**2050**
Biocrude	**3**	**4**	**5**
Biodiesel	**3**	**4**	**5**
Bio-Oil	**3**	**3**	**4**
FT-Diesel	**4**	**4**	**5**
Pyrolysis Oil	**3**	**4**	**4**
Renewable Diesel	**4**	**5**	**5**
SVO	**4**	**5**	**5**
Ammonia	**4**	**5**	**5**
LNG	**4**	**4**	**5**
Methanol	**5**	**5**	**5**
Hydrogen	**4**	**5**	**5**

Considering the functional roles, duty cycles, distances, and power demands of various vessel types in California, these studies have explored their specific characteristics and the implications for fuel choices, technologies, and port infrastructure needs.

Offshore tugs are primarily engaged in towing large vessels, assisting with offshore drilling rigs, and handling other heavy-duty marine operations. These tugs often operate in deep waters far from shore, requiring robust fuel storage solutions due to the long distances traveled. Their high-power demands necessitate fuels with high energy density and reliability. Liquefied Natural Gas (LNG) and renewable diesel are strong candidates for these vessels. They provide the needed power while reducing emissions compared to traditional marine diesel. Ammonia and hydrogen could also be considered in the future, especially if onboard storage technologies improve, given their potential for zero-carbon emissions.

Harbor tugs that operate within ports and harbor areas could assist with docking and maneuvering ships into berths. They have shorter, more frequent duty cycles with significant idling periods, which makes them suitable for alternative fuels that can handle start-stop operations efficiently. Biodiesel and hydrogen fuel cells are ideal due to their lower emissions, which is critical in populated port areas. Electric propulsion, potentially powered by hydrogen fuel cells or battery-electric systems, could further reduce emissions and improve air quality in harbors.

Articulated tugs, which operate as part of tug-barge combinations, provide flexibility and efficiency for cargo transportation over varying distances. Their mixed operational profile, which combines both short-haul and long-haul trips, requires versatile fuel options. LNG and methanol are suitable choices. They offer lower emissions while being adaptable to different operational needs. The ability to transition between fuels like renewable diesel and bio-oil can provide additional flexibility and sustainability.

Ferry vessels are designed for regular, short-distance travel, typically between fixed points. They have predictable duty cycles and frequent stops, which aligns well with the use of electric propulsion systems. Hydrogen fuel cells and batteries are particularly effective, as they offer zero-emission solutions suitable for urban and coastal routes. The implementation of these technologies can significantly reduce the environmental footprint of ferry operations, which makes them cleaner and more sustainable.

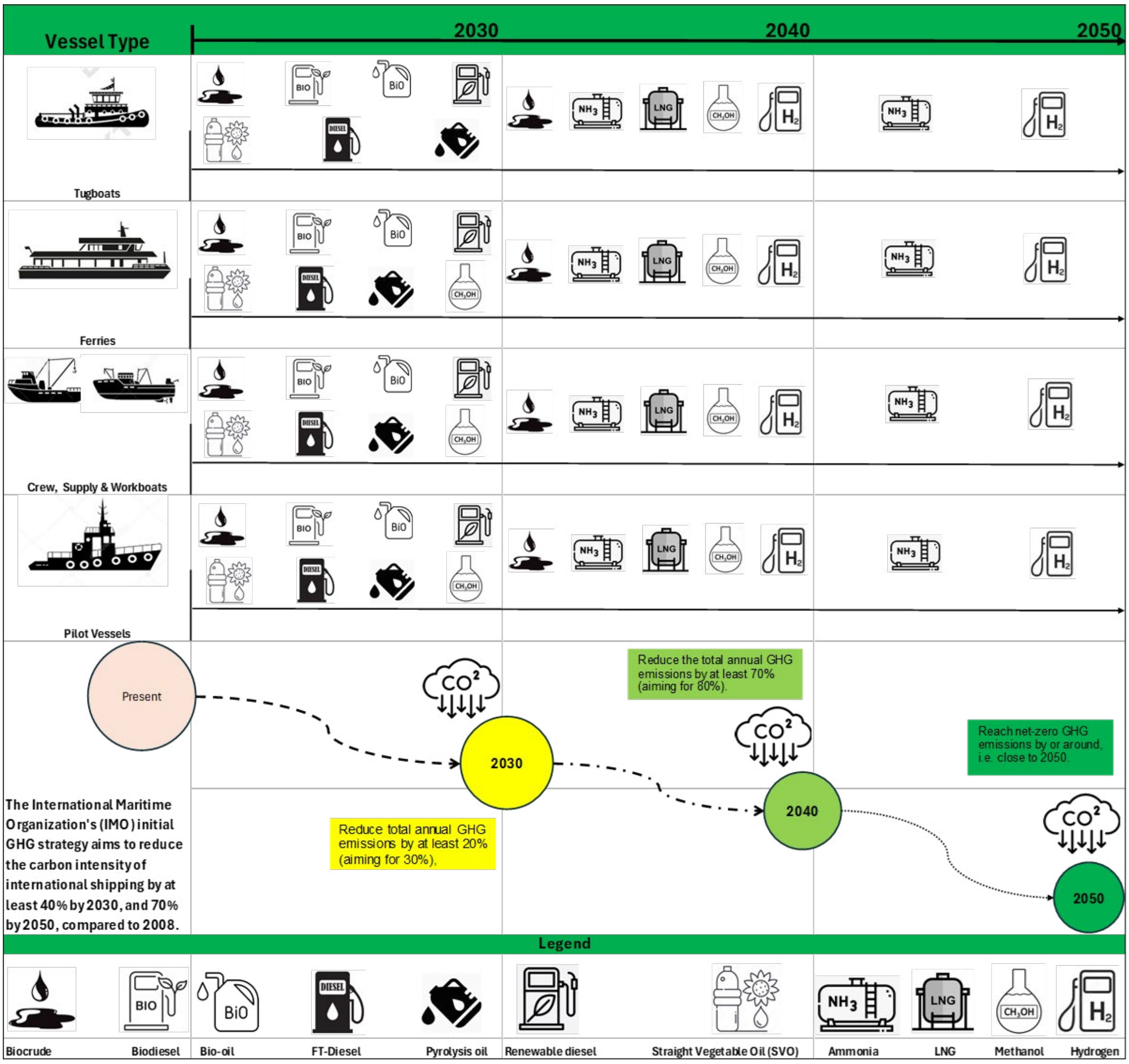
Crew supply vessels transport personnel and equipment to and from offshore platforms, operating over short to medium distances. They have moderate power demands and regular duty cycles, making them suitable for biodiesel, renewable diesel, and potentially hydrogen. The use of these fuels can enhance the sustainability of offshore operations while ensuring reliable performance and meeting regulatory requirements for emissions reductions.

Workboats and pilot vessels, although fewer in number, are essential for various support roles, including maintenance, inspection, and navigation assistance. These vessels have diverse operational profiles, often working in coastal and harbor areas with moderate power demands. Their flexibility allows for the use of a wide range of alternative fuels, including LNG, biodiesel, methanol, and hydrogen. The choice of fuel can be tailored to their specific operational needs and the availability of fueling infrastructure within ports.

In terms of port infrastructure and fueling needs, the transition to alternative fuels requires significant investment in port infrastructure to support bunkering and refueling. LNG bunkering facilities need to be expanded to accommodate the growing use of LNG in various vessel types. Similarly, ports must develop hydrogen fueling stations and electric charging infrastructure to support hydrogen fuel cells and battery-electric vessels. Biodiesel and renewable diesel supply chains should also be enhanced to ensure reliable availability.

Adopting these alternative fuels and technologies involves overcoming several challenges, including cost competitiveness, safety considerations, and regulatory compliance. Additionally, regulatory frameworks must evolve to support the safe and efficient use of these fuels, ensuring alignment with global standards and promoting the decarbonization of maritime operations.

Therefore, the diverse fleet in California presents numerous opportunities for adopting alternative fuels and technologies, tailored to the specific needs of different vessel types. A coordinated effort involving port authorities, vessel operators, and regulatory bodies is essential. This will facilitate this transition and achieve significant reductions in emissions that contribute to a more sustainable and efficient maritime industry as indicated in the IMO GHG Strategy presented in Figure 2 of this chapter.



Reduce total annual GHG emissions by at least 20% (aiming for 30%).

Reduce the total annual GHG emissions by at least 70% (aiming for 80%).

Reach net-zero GHG emissions by or around, i.e. close to 2050.

The International Maritime Organization's (IMO) initial GHG strategy aims to reduce the carbon intensity of international shipping by at least 40% by 2030, and 70% by 2050, compared to 2008.

Workstream 6:

PROJECTION OF THE SUITABILITY OF POWER OPTIONS

6 PROJECTION OF THE SUITABILITY OF POWER OPTIONS

6 – 1. SUMMARY

This report highlights the findings of a feasibility study on future power options for Commercial Harbor Craft (CHC) operating in California. The types of harbor craft studied include tug/tow boats, ferries, crew and supply boats, workboats, and pilot vessels. Barges, dredges, excursion boats, research vessels, fishing boats, coast guard/military, and oceangoing vessels are not part of this study. The study evaluates the future availability and implementation of alternative power options from 2030 through 2050. Due to the lightweight and short-range travel of CHC, they are a prime candidate for electrification as a means of reducing emissions. Hence, the focus of this study is on alternative electrical power options for CHC propulsion and auxiliary loads with the necessary supporting infrastructure such as shoreside and offshore charging facilities. The power options considered in this study are batteries, shore power, advanced nuclear, wind, solar, fuel cells, and supercapacitors. The suitability of hybrid and all-electrical power systems are also considered.

The study presents the projected timeline of availability for the specific power options being considered. These power options were evaluated by integration readiness and economic viability. One key finding indicates that only a few of the power options will be widely implemented in CHC by 2030, while most will be integration-ready by 2040. All the power options being considered are expected to be widely implemented by 2050. The study further seeks to explore which alternative power options are best suited for specific types of CHC based on operating profile and vessel design characteristics.

6 – 2. INTRODUCTION

Harbor craft play an important role in port operations, the economy, and air quality. Harbor craft include a wide variety of vessels, but for the purposes of this study, we will only be considering tug/tow boats, ferries, crew and supply boats, workboats, and pilot vessels. These vessels may do a variety of jobs in and near a single port or region. Jobs include assisting in maneuvering oceangoing vessels (OGVs) around the harbor and transporting crew and supplies to offshore facilities. Jobs also include moving cargo and people into and out of the port harbor area and providing fuel to OGVs [81].

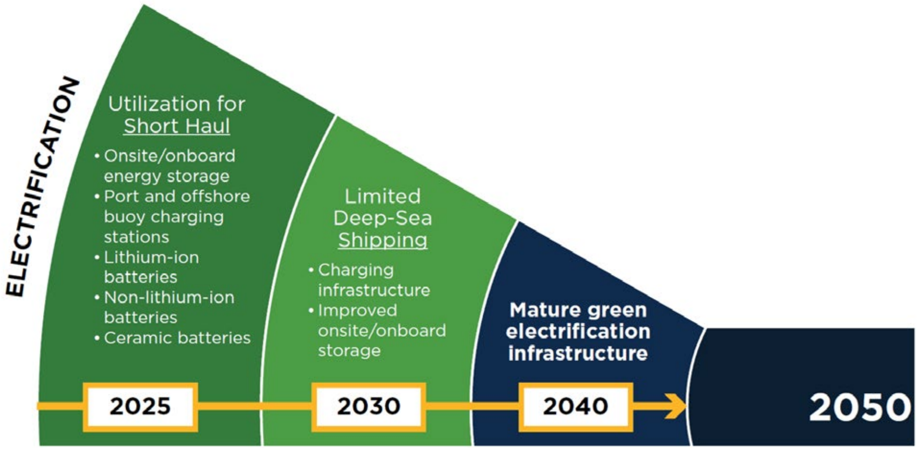
To address emissions from CHC, the California Air Resources Board (CARB) has instituted the Commercial Harbor Craft Regulations (CHCR). Efforts toward emissions reduction in CHC have focused on low engine emission technologies, diesel electric propulsion, and more recently, hybrid electric power systems. Technical solutions to improve energy efficiency and decarbonize shipping are trending toward marine electrification. Electric propulsion enables operators to optimize power production under varying load profiles. It also simplifies integration of energy storage systems and alternative power sources [82].

In regard to marine electrification, a dissertation from the Middle East Technical University titled “Evaluating Maritime Intelligent Transportation Systems” by Pense (2022) states that battery-powered, fully electric vehicles are more suitable for short-range operation on smaller vessels. This is due to limitations with battery capacities required to sustain safe navigation and operations. Increased use of shore power is also being considered as a viable power option for the future. As a result, the electric infrastructure at major ports will require significant overhaul to sustain the new demand. The use of renewable and sustainable energy sources will play a critical role in the decarbonization of the marine industry [83].

In addition to shore power, the feasibility of offshore power options is considered in this study as part of the electrification ecosystem for CHC, particularly offshore supply vessels. All-electric and hybrid offshore supply vessels will require charging infrastructure offshore, as returning to ports for charging may not be practical. Power options being considered for supplying offshore charging stations include offshore wind farms and floating nuclear power plants.

Figure 37 illustrates a summary of marine electrification trends from the perspective of American Bureau of Shipping (ABS). Through the short term, ABS anticipates growth in onboard energy storage installations and development of marine battery energy storage technologies. Alternatives to lithium-ion batteries are in different stages of research and may show promise for battery systems to become more practical and widespread in future maritime applications [5].

Figure 37: ABS – Marine Electrification Trends [4]



A larger installation base of battery energy storage systems onboard marine vessels drives the need for more charging infrastructure at ports and offshore. Offshore charging stations will need reliable supplies of sustainable energy. The 2023 ABS Sustainability Outlook discusses a diverse future ecosystem of power options for marine vessels. These include CHC, which will include alternative forms of energy such as offshore wind, floating nuclear power plants, and fuel cells. [84] During the medium term (2031 – 2040), we anticipate even more technological advancements, a wider installation base, and regulation for marine battery energy storage systems. ABS anticipates that during the long term (2040 – 2050), the marine industry will have mature green electrification infrastructure to further support marine and offshore decarbonization.

6 – 3. POWER OPTION IMPLEMENTATION

6 – 3.1 BATTERIES

Extensive research efforts in energy storage solutions have contributed to the implementation of battery storage technology in marine applications. Several promising battery technologies are being researched, including:

- Lithium-ion batteries
- Sodium-ion batteries
- Solid-state batteries
- Redox flow batteries

6 - 3.1.1 Marine Battery System Overview

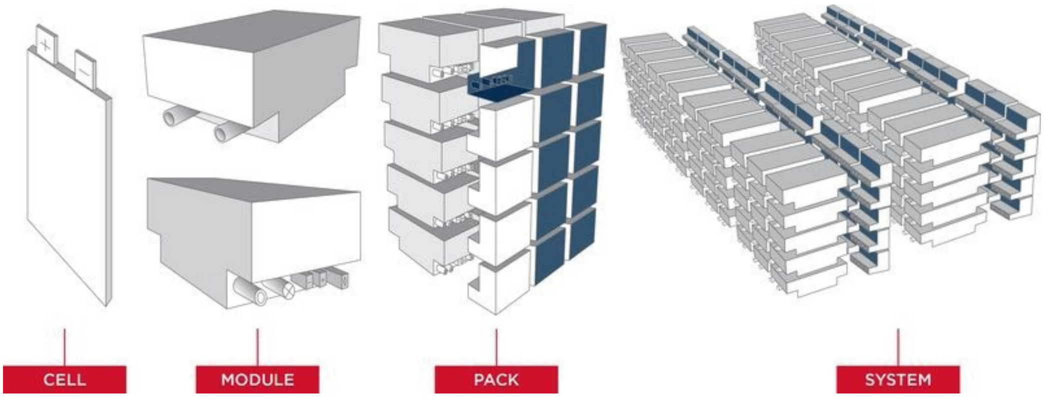
With the revolutionary evolution of electric motor designs, power electronics, and lithium-ion battery technology, all-electric propulsion will become a reality for short endurance CHCs. Unlike internal combustion engine (ICE) powered vessels, there is no consequence of vessel weight reduction during the operation of short endurance CHCs. Therefore, the design aspects of such CHCs may deviate from conventional marine vessel design. Consequently, it is always recommended to build a new vessel for battery operation instead of upgrading an existing vessel.

6 – 3.1.2 Battery Technology

Marine battery systems consist of groups of connected cells arranged in modules, and the modules are assembled into packs. The chemistry of a battery cell is a key differentiator of battery technology.

Figure 38 illustrates a typical battery system assembly. It consists of interconnected cells assembled into modules, and the modules assembled into packs. A marine battery system may consist of one or more battery packs.

Figure 38: Battery System Assembly [85]



6 – 3.1.3 Marine Battery System Risks

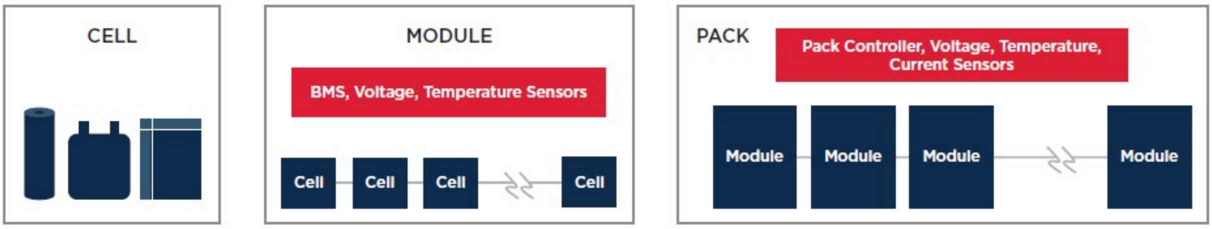
Lithium salts dissolved in organic solvents are highly flammable and contribute significantly to battery fires. For this reason, solid electrolytes are being explored. Solid electrolytes offer the dual benefit of avoiding flammable organic electrolytes and dendrite formation from lithium anodes. Dendrite formation can lead to short circuits within battery cells, posing a fire risk.

Besides thermal stability concerns, there are additional challenges with nickel manganese cobalt (NMC) lithium-ion batteries. Cobalt is needed to manufacture NMC batteries. It is a rare, expensive, element and there are ethical concerns with its supply chain. Excessive exposure to cobalt is harmful to humans.

Also, current lithium-ion batteries use flammable organic electrolytes, and NMC is vulnerable to thermal runaway. Marine battery packs are fitted with comprehensive fire extinguishing systems and continuous cooling, which increases the installation footprint of the battery system. These design requirements cause marine battery packs to have lower energy density than their automotive counterparts.

Figure 39 shows the components of a battery system, including the battery management system (BMS), which measures cell voltage, current, and temperature. The BMS has a vital protective function to isolate battery cells or modules that are showing signs of abnormal conditions. Abnormal conditions can lead to adverse consequences, such as thermal runaway.

Figure 39: Battery System Components [85]



6 – 3.1.4 Battery Research

Some of the research being conducted in the development of battery technology involves anodes. The critical factors for finding a suitable anode include high electrical potential, power capability, electrical and ionic conductivity, and safety. Due to its high electrochemical potential and high specific capacity, there is much interest in lithium as an anode. However, lithium anodes form dendrites during cycling of the battery. These dendrites are sharp protrusions that can easily pierce the separator in the battery, shorting out the battery and leading to thermal runaway. The most promising solution for using a lithium metal anode is to use a solid electrolyte with enough strength to resist dendrite penetration [86] [87].

For this reason, extensive research is being conducted on solid-state batteries. The widespread deployment of solid-state lithium batteries will almost certainly be the next significant advancement in energy storage. This is expected within 5 years. A second generation of solid-state batteries offering closer to their theoretical performance will be available within 10 years. A solid-state electrolyte prevents the risk of dendrites shorting the battery and facilitates the use of a lithium metal anode. Such a battery would have the highest specific energy of a conventional anode such as graphite. Solid-state batteries could offer up to 75% better specific energy than the best lithium-ion batteries today. In addition, solid-state batteries mitigate fire risks considerably. Marine battery packs might triple in specific energy overall within 10 years with similar increases in achievable range [88].

Due to concerns about lithium-ion battery stability and limited availability, there is ongoing research to explore the suitability of sodium-ion batteries for energy storage. Sodium is widely available, and sodium-ion batteries have an electrochemistry that resembles that of lithium-ion batteries [89]. Sodium-ion battery technology offers tremendous potential to be a counterpart to lithium-ion batteries. However, despite the similarities in electrochemistry between sodium-ion and lithium-ion batteries, there are remarkable differences in the physicochemical properties between sodium and lithium that give rise to different behaviors. This demands a more detailed study of the underlying physical and chemical processes occurring in sodium-ion batteries. It also allows great opportunity for groundbreaking advances in the field [90].

6 – 3.1.4.1 Research Specific to Marine Batteries

Due to the unique fire safety risks associated with marine battery installations, ABS and various organizations are conducting ongoing research to provide guidance to the marine industry concerning the following:

- The fire risks associated with specific current and emerging battery technologies for marine applications, considering various states of charge, normal operation, and thermal runaway conditions
- The type and volume of off-gases generated, and the toxicity and flammability of such gases
- Gas detection best practices for the types of gases various battery chemistries generate
- Recommended fire suppression technologies for various battery technologies

Other areas of ongoing research to address challenges with marine battery system installations include:

- Spacing and insulation best practices to prevent thermal runaway propagation, considering cell geometry, and insulation
- Battery degradation with calendar life

6 – 3.1.5 ABS Requirements for Lithium-Ion Batteries

ABS has published the updated *2024 Requirements for the Use of Lithium-ion Batteries in the Marine and Offshore Industries*. The 2024 edition includes new requirements for:

- Lithium-ion battery system components
- Ventilation
- Environmental control
- Gas detection
- Main and emergency sources of power
- Battery spaces
- Fire safety
- Hazardous areas
- Risk assessment approach

ABS has classed several vessels, including tugboats with lithium-ion batteries, as part of the hybrid power system for the vessel. In 2021, ABS published a white paper titled “Emerging Battery Technologies in the Maritime Industry”[29][5], which discusses the principle of operation of lithium-ion batteries, the safety risks, the environmental impact, and the cost benefits. The paper also highlights promising emerging battery technologies such as redox flow, metal-air, ammonia, and solid-state batteries [29][5].

6 – 3.1.6 Lithium-Ion Battery Cost

Lithium-ion battery costs have continued to decrease over the last decade. Forecasts indicate they will continue decreasing through 2035 [91]. The price of raw materials for manufacturing lithium-ion batteries is dropping and fading as a barrier to entry. However, this is not the case with shoreside infrastructure and power electronics needed for battery charging. Shoreside infrastructure and connection are likely to be the dominant cost driver on future projects.

6 – 3.1.7 Battery Technology Timeline

Table 57 shows the availability timeline for the major battery technologies being researched and developed for current and future marine applications. Many advancements have been made in current lithium-ion battery chemistries of the NMC type and the lithium ferrous phosphate (LFP) type. Several developments are expected over the next 10 to 15 years resulting from ongoing research in solid-state and metal-air battery chemistries. Lithium-air batteries with solid-state electrolytes for marine applications are estimated to be commercially available in 15 to 20 years.

Table 57: Availability and Timeline for Battery Technologies [88]

Battery Technology	Availability Timeline	Benefits
Lithium-Ion Cell (NMC)	Current	Highest specific energy of currently available batteries (86 W-h/kg)
Lithium-Ion Cell (LFP)	Current	Safer than NMC; less prone to thermal runaway
Lithium-Ion Cell NMC 811 – “High Nickel”	5 years	Improved safety with higher specific energy
Lithium Metal Cell: Solid -State NMC	10 years	Prevents dendrite formation, avoiding short circuits and fires
Lithium-Air Cell	15 – 20 years	Much higher specific energy with lithium anode

6 – 3.2 SHORE POWER

Shore power infrastructure can help limit emissions by allowing CHC to operate on shore power instead of running auxiliary generators while in port. Shore power consists of two main types [92]:

- Onshore power supply (OPS)
- Shoreside battery charging (SBC)

Shore power systems are categorized as either:

- High-voltage systems: These tend to be for OGVs.
- Low-voltage systems: Typically, less than 1,000 volts AC for providing power to CHC. It is best practice for CHC shore connections to adhere to the international standard for low-voltage shore connections, ISO 80005-3.

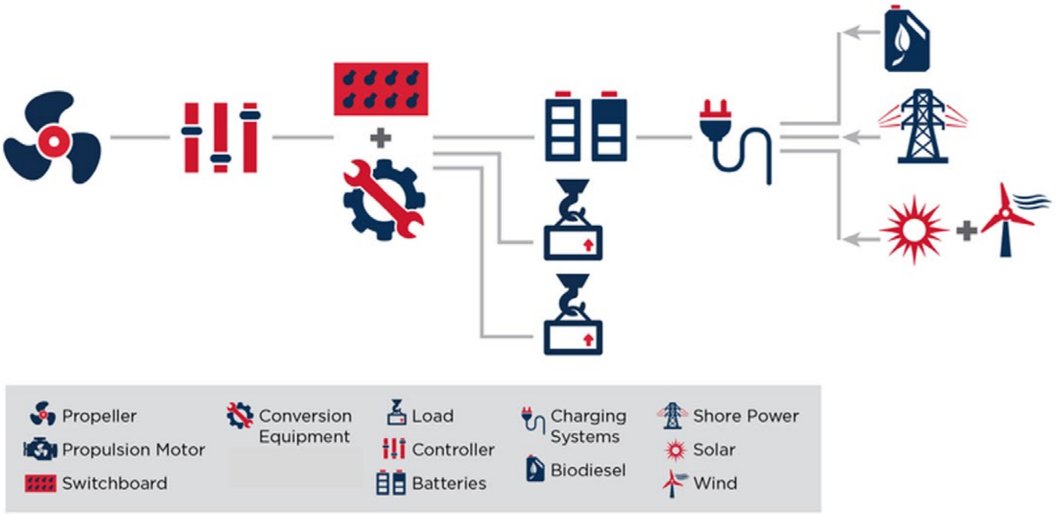
Table 58: Shore Power Voltage Ranges and ABS Notations

	HVSC	**LVSC**
ABS Notation	HVSC & HVSC-Ready	LVSC
Voltage Range	1 kV – 15 kV AC	Up to 1,000V AC and 1500V DC

6 - 3.2.1 The Future of Shore Power

Figure 40 shows a concept of shore power infrastructure of the future. Electrical energy will be supplied by a combination of alternative fuels and renewables, such as solar and wind. CHC will be primarily hybrid or all electric with installed battery systems for energy storage. The electrical energy provided by shore power connections will be used to power light vessel loads while in port or to charge battery systems.

Figure 40: Shore Power Infrastructure of the Future



6 - 3.2.2 Technological Developments in Shore Power

Electricity generation from distributed sustainable energy sources will be a suitable option to have economic and sustainable energy for marine vessels while in port near harbor areas. Sustainable energy sources include solar, wind, geothermal, tidal, nuclear, and wave energy sources. The rapid advancement of research and development in battery storage, power electronics, and information technology can help support concepts for harbor area microgrids comprising renewable energy sources. Toward that end, the School of Technology and Innovations at the University of Vaasa Finland has researched advanced communications and power electronics to help develop shore-to-ship power supplies [93].

6 – 3.2.3 Shore-to-Ship Charging

Transferring electrical power from a shore power source to a marine vessel to charge battery energy storage systems is known as shore-to-ship charging. This can be done by contact charging, wireless charging, or battery swapping.

6 – 3.2.3.1 Contact Charging

This is the most common way of establishing an electrical connection between a marine vessel and a shore power supply. On low-voltage systems, contact charging can be initiated by manually connecting a plug. On high-voltage systems, due to safety considerations, a mechanical arm can be used to automatically connect the plug. The biggest challenge with contact charging is maintaining stability of the vessel while afloat to limit the effect of wave motion that could disrupt the electrical connection [94].

6 – 3.2.3.2 Wireless Charging

This charging method involves the transfer of electrical energy using inductive coils such that the physical connection to the shore power source is not needed. Inductive wireless charging is less prone to mechanical wear and corrosion and eliminates the safety risk posed by exposed contacts. In addition, wireless charging can reduce the time it takes to establish a shore power connection, allowing more time for charging batteries [94]. Wartsila has developed an inductive wireless charging system that can transfer up to 2 megawatts of power with an air gap of 150 to 500 millimeters between the charging transmitter on the shore connection and the receiver on the vessel [95].

6 – 3.2.3.3 Wireless Power Transfer

Wireless Power Transfer (WPT) in an underwater scenario is another developing area of research. One idea under consideration is underwater wireless power stations for self-charging autonomous underwater vehicles. This groundbreaking research can open opportunities to explore underwater WPT for CHC in California. Potential drawbacks to be addressed include current disturbance, biofouling, hydrostatic pressure, seawater conductivity, and attenuation [96].

6 – 3.2.3.4 Battery Swapping

Battery swapping operations involve swapping out discharged batteries on vessels with freshly charged ones. Since this can be done quickly, ferries and other CHC that operate on strict, short schedules are prime candidates [94].

6 – 3.2.4 Shore Power Requirements

6 – 3.2.4.1 CARB CHC Regulation

The 2022 amendment to Title 17, section 93118.5 of the CARB CHC Regulation prohibits idling of main engines and auxiliary engines with a power rating of 99 kilowatts or less for more than 15 minutes, with some exceptions. From January 1, 2024, the revised CHC Regulation requires vessel owners and operators to install, maintain, and operate vessel-side equipment necessary to integrate with shore power connections. That is, if shore power is selected as a compliance method to have auxiliary power while at dock. If vessel owners or operators require harbor craft to use shore power up to 99 kilowatts, the facility owners/operators must provide available access to power and accessible connection points [97].

6 – 3.2.4.2 CARB At-Berth Regulation

CARB also introduced the 2020 At-Berth Regulation to reduce air pollution from OGVs. This regulation is currently in place at six California ports. Beginning in 2023, it will extend to additional California ports and vessel types through 2027 [98]. Some of the lessons learned from expansion of shore power driven by the At-Berth Regulation may benefit efforts toward the electrification of CHC.

6 – 3.2.4.3 EU's Fit for 55 Legislation

The European Union's EU's Fit for 55 legislation mandates a minimum reduction of 55% in GHG emissions per year by 2030 [98]. The targets and timelines for key maritime and inland ports situated along the trans-European network (TEN-T) is outlined as shown in Table 59. This legislation may drive technology readiness and availability of shore power for vessel types across the marine industry, including California CHC.

Table 59: EU's Fit for 55 – Targets & Timeline [99]

	2025	2030	2035	2040	2045	2050
Maritime GHG Reduction	2%	6%	15%	31%	62%	80%

6 – 3.2.4.4 ABS Requirements

ABS published requirements for high-voltage shore connections in 2011. These requirements, in addition to the requirements for low-voltage shore connections, are published in the *ABS 2024 Rules for Building and Classing Marine Vessels*. Because the management of cable systems for shore power connections is critical to safety, ABS is currently working on an update to the cable management system requirements associated with high-voltage and low-voltage shore connections.

6 – 3.2.5 Shore Power Cost

Retrofitting vessels with shoreside electricity systems bears a significant cost. Jingjing Yu et al. claim the average payback time for retrofitting vessels calling on the Dalian Port in China will be 4 years. Additionally, the environmental benefit of using shoreside electricity can be up to 128 million USD [100]. The cost of shore power infrastructure can significantly impact implementation decisions. This is because such capital investments will have to be economically viable to gain acceptance.

6 – 3.2.6 Notable Projects

The technological developments, policy frameworks, and lessons learned from the projects listed below can be applied to the electrification of California CHC for emissions reduction.

6 – 3.2.6.1 Port and Vessel Owner Collaboration

In Europe, the Interreg Maritime Environmentally Friendly Transport System (METRO) project seeks to promote using electrical propulsion and energy storage systems onboard ships that operate in the North Adriatic Sea. This is coupled with well-designed charging infrastructure at the ports [101]. Regarding California CHC, similar collaboration between ports and owners can help pave the way for hybridization of existing CHC and construction of new all-electric and hybrid CHC. It could also help pave the way for charging infrastructure at ports to support electrified CHC. Ports and vessel owners working in tandem to develop shoreside charging infrastructure and vessels equipped for charging may deliver more promising results for CHC electrification than parties working individually.

6 – 3.2.6.2 Charging Infrastructure Development

ABS, in collaboration with CharIN (a company that promotes charging standards for charging systems), is currently supporting the Maritime Administration (MARAD) and Crowley with the development of a Megawatt Charging System (MCS) capable of providing power above 1,000 volts DC to enable high-power, megawatt-level charging of large CHC.

6 – 3.2.7 Barriers to Shore Power Implementation

Barriers to the expansion of shore power that California's ports are likely to face include the following:

- Investment needed for shore power infrastructure development
- Modifications to vessels for retrofitting with shore power connections
- Upgrades to electric grid infrastructure due to increased demand
- Cost and complexity of automated cable management systems for improved safety
- Lack of charging standards in relation to:
    - Electrical connections
    - Cable management systems
    - Communication protocols

The increased electrical load demand posed by onshore power supplies, shoreside charging infrastructure, and port electrification can significantly increase the peak demand on the California grid. Such sudden and large increases in load demand can make generation dispatch and power system planning very challenging for utilities. One approach to addressing this challenge is to install more sustainable generation capacity to support the grid during times of peak demand. However, it is worth noting that some renewable energy sources are intermittent and contribute to power system instability. Alternative solutions that can be considered include the following:

- Distributed power generation using sustainable sources and energy storage systems installed near California's ports to relieve the additional stress on the grid.
- Offshore generating plants and energy storage systems to supply power to offshore charging stations; generating plants will likely include floating nuclear power plants and offshore wind farms.

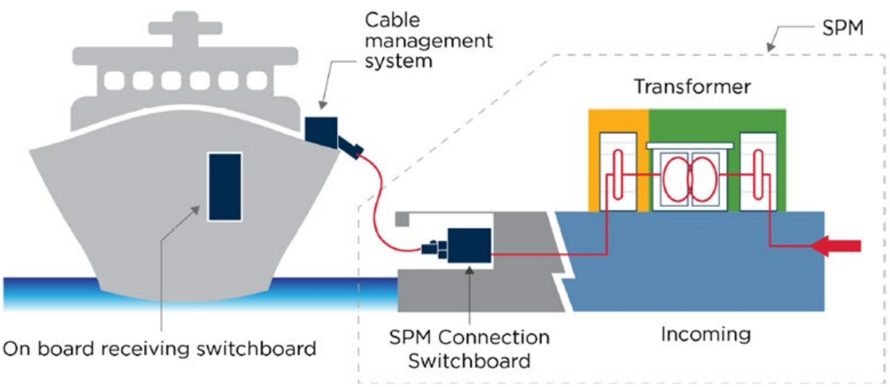
6 – 3.2.8 Offshore Charging Stations

With the onset of offshore wind farms and the potential for floating nuclear power plants, some companies are building mooring buoys to operate as offshore charging stations. The 2024 publication of the *ABS Rules for Building and Classing Single Point Moorings* includes requirements for offshore charging connections and offshore charging stations.

Another approach is to use marine vessels or offshore units with power plants installed onboard, primarily for supplying power to consumers or having the power grid serve other assets. These power generating units are called power service vessels. ABS published the *2022 Requirements for Power Service for Marine and Offshore Applications*, which addresses requirements for power service vessels. These include power service barges, power service ships, power service offshore installations, and power service mobile offshore units. Power service vessels can be used to charge batteries on CHC without docking at a port.

Timeline projections for the availability of offshore power that can be used for battery charging are discussed in section 6 - 3.5.1 of this report.

Figure 41: Marine Vessel Being Charged from a Charging Buoy



6 – 3.3 FUEL CELLS

Fuel cell systems are an attractive solution for onboard ship power generation. These cells have the potential for being more efficient and cleaner than conventional ICEs and gas turbines. Moreover, fuel cells can be fully integrated into an all-electric ship concept.

Figure 42: Fuel Cell Use for Battery Charging

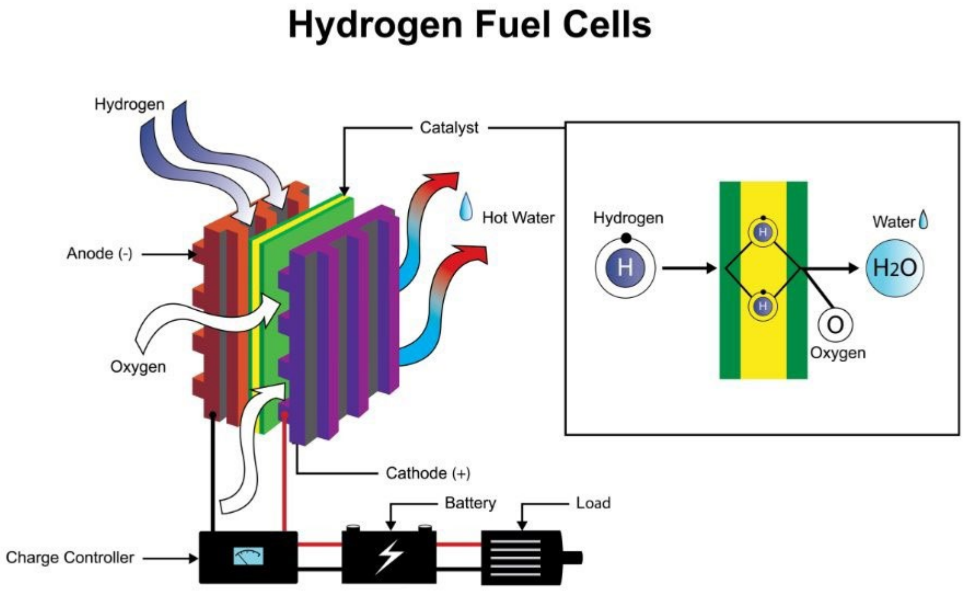


Table 60: Fuel Cell Types and Characteristics

Type	Mobile Ion	Operating Temp.
Proton Exchange Membrane (PEM)	H^+	30 –120°C
Alkaline Fuel Cell (AFC)	OH^-	100 – 250°C
Phosphoric Acid Fuel Cell (PAFC)	H^+	150 – 220°C
Molten Carbonate Fuel Cell (MCFC)	$CO32^+$	600 – 700°C
Solid Oxide Fuel Cell (SOFC)	$O2^-$	650 – 1,000°C

6 – 3.3.1 Commercial Harbor Craft Candidates for Fuel Cells

6 – 3.3.1.1 Ferries

Ferries make great candidates for fuel cell power due to their short haul, quick turnaround operating characteristics. For successful implementation in ferries, fuel cell-powered drive trains need to meet the following requirements [102]:

- Economic operation
- Reliability
- Simplicity
- Flexibility
- System availability
- Power density

6 – 3.3.1.2 Leisure Craft

For leisure craft, fuel cell systems need to have a very high-power density with sustained periods of no use, while supporting safe operation [102].

6 – 3.3.1.3 River Vessels

Fuel cells are gaining traction for electricity production for longer runs on inland rivers. Parker (2023) of BDP1 Consulting Ltd. said, “In the next 15 years and beyond, we expect the emerging investments being made today in hydrogen fuel technology to substantially transform the marine fuel landscape.” [103] For the near term, methanol and ammonia are being used as hydrogen carriers to explore electricity generation from hydrogen fuel cells on river vessels.

6 – 3.3.2 Projects with Marine Fuel Cell Systems

6 – 3.3.2.1 ABB

- Marine fuel cell power solutions for high and low voltage and AC and DC power systems [104]

6 – 3.3.2.2 All American Marine, Inc.

- All American Marine, Inc’s (AAM) delivery of the first-ever commercial hydrogen fuel cell zero-emissions passenger ferry in the world. Switch Maritime owns the vessel named Sea Change and will operate in the California Bay area [105].

The integration of fuel cells with battery energy storage systems (BESS) is a promising arrangement that allows marine battery systems to be charged while vessels are at sea. Several marine research projects that incorporate integration of fuel cells with BESS are currently being implemented with timelines as shown in Table 61.

Table 61: Overview of Research Projects of Maritime SOFC Applications [106]

Project	Year	Fuel Type	Fuel Cell Type	Ship Type	Capacity of Demonstrator (kW)
Nautilus	2020 – 2024	LNG	SOFC	Cruise	60
ShipFC	2020 – 2025	Ammonia	SOFC	Offshore	2,000
FuelSOME	2022 – 2026	Ammonia, MeOH, H2	SOFC	Cruise	500
HELENUS	2022 – 2027	LNG	SOFC	Cruise	500

Barriers to the commercialization of fuel cells in CHC are not only cost related, they include [107]:

- Long startup time
- Low power density
- High cost of catalysts
- Thermal control
- High cost of reformers and membranes
- Low efficiency of the oxygen electrode
- Periodic replacement of cells
- Complexity
- Challenging fuel processing requirements
- Need to replace cells periodically

These barriers could delay the widespread use of fuel cells as a major source of power on CHC.

6 – 3.3.3 ABS Requirements for Fuel Cells

ABS published the *Requirements for Fuel Cell Power Systems for Marine and Offshore Applications* in 2023. An update will be made to these requirements in 2024. ABS is currently participating in a new technology qualification project that consists of an inverter module and an integrated ammonia reactor system for a fuel cell application.

6 – 3.4 SOLAR PHOTOVOLTAIC

Solar power for marine vessels is emerging as a power option due to the advantages of noise reduction, clean energy generation, and low cost of solar panels.

Solar photovoltaic (PV) electricity generation is known to be intermittent due to the inconsistency of solar irradiation. During cloudy periods, the output of PV panels can drop significantly, and they do not produce power at night. This intermittency affects power system stability, which is critical for marine vessels.

6 – 3.4.1 Environmental Factors

The most important distinction between the mainland and marine PV applications is the environmental conditions. These conditions force PV systems to be more tolerant to extreme winds, high humidity, and salt. [108] Some of the most recent PV panels developed and available in the marine market are those made using mono-crystalline cells with polymers of high strength. PV solar panels made from mono-crystalline cells are specified to withstand harsh marine environments. [85]

Wind speed and direction are two factors that affect the orientation of solar panels installed on a marine vessel. The marine environment can also be harmful for both the electronics and the panels of a PV system. The high levels of humidity and salt can cause short circuits and induce corrosion to the mechanical parts of the converters. Consideration should be given to higher ingress protection ratings for the wide-scale installation of solar panels on marine vessels to ensure adequate levels of protection against environmental conditions [108].

There are many additional considerations that could impact the implementation of solar panels on marine vessels of the future. PV panel metallic frames must be specially constructed due to the corrosive nature of the marine environment. Space provisions for their installation should be made such that the solar panels do not impede the cargo and human transfer. They should also not cover places with financial impact such as decks, storage halls, and tanks. Additionally, they should be kept out of reach to prevent electrical shocks and damage to PV panels and converters while allowing adequate access for maintenance [108].

6 – 3.4.2 Distributed Solar Power Generation

Aside from solar panels on vessels, ports are increasingly becoming involved in alternative energy as they look to use their facilities to contribute to reducing emissions. While much of the attention is on alternative fuels and wind energy, several projects are also looking to use solar power as a future power option for ports. The Port of Corpus Christi in Texas is launching a new partnership to use available land at the port to potentially become the location for a large solar farm. [109] The expansion of green infrastructure at ports helps to support CHC electrification, because CHC will need to charge their batteries while in port. Projects that take the dependencies between port infrastructure development and CHC electrification into consideration can help reduce emissions from California CHC.

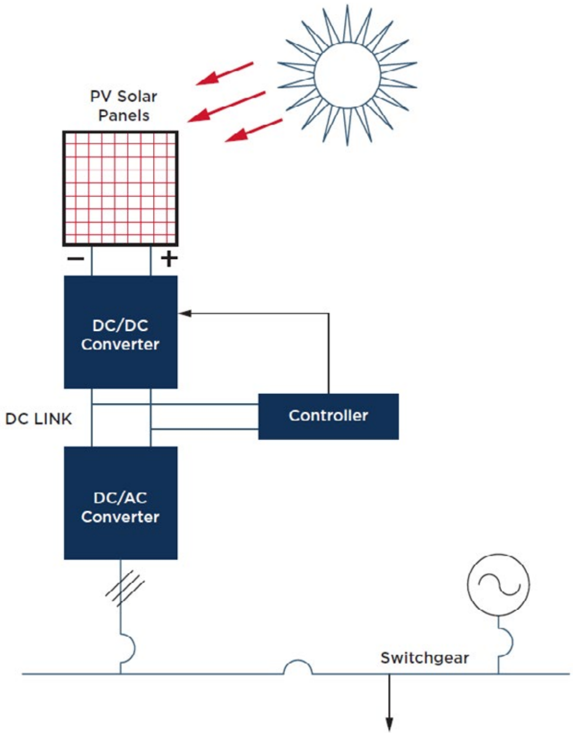
6 – 3.4.3 ABS Solar Power Requirements

ABS has published requirements for solar PV electric power generation systems in section 5 of the 2024 *Requirements for Hybrid and All-Electric Power Systems for Marine and Offshore Applications* [85].

6 – 3.4.4 Drawbacks of Solar PV for CHC

Figure 43 below shows a marine PV solar arrangement where the solar panels are connected in parallel with other generating sources on the main bus. Solar PV panels produce a DC voltage when they receive solar irradiation. In an AC distribution system, the DC output of the solar panels needs to be inverted to AC using power electronic converters (PEC) to supply power to the main switchboard. One of the challenges posed by the introduction of PECs is generation of heat due to harmonic waveforms produced within the PEC.

Figure 43: Marine Solar PV Arrangement [85]



Another challenge with this type of arrangement is solar PV panels are not being able to maintain the stability of the vessel's power system. This is primarily due to two reasons:

- There is an intermittency of solar irradiation resulting in fluctuating voltage output of the solar panels.
- PECs have been traditionally programmed to trip off the main bus in the event of a disturbance instead of attempting to ride through the disturbance and maintain power to vessel.

For these reasons, solar PV is not a suitable energy source to establish the voltage and frequency of the main bus. Solar PV always needs to be accompanied by a more stable power source that will establish the bus voltage and frequency and maintain the stability of the power system through disturbances. More stable power sources include a battery system or an AC generator.

6 – 3.5 WIND POWER

As wind power technology continues to advance and scale, CHCs are well positioned to harness this renewable energy resource by using electricity generated from wind turbines to charge onboard energy storage systems. Offshore wind farms can supply power to offshore charging stations with minimal transmission losses due to shorter transmission cable runs. Onshore wind farms can supply power for shoreside battery charging via distribution through the California power grid or a microgrid near a port.

6 – 3.5.1 Floating Offshore Wind

Nearly 40 gigawatts of offshore wind capacity are expected throughout the United States by 2040, totaling a $100 billion investment. California is one of the key states for floating wind farms [110]. The electricity that offshore wind farms generate can be distributed to offshore charging stations to charge battery systems on crew boats and supply boats. Offshore charging infrastructure can include single point moorings, mobile offshore units, offshore substations, or power service vessels.

California has set ambitious goals of installing up to 5 gigawatts of offshore wind by 2030 and 25 gigawatts by 2045. Three key enablers that will contribute to achieving this goal include [111]:

- Economies of scale to reduce costs
- Procurement at scale in the purchase of energy from these large floating wind installations
- Development of California's port infrastructure and a multi-port strategy plan to support offshore wind assembly, construction, and maintenance

The rapid expansion of offshore wind changes the energy landscape in ways that can impact the timeline and implementation of offshore wind. Some of these impacts include:

- Increasing demand for wind farm support vessels
- Cost reductions through larger turbines
- More floating wind energy projects
- Infrastructure development
- Complexity of installations
- Operating costs
- Training
- Environmental and regulatory challenges

6 – 3.5.2 Alternative Arrangements for Floating Wind Power

Due to space limitations, installing wind turbines on CHC is not a realistic path to electrification. An alternative arrangement for consideration is to install wind turbines above the deck of nearby power service vessels. For example, with a tug and barge configuration, a wind turbine may be installed on the barge, and the tug can connect to the barge to recharge its energy storage system. [112] This arrangement would represent another type of floating wind power infrastructure that can be harnessed to support electrification of CHC.

6 – 3.5.3 ABS Requirements for Wind Power

ABS has developed requirements for wind electric power generation systems. These requirements can be found in section 6 of the 2024 publication of the *Requirements for Hybrid and All-Electric Power Systems for Marine and Offshore Applications*.

6 – 3.6 NUCLEAR POWER

In recent years, there has been significant research conducted on nuclear energy. In 2021, the U.S. Department of Energy funded a total of $8.5 million to five projects to advance promising nuclear technologies. As a recipient of one of these projects, ABS is focusing on addressing the hurdles in the maritime domain. This is so that new reactor technology can be rapidly deployed for commercial applications. Advanced nuclear technology is well positioned to be one of the strongest tools available to help the industry achieve its aggressive decarbonization goals [113].

6 – 3.6.1 Advanced Nuclear Reactors

- Advanced reactors have design improvements from conventional reactors and are expected to reduce economic, security, technical, safety, and regulatory barriers. Advanced reactors may have inherent safety features, lower waste yields, superior reliability, and resistance to proliferation. They may also have increased thermal efficiency and integration with electric and non-electric applications. There are several types of advanced nuclear reactors. They include:
- Small modular light water reactors (LWR)
- Sodium fast reactors (SFR)
- Lead fast reactors (LFR)
- Fluoride high-temperature reactors (FHR)
- Molten salt reactors (MSR)
- High temp gas-cooled reactors (HTGR)
- Heat pipe reactors

MSRs are seen as promising advanced reactor technology because they operate at higher temperatures, which leads to increased efficiency in generating electricity. In addition, low operating pressures can reduce the risk of pressure release and a resulting loss of coolant event in the case of an accident. This enhances the safety of the reactor. MSRs also generate less high-level waste, and their design does not require solid fuel, which eliminates the need to build and dispose of it [114].

6 – 3.6.2 Barriers to Advanced Nuclear Implementation

Barriers to implementation of advanced nuclear were identified in a 2023 report published by the Nuclear Energy Institute (NEI), "Advanced Reactor Roadmap – Phase 1: North America." These barriers can hinder the pace of widespread adoption of advanced nuclear power. Some highlighted barriers include regulatory complexity regarding licensing and frameworks for security arrangements, certified crew and operators, and advanced technology demonstration and testing. Also included are the current low availability of advanced fuels and supply chains. These challenges can be addressed systematically by working closely with regulators, designers, and the wider nuclear industry to develop infrastructure capabilities. After the first movers can showcase success, efficiency in regulations, design, and costs can be achieved by knowledge sharing best practices and increasing the rate of learning. [115] These were general comments made in the report regarding the overall nuclear industry, regardless of specific application. However, these comments hold true for the marine industry, as floating nuclear power plants are anticipated to be a viable power option in the next decade.

6 – 3.6.3 Acceptance Criteria for Advanced Nuclear

For advanced nuclear to achieve integration readiness by the mid-2030s, the NEI [115] suggests that certain attributes must exist, including the following:

- Public acceptance and support for advanced reactors is to be available locally and regionally.
- Multiple approved and licensed designs exist to meet market demand and variable use cases.
- The timeline from technology development to deployment is to be no longer than 3 years.
- Developers have deployment scales of tens of reactors per year, with a commissioning period of less than one year to operation.
- Projects can deliver technology solutions, construction, and operational facilities on schedule and on budget with coordination from industry vendors, suppliers, and contractors.
- Advanced reactor technology is market competitive for capital and operational expenses, with decreases over time due to learning rates, operational experience, and engineering improvements.
- Nuclear energy is included in government energy and climate policies, along with other low or zero-carbon energy solutions.
- Advanced technologies can showcase safe operations and successful demonstration to meet industry goals.

Based on these criteria, if land-based implementation of advanced nuclear reactors gains widespread acceptance by the mid-2030s, implementation on marine vessels and offshore units will soon follow. With these projections, it is possible that advanced nuclear can achieve a mature integration readiness level and favorable economic viability by the early 2040s.

6 – 3.6.4 Examples of Floating Nuclear Power Plants

There is a growing trend in floating small modular reactor (SMR) offerings, a category of advanced nuclear reactors that have a power capacity of up to 300 megawatts electric per unit. These reactors harness nuclear fission to generate heat to produce energy and are a fraction of the size of a conventional reactor. They offer potential benefits of factory construction, transport, or even export as a marine plant for plug-and-play access to reliable electricity and heat supplies [116].

Canada's Prodigy Clean Energy and the United States' NuScale are collaborating on the design of a transportable sea-based advanced reactor that can generate safe, affordable, and reliable electricity at grid-scale at any coastal location worldwide [117]. The idea is to design transportable nuclear power plants comprising NuScale's small nuclear reactor modules packed into Prodigy's prefabricated and relocatable power plant structures. They would be standardized to deploy nuclear power safely and securely in various environments [118].

The ThorCon Company is developing liquid fission power plants. It is currently working on a scale-up of the United States Oak Ridge National Laboratory Molten Salt Reactor Experiment (MSRE). The technology is expected to generate electricity cheaper than coal. ThorCon has proposed a project to the Indonesia government to build a 3.5 gigawatt fission power project. The estimated timeframe for the project from design to production of multiple units at a shipyard is 8 years [119].

Ulstein has launched "Ulstein Thor," a concept vessel that will feature a Thorium MSR to generate vast amounts of clean, safe electricity. This enables the vessel to operate as a mobile power/charging station for a new breed of battery-driven cruise ships [120]. This concept may be applied to other types of vessels, such as harbor craft, that can be powered or charged from nearby power service vessels fitted with MSR power plants.

Crowley Marine has teamed with nuclear power leader BWX Technologies Incorporated through a memorandum of understanding for a ship concept that has the potential to generate alternative, zero-carbon emission energy for defense and disaster needs by including a microreactor on board. This new vessel concept uses traditional propulsion while carrying a

5 to 50 megawatt modular reactor that can be activated upon arrival at a destination. It can then be deactivated and transported after the power supply is discontinued. Buoyed power delivery cables will enable the ships to deploy energy connections to shore. Shallow draft hulls allow these power service vessels to maneuver to strategically deliver power for military activities or disaster-stricken port communities without the need for port infrastructure [121]. The use of similar concepts can be applied to supply power for charging batteries on California CHC.

6 – 3.7 SUPERCAPACITORS

Supercapacitors, as a commercialized energy storage device, exhibit beneficial characteristics. These characteristics include high-power density, a fast-charging/discharging process, no thermal runaway characteristics, and a wide operating-temperature range [122].

However, supercapacitors have lower energy density compared to lithium-ion batteries and may not be suitable for long duration loads. They are effective at providing power during transient increases in load demand, but not for sustained power dissipation. Hence, supercapacitors complement BESS well in a marine hybrid configuration. In these, the batteries provide the sustained power needed, while the supercapacitors provide momentary bursts of power and fast recharge.

ABS requirements for supercapacitor applications can be found in the 2022 publication of *The Use of Supercapacitors in the Marine and Offshore Industries*. Fuel cell applications are to meet the basic safety principles, such as having sufficient power generation (storage) capacity, adequate standby and emergency power sources, continuity of supply if there is a fault, and general electrical safety.

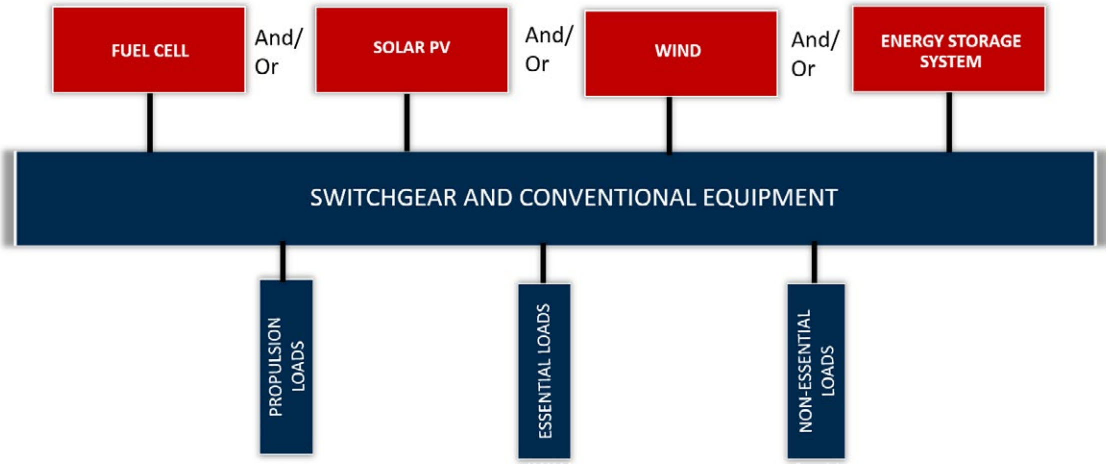
6 – 3.8 ALL-ELECTRIC POWER SYSTEMS

The 2024 ABS *Requirements for Hybrid and All-Electric Systems for Marine and Offshore Applications* defines an all-electric power system as utilizing only non-conventional sources of power. Examples include batteries, fuel cells, supercapacitors, wind, solar, and nuclear as described in section 3 of this report. Vessels with such arrangements also incorporate specialized power management and energy management systems.

The suitability of a CHC for an all-electric power system depends on factors such as:

- Operational profile
- Travel distance
- Availability of charging infrastructure
- Vessel weight

Figure 44: Example of Marine All-Electric Power System [123]



6 – 3.8.1 All-Electric Tugs

Some CHC, such as harbor assist tugs, are prime candidates for all-electric power systems. This is because they are frequently waiting at a port where they could be charging between the times they assist OGVs into and out of the port. While most of the work of a harbor tug is light assistance, occasionally, harbor tugs perform heavy-assist duties. For an all-electric harbor tug, the battery system must be sized with sufficient power for heavy-assist loads when needed.

In addition, the battery system must be sized with sufficient energy to allow an all-electric tug to operate for extended durations if needed. Examples include assisting ships during emergencies, such as extreme weather events (e.g., hurricanes), groundings, and other navigational issues. In some instances, all-electric tugs may need multi-day power capabilities, even if such capabilities are only used periodically. Sizing the battery systems for extended operation can significantly impact the capital cost of all-electric tugs.

The first all-electric tug in the U.S. will soon begin operation in the Port of San Diego. A microgrid charging facility is currently under construction that will allow vessels to recharge quickly while reducing the peak demand on the California power grid [124].

6 – 3.8.2 All-Electric Ferries

Ferries make good candidates for all-electric propulsion because they travel shorter distances. They can also operate on smaller battery systems, which weigh less and are faster to recharge [125]. Two all-electric ferries, which have short travel distances, are lightweight, and have a fast recharge time, are currently providing touring services for Niagara Falls. Each trip consumes a lot less energy than the installed capacity, and the battery systems are recharged with locally generated hydropower.

6 – 3.8.3 Barriers to All-Electric CHC

One of the main drawbacks to implementing all-electric power systems on smaller CHC is cost. Currently, all-electric tugs cost twice as much as their diesel-mechanical counterparts. All-electric ferries cost about 50% more than their diesel-mechanical counterparts.

Besides the capital cost of building all-electric CHC, charging infrastructure costs will impact wide-scale electrification. Some CHC types, such as ferries, may require fast charging due to their quick turnaround times. Fast-charging battery systems will require higher levels of power distribution services at California's ports, putting additional stress on the power grid. This necessitates electrical infrastructure upgrades at the generation, transmission, and distribution levels, which will drive up costs and extend the timeframe for projects.

Fast charging can also pose the risk of performance degradation to batteries and reduction of cycle life.

Another barrier is the lack of available space for the installation of redundant battery systems. For such vessels, alternative mitigation arrangements need to be in place to address the risk of failure of the battery system. Failure risks include thermal runaway leading to off-gas release, fire, and/or explosion. In addition, if the battery system needs to be isolated from the electrical system for safety reasons, the vessel will lose power for propulsion, steering, and other essential services. In such cases, mitigation arrangements may include support from other vessels in the operational area assigned to provide assistance.

6 – 3.9 HYBRID ELECTRIC POWER SYSTEMS

The 2024 ABS *Requirements for Hybrid and All-Electric Systems for Marine and Offshore Applications* defines a hybrid electric power system as utilizing multiple sources of power, both non-conventional and conventional sources.

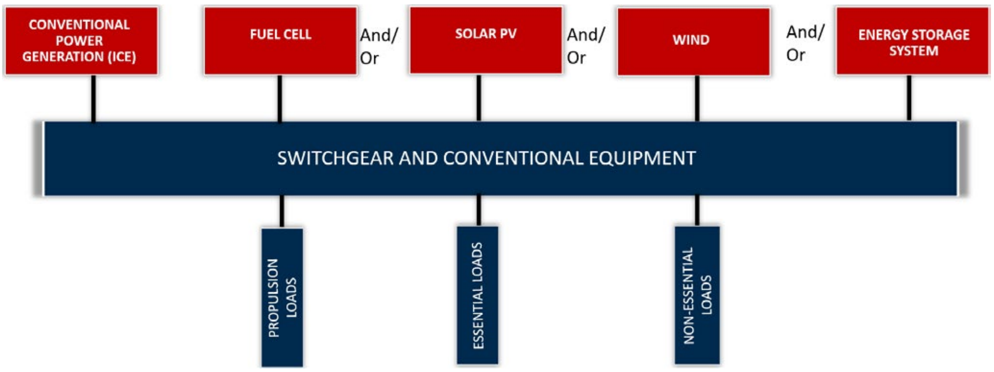
Examples of non-conventional sources include:

- Batteries
- Supercapacitors
- Fuel cells

Examples of conventional sources include:

- Internal combustion engine-driven generator sets
- Shaft generator driven by a main engine

Figure 45: Example of Marine Hybrid Electric Power System [85]



6 – 3.9.1 Hybrid Electric Power System Applications

Hybrid-powered vessels are more effective for longer runs due to limited range between charges. Most hybrid arrangements primarily consist of batteries and diesel engines. In the future, fuel cells may replace diesel engines. Like diesel engines, fuel cells are sluggish to respond to load changes, and have poor efficiency when operated away from the optimum operating point. Existing hybrid ferries, workboats, tugs, and offshore vessels have consistently demonstrated 15 – 30% fuel savings over comparable diesel boats [88].

6 – 3.9.2 Hybrid Electrical Power System Requirements

ABS issued several publications related to hybrid marine vessels in the past. The updated *Requirements for Hybrid Electric Power Systems* was published in 2024 and includes requirements for all-electric vessels. Articles and papers published about hybrid electric power systems include the *ABS Advisory on Hybrid Electric Power Systems* and *Practical Considerations for Hybrid Electric Power Systems Onboard Vessels*. ABS also offers simulation services to assist clients in the optimization of hybrid electric power systems, which enable decarbonization by reducing fuel consumption.

6 – 3.9.3 Projects with Hybrid Electrical Power Systems

ABS's involvement with hybrid vessels includes the classing of 67 vessels with the ESS-LiBattery Notation, and the classing of 18 vessels with the HYBRID-IEPS notation. These vessels include CHC, such as tugboats, platform service vessels (PSV), and offshore supply vessels (OSV).

6 – 3.9.3.1 Hybrid PSV

The first hybrid vessel classed by ABS was the 5,312-dwt Harvey Energy LNG/Diesel Electric PSV integrated with a lithium-ion battery system. The hybrid solution included the battery energy storage system and power electronics optimized to work together through an energy management system. The outcome of this initiative was over 20% fuel savings and major reductions in carbon emissions [126].

Figure 46: Harvey Energy – First ABS-Classed Hybrid Vessel [126]

6 – 3.9.3.2 Hybrid OSV

ABS also classed Seacor's first OSV with hybrid power integration, as discussed in the case study presented in Workstream 4 of this report.

6 – 3.9.3.3 Hybrid Ferries

Multiple ferry electrification projects that use battery energy storage are planned for the short, medium, and long term, particularly in the U.S. and Europe. A few examples of such projects include the following:

- Red and White Fleet, which operates in the San Francisco Bay Area, plans to have a zero-emissions fleet by 2025 [127].

- The country of Norway wants two-thirds of the ferries that carry passengers and cars around its coasts to be electric by 2030.
- Swedish-based ferry operator Stena Line plans to operate the first large seagoing ferry to run solely on fossil-free power on the Gothenburg – Frederikshavn route by 2030. The Stena Elektra will be able to run totally on battery power for at least 50 nautical miles [128].
- The city of New York recently received funding to install shoreside rapid-charging infrastructure to support hybrid electric ferries. Construction is expected to begin in 2025 [129].

Washington State Ferries (WSF) has published a detailed near-term, medium-term, and long-term plan for vessel and port electrification through 2040. Table 62 shows the planned composition of the ferry fleet from 2023 through 2040. As conventional diesel-powered ferries are retired, new hybrid-capable vessels are being constructed. Additionally, some existing diesel-powered vessels are being converted to hybrid electric.

Table 62: Washington State DOT Planned Fleet Composition [130]

Planned Fleet Composition	2023	2030	2040
Plug-in Hybrid	4	12	22
Diesel	18	13	4
Total Fleet Size	22	25	26

With this newer green composition, WSF is poised to achieve the following significant fuel savings:

- 2018 fuel consumption – 19 million gallons
- 2040 fuel consumption – 9.5 million gallons

Not only does this have significant positive effects on the environment, but it also has tremendous cost savings [130].

With a total of 46 ferries in its fleet, the state of California can apply similar hybridization strategies. They can expect similar results by converting the ferry fleet to hybrid and building new ferries with hybrid power trains through 2040.

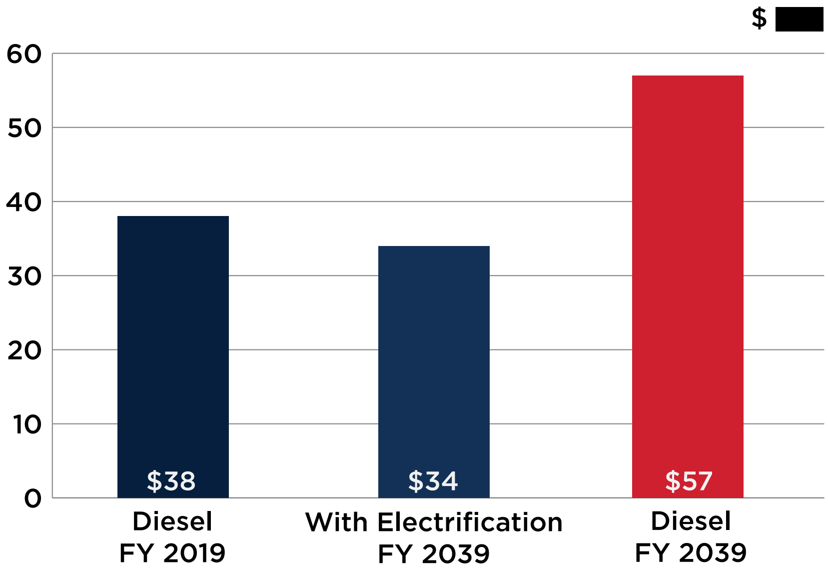
Table 63 summarizes the Washington State DOT's near-, medium-, and long-term plans for electrification of ferries and terminals. The plan proposes that most of the state's fleet will be hybrid electric vessels by 2040, with charging infrastructure available at various terminals.

Table 63: Washington State DOT Investment Plan [130]

Planning Category	**Near Term (2019 - 2021)**	**Medium Term (2022 - 2027)**	**Long Term (2028 - 2040)**
Capital Investment	$340M	$2.5B	$5.1B
Vessels	Construction of five new vessels	Construction of five new vessels	Delivery of 11 new vessels
	Existing vessel electric hybrid	Three existing vessels converted to electric hybrid	26 operational vessels by 2031
Terminals	Charging infrastructure at two terminals		Upgrades to support hybrid electric vessels
	Construction of two terminals complete	Second operational vessel slip	Tie up slip-to-slip conversion
Workforce	Preparation of workforce development plan	Workforce development plan complete	
	Training & outreach to attract and retain employees	More investment in training and outreach	
Service	One service relief vessel High service reliability risk	10 weeks out of service for maintenance per vessel	12 weeks out of service requirement met

It is anticipated that the capital investments will lead to long-term operational cost savings. As shown in Figure 47, the projected cost of fuel with electrification in 2039 will be lower than the cost of diesel in 2019. It will be significantly lower than diesel in 2039 without electrification.

Figure 47: Projected Energy Cost Savings [130]



Parallels can be drawn between the Washington State's ferry hybridization project and efforts to decarbonize California's ferries. Since ferries generally have similar duty cycles and power requirements, similar results may be expected. Lessons learned may be applicable to both states.

6 – 3.9.3.4 Hybrid Tugboats

Multiple hybrid tugboats are being constructed worldwide; this trend is expected to continue as a strategy for reducing CHC emissions. ABS has been involved in the classification of several of these tugs. In August 2023, Kirby Corporation christened the Green Diamond, which it described as the nation's first plug-in hybrid electric inland towing vessel. Modeling results indicate an anticipated 88 – 95% reduction in emissions while operating on shore power, and 27% reduction while operating in hybrid mode [103].

6 – 4. AVAILABILITY TIMELINE

In this study, economic viability and integration readiness are the two primary factors considered for estimating the alternative power option availability and implementation projections for various CHC.

6 – 4.1 ECONOMIC VIABILITY

Economic viability is evaluated primarily by comparing the payback time, levelized cost of electricity for generating sources, and levelized cost of storage for energy storage systems.

LEVELIZED COST OF ELECTRICITY [131]

- The Levelized Cost of Electricity (LCOE) represents the average revenue per unit of electricity generated required to recover the capital, operational, and maintenance costs of a generating asset over its lifetime.

LEVELIZED COST OF STORAGE [131]

- The Levelized Cost of Storage (LCOS) is a similar metric to LCOE; however, it is concerned with the electricity discharged since energy storage systems do not generate electricity.

Table 64 summarizes the LCOE and LCOS for some power options through the short term. Solar and onshore wind are shown to be the most cost-effective power options. Offshore wind will still be costly in 2030, but not as costly as battery storage.

Table 64: LCOE & LCOS for Power Options [131]

LCOE and LCOS for New Resources Entering Service (2021 $/MWh)			
	2024	**2027**	**2030**
Wind, Onshore	37.8	40.23	40.08
Wind, Offshore	-	136.51	98.01
Solar	36.07	36.49	33.42
Battery Storage	131.98	128.55	120.47

Other estimates indicate that LCOE for floating offshore wind will drop globally below $100 per megawatt-hours by 2025. It will drop even further to $40 per megawatt-hours or lower by 2050 [111].

6 – 4.2 INTEGRATION READINESS

Integration readiness level (IRL) is a more appropriate metric for evaluating power options in this study as opposed to technology readiness level (TRL). This is because IRL gives an indication of compatibility of the new technology with existing technologies. In addition, IRL is useful for assessing whether the new technology is ready to be integrated in a marine application. IRL levels 1 through 9 are defined in Appendix 1 of this report.

6 – 4.3 ASSESSMENT OF POWER OPTIONS THROUGH THE PERIOD

Table 65 summarizes the economic viability and IRL of the power options being considered for California CHC from 2030 through 2050. Lithium-ion batteries, solid-state batteries, fuel cells, and solar PV demonstrate the highest IRL in 2030.

Solar PV is the most economically viable power option in 2030. It is worth noting that while some power options demonstrate high IRL, high costs prohibit wide-scale implementation. Such is the case for lithium-ion batteries and fuel cells. The costs of these power options are expected to decrease with technological advancements over time.

Most power options will achieve integration readiness by 2040. All-electric vessel adoption rates may be impacted by challenges with charging infrastructure availability at ports and offshore. All-electric vessel scalability will depend largely on charging infrastructure readiness. In turn, charging infrastructure will only be economically viable with a significant population of all-electric vessels to use charging services at ports and offshore.

Table 65: Projected Viability and Integration Readiness of Power Options Through 2050

Power Option	Economic Viability			IRL		
	2030	2040	2050	2030	2040	2050
Li-Ion Batteries	2	4	5	5	5	5
Solid-State Batteries	2	4	5	4	5	5
Metal-Air Batteries	2	3	5	3	4	5
Redox Flow Batteries	2	3	5	3	5	5
OPS	3	5	5	3	5	5
Shoreside Battery Charging	2	3	5	3	5	5
Offshore Charging Stations	3	5	5	3	5	5
Supercapacitors	3	5	5	3	5	5
Fuel Cells	3	5	5	5	5	5
Advanced Nuclear	3	5	5	3	5	5
Offshore Wind	4	5	5	3	5	5
Solar – Off Vessel	5	5	5	5	5	5
Solar – Off Vessel	5	5	5	5	5	5
All-Electric Power Systems	2	4	5	4	5	5

Notes: The colors depicted in Table 65 are denoted as shown in the 1 through 5 scale described in Table 66 below.

Table 66: Five-Point Evaluation Scale for Power Options

Color Indicators					
Grade or Ranking	1	2	3	4	5
Meaning	Very Poor	Poor	Average	Good	Very Good

i. The mapping of each evaluation category to the 5-point scale is as defined below:

  a. (IRL source: IEC/TS 62600-4): IRL 1 and 2 is red, IRL 3 is light red, IRL 4 – 6 is yellow, IRL 7 is light green, and IRL 8 and 9 is green.

  b. Economic viability is based on LCOE and LCOS and the payback time of an alternative power option verses diesel power generation. One is much higher than diesel (red), 2 is slightly higher than diesel (light red), 3 is equal to diesel (yellow), 4 is slightly lower than diesel (light green), and 5 is much lower than diesel (green).

ii. The above-listed allocations for red, light red, yellow, light green, and green in this section of notes are for preliminary guidance. Additionally, the listed selection criteria is not an exhaustive list. The weightage of each of the factors may vary, and the final evaluation is based on a mix of qualitative and quantitative factors.

iii. Each power option is expected to improve in IRL with time.

iv. Each power option is expected to become more cost effective as technology scales with time.

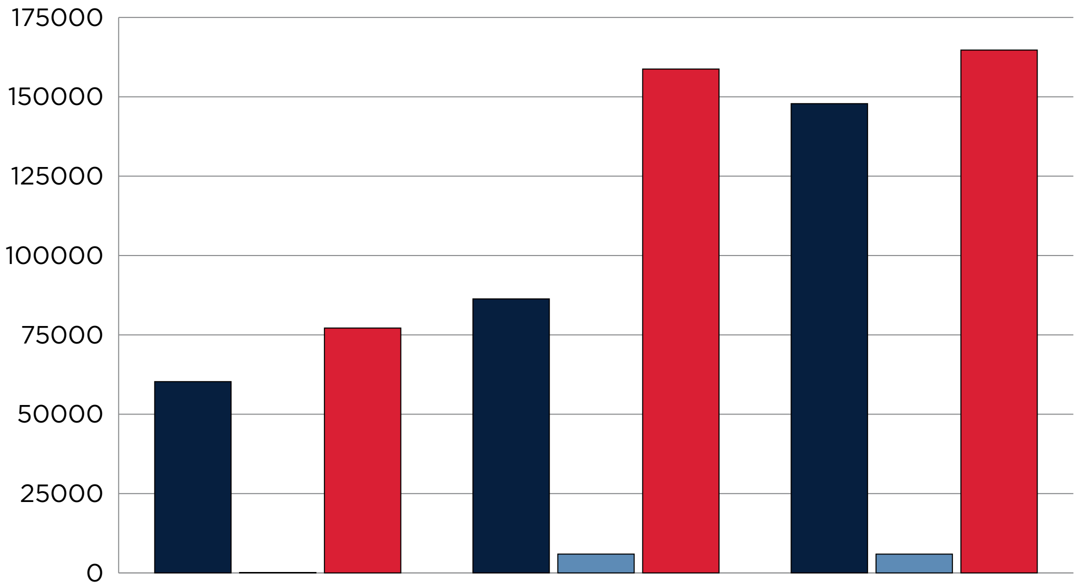
6 – 4.4 POWER OPTION PROJECTION BY VESSEL TYPE

The suitability of a power option for a specific CHC depends heavily on the design and operational profile of the vessel. Operational profiles of California CHC were described in detail in Workstream 2, section 4 of this report. These operational profiles were reviewed to make inferences about the best-suited power option projections for each CHC type.

6 – 4.4.1 Tugboats

Tugboats with California's CHC fleet are categorized as articulated tugs, harbor tugs, and offshore tugs. Figure 48 shows a graphic of the operational profile of these three tugboat types as discussed in Workstream 2, section 4 of this report. The hours indicated are the total operating hours of each type of tugboat in California's fleet during the year 2020.

Figure 48: Operating Profile of California Tugboats



	Articulated Tug	Harbor Tug	Offshore Tug
Cruising	60271	86336	147840
Maneuvering	118	5940	5930
At Anchor	77148	158742	164722

The graph indicates a similar pattern among articulated tugs, harbor tugs, and offshore tugs for the proportion of operating hours spent cruising, maneuvering and at anchor. For such operating profiles, where tugboats spend most of their operating time at minimal power and a small proportion of their time at peak power, suitable alternative power options for tugboats are suggested as follows:

Batteries

Batteries are great for supplying peak power almost instantaneously. Unlike diesel engines, batteries do not experience adverse consequences when light loaded. Therefore, they can provide power for tugboats during heavy- and light-load operations. Batteries will continue to be a viable power option for tugboats in hybrid and all-electric configurations.

Supercapacitors

Since supercapacitors are the most dense electrical energy storage devices, they can be used to meet pulse power demand during maneuvering operations. They thereby reduce the size of the battery system.

Supercapacitors are also beneficial to the battery system because the battery capacity will be reduced significantly if the battery discharge rate is increased to meet peak demand. In addition, the longevity of the battery system will be compromised if it is allowed to operate at high discharge rates.

Fuel Cells

Fuel cells are suitable for tugboats, but they may be limited in size due to lack of available space for storing energy sources, such as hydrogen, natural gas, ammonia, and methanol.

Shore Power

Shore power will continue to be a viable power option for tugs, both as onshore power supplies for auxiliary power, and shoreside battery charging to recharge the vessel's battery system.

Floating Nuclear Power Plants

In the medium term, floating nuclear power plants installed near ports may become a viable power option for charging batteries on tugboats.

6 – 4.4.2 Ferries

Ferries typically operate for short distances of 30-minute durations or less. They usually dock at regular locations and have quick turnaround times. Based on this operating profile, suitable alternative power options for ferries are suggested as follows:

Batteries

Hybrid ferries will continue to contribute to greenhouse gas (GHG) emissions. Due to the shorter ranges, lower power demand, and predictable schedules of ferries, all-electric ferries are a good candidate for CHC decarbonization.

Solar

Solar is a viable renewable energy source for ferries because of the low power demand and available space to install solar panels.

Fuel Cells

Fuel cells can make a great complement to battery systems on ferries by allowing batteries to be continually charged during operation. This arrangement can help increase the range of electric ferries, thereby reducing the number of stops for charging and charging time. In addition, smaller battery systems may be used, reducing the weight and required power demand for ferries.

Shore Power

As more hybrid and all-electric ferries come into service at California's ports, shore power connections will be needed for battery charging.

6 - 4.4.3 Pilot Boats

Pilot boats are used for escorting ships while navigating ports. During a typical operation, a pilot boat will transit to ship and escort the ship into a port. When the ship is ready to depart, the pilot boat will escort it out and then return to the port. Pilot boats typically operate for about 90 minutes at a time. Considering the operational profile of pilot boats, suitable alternative power options are suggested as follows:

Batteries

Battery systems will likely form a significant part of the power system of hybrid and all-electric pilot boats. Battery installations can be small and lightweight due to the low power demand of pilot boats.

Solar PV

Solar panels may be considered for pilot boats due to their low power demand. Solar panels can be used to charge the batteries while a pilot boat is not operating.

Shore Power

Since the batteries on pilot boats will need to be charged, shoreside charging infrastructure will become necessary to facilitate electrification of pilot boats.

6 - 4.4.4 Offshore Supply Vessels

The load profile of an OSV depicted in Table 67 was used by Geugan et al. [132] to study the optimization of ship design and operational life of OSVs. This load profile is assumed to be representative for an OSV operating out of a California port. It is noted that the vessel load demand is high most of the time, and only 20% of the vessel's operating time is spent at the harbor with minimal demand.

Table 67: Load Profile of an OSV [132]

Operating mode	Relative Time Spent (%)	Total Load (kW)
Harbor	20	300
Transit 11 kn	10	2,742
Transit 13 kn	10	3,300
Standby Calm Weather	20	2,021
Standby Harsh Weather	10	3,444
DP2 Calm Weather	20	2,521
DP2 Harsh Weather	10	3,944

Batteries

In the short term, battery systems will likely be part of the energy storage arrangement onboard hybrid OSVs. As battery technology advances and longer-range travel becomes achievable, all-electric OSV designs may be considered in the medium and long term.

Fuel Cells

Large fuel cell installations require available space for storing energy sources, such as natural gas, hydrogen, methanol, or ammonia. OSVs can be considered such applications.

Shore Power

Shore power is expected to remain a viable power option for OSVs, for auxiliary power while in port, and for charging the battery system while in port.

Offshore Charging Stations

Since OSVs operate offshore, offshore charging infrastructure may be used for charging battery systems on OSVs without having to return to a port. Wide-scale implementation of offshore charging infrastructure may become an enabler of OSV electrification.

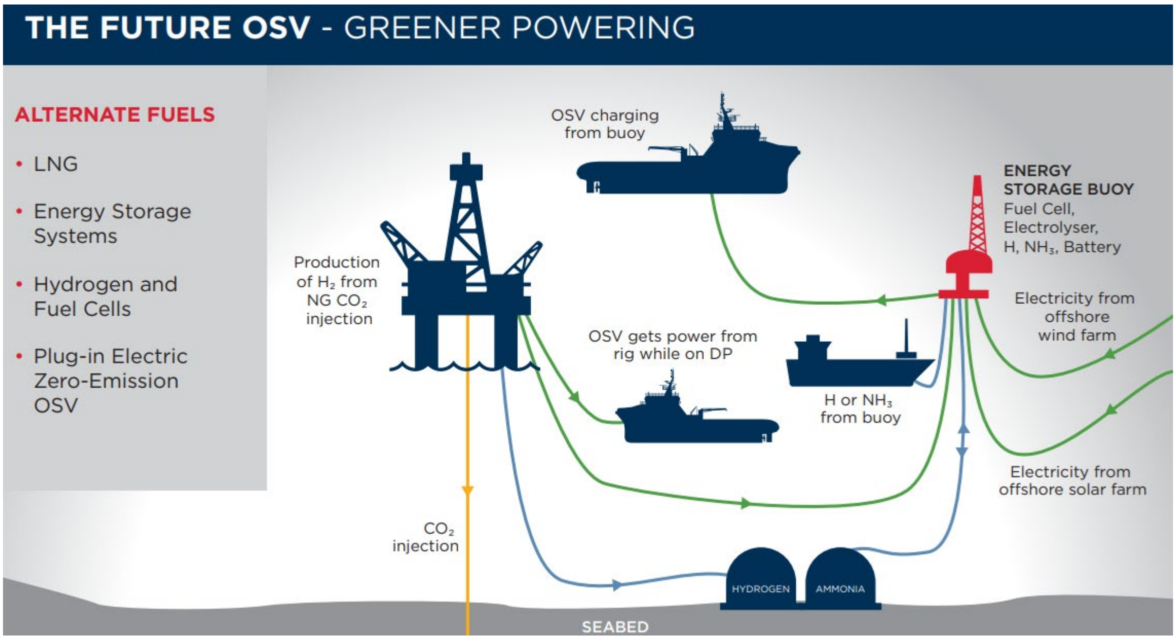
Floating Nuclear Power Plants

In the long term, floating nuclear power plants installed offshore may become a viable power option for charging batteries onboard OSVs.

The power option outlook for the decarbonization of OSVs goes beyond electrification. Production and consumption of alternative fuels and carbon capture can also play a significant role in the future of offshore operations for OSVs and PSVs. Figure 49 depicts the future of OSVs, highlighting multiple new initiatives that can work in tandem toward decarbonization efforts, including:

- Production of hydrogen and ammonia
- Consumption of hydrogen and ammonia in fuel cells for electricity generation
- Storage of electrical energy generated from fuel cells, offshore wind turbines, and offshore solar farms
- Storage of hydrogen and ammonia
- Charging and powering of OSVs from offshore electrical infrastructure
- Injection of carbon dioxide

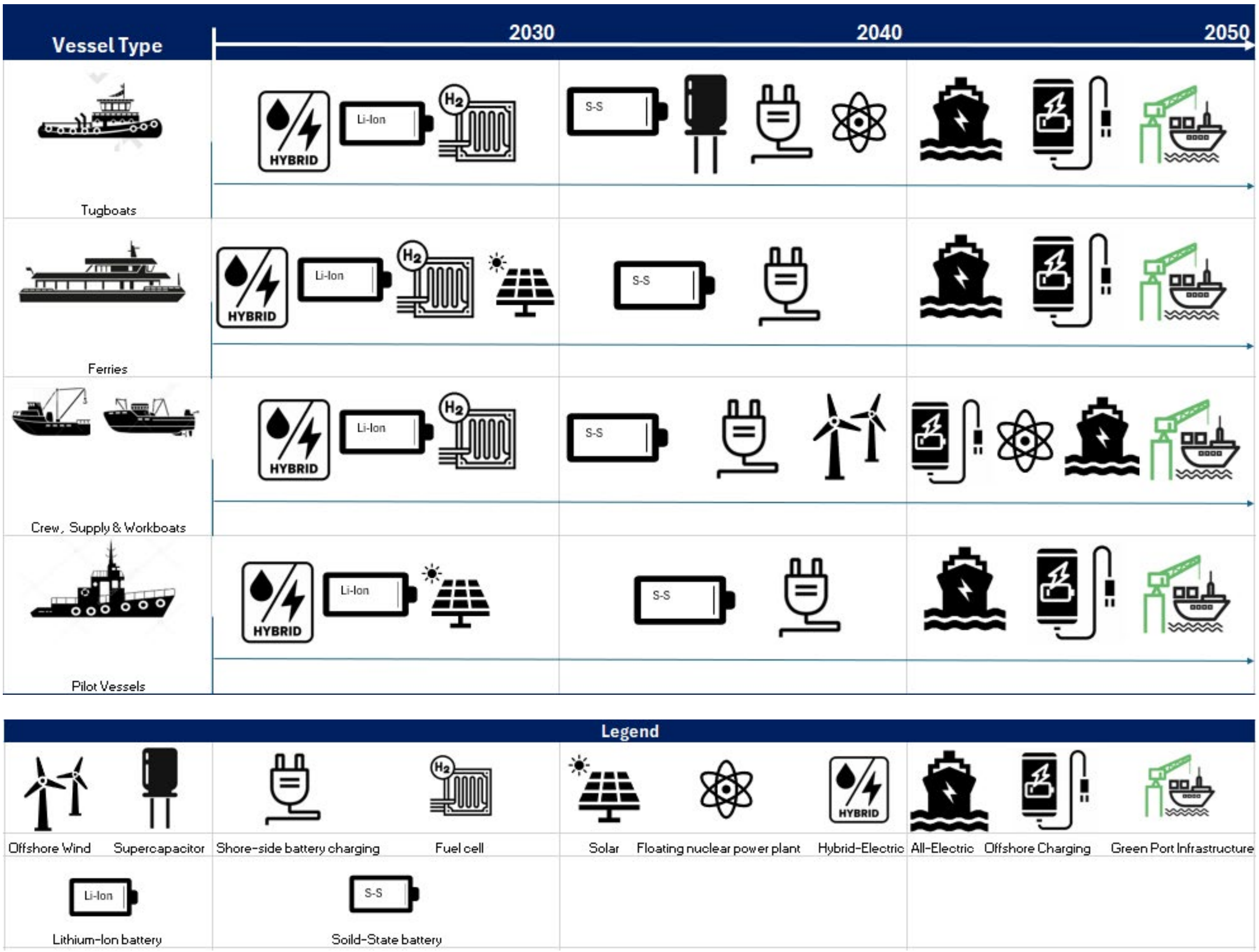
Figure 49: The Future OSV [133]



6 – 4.5 POWER OPTION PROJECTION SUMMARY

Figure 50 summarizes the projected power option implementation by vessel type through 2050. Power options are shown on the timeline based on when they are projected to be economically viable and ready for implementation in each type of CHC, in line with the discussion in section 4.4 above.

Figure 50: Projected Power Options by Vessel Type



6 – 5. CONCLUSIONS

1. Several alternative power options appear promising for the electrification of CHC through 2050, but no one option provides a comprehensive solution. Various combinations of power options seem best for specific CHC types, depending on factors such as operating profile and vessel design.
2. A few of the alternative power options studied will be integration-ready for CHC applications by 2030, but several more will be mature by 2040. All power options with the required supporting infrastructure will be mature by 2050.
3. While battery costs have declined significantly, advancements in battery technology will further reduce cost, improve safety, and maximize performance. This will lead to greater adoption of battery power for propulsion and CHC electrification.
4. Other marine power options will be developed in parallel with battery technology to support charging batteries on vessels. Fuel cells can be a great complement to batteries for this purpose, facilitating longer-range travel with continual recharging. Supercapacitors are a great addition to batteries to support transient power system performance.
5. All-electric vessels will find more widespread adoption from 2040 to 2050.
6. Shoreside charging infrastructure and vessel charging connection systems are likely to be the dominant cost drivers on future CHC electrification projects.

7. The scope of advanced nuclear technology for marine applications is not currently focused on power for propulsion, but on floating nuclear power plants onshore, offshore, and on PSV. Nuclear-powered infrastructure can be used to charge batteries on CHC, such as tugboats and OSVs. Floating nuclear power plants are projected to be viable by the early 2040s.
8. Solar PV on land-based systems may find increasing use in microgrids located near ports, power grid infrastructure, offshore installations, and on-vessel installations for electricity generation.
9. The use of offshore wind to support the electrification of California CHC is projected to be viable between 2030 and 2040. Crew boats, supply boats, and workboats may benefit by having their onboard batteries charged offshore.
10. Careful consideration should be given to the availability of power from the California grid to support onshore charging and shore power services required to support CHC electrification.

Workstream 7:

APPLICABLE FEDERAL, STATE, AND LOCAL ENVIRONMENTAL REGULATIONS

7 APPLICABLE FEDERAL, STATE, AND LOCAL ENVIRONMENTAL REGULATIONS

7 – 1. SCOPE

According to California Air Resources Board's (CARB's) Final Regulation Order Commercial Harbor Craft Regulation [134], "harbor craft" means any private, commercial, government, or military marine vessel, including:

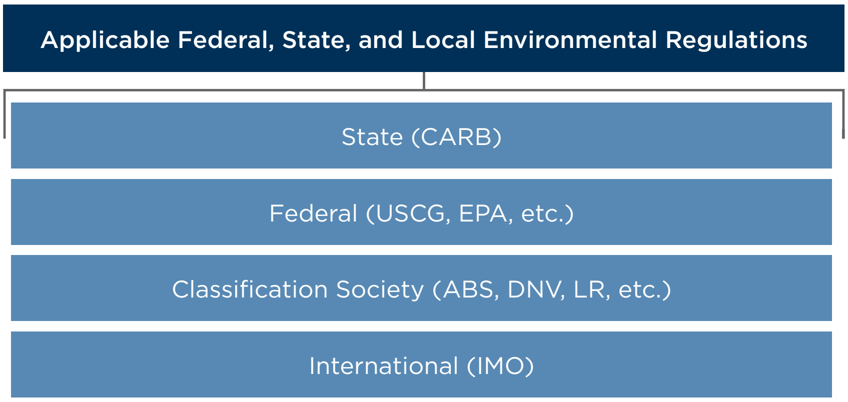
- Passenger ferries
- Excursion vessels
- Tugboats
- Oceangoing tugboats
- Towboats
- Push boats
- Crew and supply vessels
- Work boats
- Pilot vessels
- Supply boats
- Fishing vessels
- Research vessels
- Barge and dredge vessels
- Commercial passenger fishing vessels
- Oil spill response vessels
- U.S. Coast Guard vessels
- Hovercraft
- Emergency response harbor craft
- Barge vessels that do not otherwise meet the definition of oceangoing vessels or recreational vessels

However, as per the limitations of this study, select types of harbor craft are examined within this report.

Table 68: Vessel Types Included in the Study

Harbor Craft Included in Study	Harbor Craft Excluded in Study
1. Tug/Tow Boats 2. Ferries 3. Crew & Supply Boats 4. Workboats 5. Pilot Vessels	1. Barges 2. Dredges 3. Excursion Boats 4. Research Vessels 5. Fishing Boats 6. Coast Guard/Military 7. Oceangoing Vessels

Figure 51: Applicable Federal, State, and Local Environmental Regulations



Since most of the vessels included in the study do not fall under the international regulatory scheme, this subsection of the report focuses on the applicable federal, state, and local regulations. However, it is recognized that there is a possibility of a minor subset of vessels falling under the international regulatory scheme, so those regulations are also briefly covered. Class society regulations are relatively robust for these emerging fuels and technologies and are generally applicable to harbor craft, hence discussed in this report.

Table 69: Summary of Applicable Regulations

Alternate Fuel	State	Federal	Class	International
Renewable Diesel	✓	✗	✗	✗
Biodiesel	✓	✗	✓	✓
Natural Gas	○	✓	✓	✓
Hydrogen	○	✗	✓	○
Ammonia	○	✗	✓	○
Methanol	○	✗	✓	✓
Diesel	✓	✓	✓	✓
Synthetics	○	✗	✗	○
Hybrid Electric	○	✗	✓	✗
Battery	○	✓	✓	✓
Fuel Cell	○	✗	✓	✓

Notes:

✓ Indicates specific regulatory requirements; see subsequent sections for explanation.

✗ Indicates no specific regulation.

○ Indicates regulation is in development or partially present.

Table 70: Available/Draft IMO Requirements/Regulations/Guidelines/Interim Guidelines for the Use of Alternate Fuels

Alternate Fuel	IMO Documents for the Use of Alternate Fuels
LNG	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code)
Biofuels	MEPC 77/7/7, Interpretation of Regulation 18.3 of MARPOL Annex VI, Related to Biofuels MEPC.1/Circ.795/Rev.6, Unified Interpretations to MARPOL Annex VI MEPC.1/Circ.905, Interim Guidance on the Use of Biofuels Under Regulations 26, 27, and 28 of MARPOL Annex VI (DCS and CII)
Hydrogen	**DRAFT** Interim Guidelines for the Safety of Ships Using Hydrogen as Fuel [CCC10]
Ammonia	**DRAFT** Interim Guidelines for the Safety of Ships Using Ammonia as Fuel [Carriage of Cargoes and Containers (CCC) 10]
Methanol	Maritime Safety Committee (MSC).1/Circ.1621, Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel
Synthetics	**DRAFT** Interim Guidelines for the Safety of Ships Using Low-Flashpoint Oil Fuels (CCC 10)
Fuel Cell	MSC.1/Circ.1647, Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installations
Shore Power	MSC.1/Circ.1675, Interim Guidelines on Safe Operation of Onshore Power Supply (OPS) Service in Port for Ships Engaged on International Voyages

Table 71: Class Society Regulations[49]

Alternate Fuel	IMO Documents for the Use of Alternate Fuels
LNG	• ABS Marine Vessel Rules 5 – 13 (Vessels Using Gases or Other Low-Flashpoint Fuels) • DNV-RU-SHIP Pt.6 chapter 2, Section 5, Gas-Fueled Ship Installations – Gas-Fueled LNG • LR-RU-012 Rules and Regulations for the Classification of Ships Using Gases or Other Low-Flashpoint Fuels
Biofuels	• ABS Marine Vessel Rules 5 – 1 (Alternative Fuels – Biofuels) • LR-GN-026 Guidance Notes for Class and Statutory Approval and Use of Marine Biofuels
Hydrogen	• ABS Requirements for Hydrogen-Fueled Vessels • Det Norske Veritas (DNV) Handbook for Hydrogen-Fueled Shipping • LR-RU-012, Appendix LR3, Requirements for Ships Using Hydrogen as Fuel
Ammonia	• ABS Guide for Ammonia-Fueled Vessels Published • DNV part 6, chapter 2, Section 14, Gas-Fueled Ship Installations – Gas-Fueled Ammonia • LR-RU-012 Appendix LR2, Requirements for Ships Using Ammonia as Fuel
Methanol	• ABS Requirements for Methanol- and Ethanol-Fueled Vessels • DNV part 6 Additional Class Notations, Section 6 – Low-Flashpoint Liquid-Fueled Engines – LFL Fueled • LR-RU-012, Appendix LR1, Requirements for Ships Using Methyl Alcohol (Methanol) or Ethyl Alcohol (Ethanol) as Fuel

---

[49] This is not a comprehensive compendium of all class regulations, but ABS, DNV, and LR are covered where available.

Alternate Fuel	IMO Documents for the Use of Alternate Fuels
Hybrid	• ABS Requirements for Hybrid Electric Power Systems for Marine and Offshore Applications • DNV RU-SHIP part 6, chapter 2, Propulsion, Power Generation and Auxiliary Systems • LR Rules and Regulations for the Classification of Ships (Hybrid Power/[+])
Batteries	• ABS Requirements for Use of Lithium-Ion Batteries in the Marine and Offshore Industries • DNV Rules for Classification of Ships (Battery [Power], Battery [Safety]) • LR Guidance Note on Large Battery Installations
Fuel Cells	• ABS Requirements for Fuel Cell Power Systems for Marine and Offshore Applications • DNV-RU-SHIP part 6, chapter 2, Section 3, Fuel Cell Installations • LR-GN-016 Guidance Notes on the Installation of Fuel Cells on Ships
Shore Power	• ABS Marine Vessel Rules 6 – 4 (Low- and High-Voltage Shore Connection) • DNV-RU-SHIP part 6, chapter 7, Section 5, Electrical Shore Connections – Shore Power • LR-RU-001, part 7, chapter 13 – Onshore Power Supplies

The Environmental and Regulatory Setting, Appendix D-2: Attachment A [135], on the CARB Commercial Harbor Craft Regulation amendments page, posted on September 21, 2021, lists a very detailed description of all applicable environmental and regulatory laws, including the topics listed in Table 72.

Table 72: Environmental and Regulatory Laws Included in CARB CHC Regulation Amendments

Environmental and Regulatory Laws Included in CARB CHC Regulation Amendments		
• Aesthetic Resources • Agriculture and Forestry Resources • Air Quality • Biological Resources • Cultural Resources • Energy Resources	• Geology and Soils • GHGs • Hazards and Hazardous Materials • Hydrology, Water Quality, and Water Supply • Land Use and Planning • Mineral Resources	• Noise • Employment, Population, and Housing • Public Services • Recreation • Transportation and Traffic • Utilities and Service Systems

The focus of this MARAD report is the future energy options for commercial harbor craft operating in California, including environmental regulations. Therefore, only energy and environmental regulations are discussed in detail in this report. All other regulations can be explored from the existing CARB Environmental and Regulatory Setting, Appendix D-2: Attachment A report.

This report significantly refers and infers from the available compendium of research done by CARB on regulations for alternative fuels and technologies. This particularly includes the Technical Support Document and Assessment of Marine Emission Control Strategies, Zero-Emission, and Advanced Technologies for Commercial Harbor Craft, Appendix E. This report builds on Appendix E, which was published on September 21, 2021.

7 – 2. FUELS

Table 73: Definitions for Various Alternative Fuels Per CARB CHC Regulation

Alternate Fuel	IMO Documents for the Use of Alternate Fuels
Alternative Fuel	"Alternative fuel" means natural gas, propane, ethanol, methanol, gasoline, hydrogen, electricity, or other technologies that do not meet the definition of CARB diesel or alternative diesel fuel. Alternative fuel also means any mixture that only contains these fuels.
Renewable Diesel	"Renewable diesel" or "R100" means a diesel fuel substitute produced from non-petroleum renewable sources, including vegetable oils and animal fats. Renewable diesel must meet the American Society for Testing Materials (ASTM) specification D975 (May 1982), which is incorporated herein by reference. Renewable diesel can also mean a blend of 99% (R99) renewable diesel by volume.
Alternative Diesel Fuel (Biodiesel)	"Alternative diesel fuel" means any fuel used in a diesel engine that is not commonly or commercially known, sold, or represented by the supplier as diesel fuel No. 1-D or No. 2-D, pursuant to the specifications in ASTM D975-81, "Standard Specification for Diesel Fuel Oils," as modified in May 1982, which is incorporated herein by reference. Additionally, it does not require engine or fuel system modifications for the engine to operate, although minor modifications (e.g., recalibration of the engine fuel control) may enhance performance. Examples of alternative diesel fuels include biodiesel and biodiesel blends not meeting the definition of CARB diesel fuel, Fischer-Tropsch fuels, emulsions of water in diesel fuel, and fuels with a fuel additive, unless: A. The additive is supplied to the engine fuel by an onboard dosing mechanism B. The additive is directly mixed into the base fuel inside the fuel tank of the engine C. The additive and base fuel are not mixed until engine fueling commences, and no more additive plus base fuel combination is mixed than required for a single fueling of a single engine
CARB Diesel	"CARB diesel fuel" means any diesel fuel that meets the specifications of vehicular diesel fuel, as defined in Title 13, CCR, Sections 2281, 2282, 2284, and 2299, and Title 17 CCR, Section 93116.

Biodiesel (BD) and renewable diesel (RD) are often used interchangeably. However, these are two distinct fuels within the context of California, as shown in the definitions. Though RD and biodiesel are both biomass-based diesel fuel replacements, the distinctions are very important in the California region. They both come from the same feedstock[50] but use different production processes. This results in different products having different chemical, physical, and environmental properties. RD is similar to conventional petroleum but has low aromatic hydrocarbons. RD also has a lower emission profile when compared to biodiesel.

7 – 2.1 RENEWABLE DIESEL

RD fuel is a synthetic diesel fuel derived from non-petroleum renewable resources, distinct from BD. RD undergoes a hydrogenation process during its production, eliminating all oxygen from vegetable oils. This results in increased fuel efficiency and significantly extended storage life due to reduced fuel oxidation. Unlike biodiesel, RD can be derived from lower-quality feedstock and has higher cetane numbers and energy density. Starting January 1, 2023, all California harbor craft must utilize diesel fuel containing 99% or more RD (R99).

---

[50] Example: animal tallow, used cooking oil, soybean oil

RD can be manufactured from renewable feedstocks through various methods. These include hydrotreating, enzymatic reactions for hydrocarbon synthesis, and the utilization of biomass feedstocks for partial combustion to produce syngas (carbon monoxide and hydrogen), followed by the Fisher-Tropsch Reaction to create complex hydrocarbons.

Under the California Low Carbon Fuel Standard (LCFS) program, credits are allocated to low carbon fuels based on the difference between their carbon intensity and an annual benchmark. Carbon intensity is measured in gCO_2e/MJ of fuel energy used, with the benchmark decreasing yearly until it reaches a 20% reduction by 2030 compared to the 2010 baseline of CARB gasoline or diesel. After 2030, the LCFS will continue to require a 20% reduction in the transportation fuel pool.

According to United States Energy Information Administration, the bulk of RD consumption in the United States is centered in California, yet the majority of it is not produced within the state's borders. In 2021, California's utilization of RD surpassed the amount generated locally by more than eightfold. California primarily sourced its RD from other states or imported it, predominantly from Singapore. The surge in California's RD consumption followed the implementation of its LCFS in 2011. Over the decade from 2011 to 2021, consumption grew from 1 million barrels to 28 million barrels annually. California offers rebates to customers purchasing RD, thereby stimulating its usage within the state by enhancing its economic viability compared to biodiesel.

In 2021, Oregon was the only other state where RD saw consumption, though it only represented less than 1% of the national total. Oregon mandates that petroleum diesel fuel sold within its borders must be blended with either biodiesel or RD. As of 2023, Washington state also joined this trend by requiring petroleum diesel to be blended with biodiesel or RD; however, EIA data for 2023 was unavailable.

7 – 2.2 BIODIESEL

BD is a mono-alkyl ester or "fatty acid methyl ester" (FAME), which is derived from sustainable non-petroleum sources like vegetable oil or animal fats through a catalyzed transesterification process. Due to its oxygenated methyl-ester nature and distinct viscosity, bulk-density, and bulk modulus compared to CARB diesel or RD, BD can potentially mitigate engine-out particulate matter (PM) under specific load conditions. However, the additional oxygen atom and viscosity differences may inadvertently lead to advanced injection timing. This results in higher peak combustion pressures and temperatures, thereby increasing engine-out nitrogen oxide (NO_x) emissions under certain load conditions.

Apart from the issue of increased NO_x emissions at higher engine loads, BD poses various logistic and technological challenges for end users. Blends exceeding 30% cannot be directly used in unmodified older engines or vessel fuel systems designed for petroleum diesel. BD's compatibility issues may cause degradation of elastomer seals, hoses, and O-rings in older engine fuel systems that lack synthetic Teflon or Viton™ elastomers. This potentially leads to fuel leaks, injection pump failures, and engine damage.

Furthermore, BD's strong detergent properties can dislodge accumulated residues in fuel tanks and lines, potentially causing clogs and engine malfunctions if not properly managed. Storing BD presents challenges as it attracts water and deteriorates over time, forming corrosive acids. It also supports microbial growth in storage tanks, leading to contamination issues. Cold weather performance is also compromised due to BD's high viscosity and tendency to gel at lower temperatures. Low-quality BD may contain trace amounts of metals from the production process, which can block injector nozzles. Historically, BD has not been widely distributed through pipelines.

Though biodiesels have been given a reprieve under the International Maritime Organization (IMO) international scheme, the use of biofuels is not approved for the California region, which currently incentivizes RD.

7 – 2.3 NATURAL GAS

A 2018 University of California Riverside study conducted on a hybrid diesel-electric roll-on-roll-off ferry using dual-fuel LNG/diesel engines, found that the Wartsila 9L-34DF dual-fuel diesel-cycle LNG engines significantly reduced engine-out PM and NO_x emissions by 93% and 92%, respectively. However, the overall emissions of the ferry when using LNG fuel showed higher levels of formaldehyde (HCHO) and methane (CH4) slip emissions compared to diesel fuel. Formaldehyde is a known carcinogen. The study suggested that employing an oxidation catalyst aftertreatment system could theoretically reduce 95% of formaldehyde and carbon monoxide (CO) tailpipe emissions. However, this approach would not address the methane slip issue. Methane is a greenhouse gas (GHG) with a global warming potential (GWP) of 28 – 36 relative to CO_2. In response to these findings, Commercial Harbor Craft (CHC) Regulation introduced a 1.0 g/bhp-hr limit for CH4 emissions, allowing engines of any fuel type emitting a small amount of CH4 to be used.

While LNG/CNG engines have not been adopted in CHC operations in California yet, several engine manufacturers and third-party retrofit companies are either developing or have developed LNG/CNG marine propulsion engine platforms. These are typically for larger engines. For example, Caterpillar offers the spark-ignited U.S. Environmental Protection Agency (EPA) Category 1 G3516 marine engine with 1,550 kilowatt at 1,500 revolutions per minute. Optifuel Systems is a company adapting land-based CNG/LNG engines for marine and off-road applications. The Cummins ISX12N, a U.S. EPA Category 1 natural gas on-road engine is another example suitable for CHC application. Marinizing on-road natural gas engines according to the requirements of 40 CFR 1042.605 could offer significant emissions reduction opportunities.

Nationally and globally, natural gas engines have been deployed in various CHC categories, including roll-on/roll-off (RORO) cargo ferries. Though there is potential for natural gas power in future CHC applications in California, challenges such as methane slip, and lower volumetric energy density of LNG fuel compared to distillate fuels, must be addressed. Retrofitting existing diesel-powered vessels to use natural gas is costly and requires a significantly larger volume of LNG fuel required compared to diesel fuel. Harbor craft also do not typically require higher-powered engines. The well-developed regulatory framework for LNG is an advantage, but the type of harbor craft studied here might see less adoption of LNG due to the challenges listed and possible non-carbon alternate fuels.

7 – 2.4 AMMONIA

Generally, the regulation surrounding the use of ammonia on marine vessels lacks robustness at national, regional, and international levels. This is due to its limited usage and the absence of commercial engines as of January 2024. Although an alternative design process exists for using ammonia, requiring risk assessments and approval from flag administrations, and the non-availability of engines and straightforward regulatory process has hindered its adoption. However, once these issues are addressed, there is an anticipation of significant growth in the use of ammonia.

In the long run, the IMO aims to amend the IGF Code to incorporate detailed requirements for all gases and low-flashpoint fuels utilized in the maritime sector. While experience is gained with these fuels, interim guidelines for ammonia, such as MSC.1/Circ.1621 (2020) for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (2020) are expected to be established. Until guidelines for other fuels, like ammonia, become available, the IGF Code remains applicable.

7 – 2.5 HYDROGEN

The regulatory framework for utilizing liquefied hydrogen in marine vessels is currently evolving within the IMO. A document titled "Report of the Correspondence Group on liquefied petroleum gas (LPG) , Hydrogen, Low-Flashpoint Oil Fuels and amendments to the IGF Code" (CCC 8/3) dated June 21, 2022, sheds light on the ongoing efforts at the IMO level regarding hydrogen fuel usage. This document indicates the development of safety guidelines for ships using hydrogen as fuel. It follows the structure of the IGF Code, with an emphasis on ensuring compatibility with existing guidelines for ships utilizing fuel cell power installations (MSC.1/Circ.1647).

Annex 9 of the CCC 8/3 document presents the “Draft Interim Guidelines for the Safety of Ships Using Hydrogen as Fuel.” While this publicly available draft offers insight into forthcoming regulations, it should be noted that its content is subject to change before final publication.

The approval and endorsement of flag administrations are crucial for the success of hydrogen-fueled vessels. Therefore, involving the U.S. Coast Guard (USCG) early in the vessel design process is recommended for projects involving U.S.-flagged vessels.

In the interim, several standards, requirements, and guidelines serve as pathways for those seeking to adopt hydrogen as fuel for their vessels. These include MSC.1/Circ.1455, “Guidelines for the Approval of Alternatives and Equivalents as Provided in Various IMO Instruments” (2013), MSC.1/Circ.1212, “Guidelines on Alternative Design and Arrangements for Safety of Life at Sea (SOLAS) Chapters II-1 and III” (2006), and the Interim Recommendations for the carriage of liquefied hydrogen in bulk (MSC.420[97]), albeit indirectly applicable.

The adoption of hydrogen as fuel is expected to gain momentum in the future, partly due to the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, a significant outcome of MEPC 80 (Resolution MEPC.377[80]). This strategy, which surpasses the Initial 2018 Strategy in ambition, is likely to drive further interest in environmentally friendly fuel alternatives.

7 – 2.6 SYNTHETICS

The IMO is currently deliberating on the acceptance of lower SOLAS flash points for fuel oils. The IMO has developed the Maritime Safety Committee’s CCC sub-committee with devising draft amendments to the IGF Code to incorporate new safety measures for vessels utilizing low-flashpoint oil fuels. There is a recognized necessity for IMO regulations pertaining to such fuels, with suggestions to encompass a broader spectrum of oil-based fossil fuels, liquid biofuels, synthetic fuels, and their mixtures, all with flashpoints below 60°C.

The interim guidelines for the safety of ships using low-flashpoint oil fuels are anticipated to be finalized in 2024. These guidelines aim to establish an international benchmark for ships utilizing oil-based fossil fuels, synthetic fuels, and biofuels with flashpoints ranging between 52°C and 60°C. A Correspondence Group will continue deliberations and deliver a report to CCC by September 2024.

7 – 2.7 METHANOL

The IGF Code establishes standards for ships utilizing gases or low-flashpoint fuels. They ensure the safe arrangement, installation, control, and monitoring of related machinery, equipment, and systems. Its core objective is to minimize risks to the ship, crew, and environment associated with the specific nature of these fuels.

Additionally, the IMO MSC has adopted MSC.1/Circ.1621, which outlines interim guidelines for ships using methyl/ethyl alcohol as fuel. These guidelines aim to establish international standards for vessels utilizing methyl/ethyl alcohol as fuel, following a similar philosophy to the IGF Code.

The IGF Code primarily addresses natural gas usage, but employing other low-flashpoint fuels through this framework requires additional steps. This entails conducting thorough risk assessments and engineering analyses tailored to each vessel’s use of such fuels. While the IGF Code outlines these requirements, the specific extent and process are to be determined in collaboration with the Flag Administration. This involves utilizing recognized risk analysis techniques to identify, eliminate, or mitigate potential risks with documentation of the entire process.

Furthermore, to facilitate the adoption of methanol and ethanol as marine fuels, the IMO, during its ninety-ninth session, called upon the ISO to develop standards for these fuels and their couplings. The ISO/CD 6583 – Specification of Methanol as a Fuel for Marine Applications standard is currently in development.

Leading class societies such as ABS, LR, and DNV have issued their own requirements and regulations governing the use of methanol. Moreover, IACS Recommendation No.146, concerning Risk Assessment as Required by the IGF Code, can also be applied to methanol usage.

7 – 2.8 DIESEL

CARB is the lead agency for climate change programs and oversees all air pollution control efforts in California to attain and maintain health-based air quality standards [136]. The Clean Air Act requires United States EPA to set National Ambient Air Quality Standards for six commonly found air pollutants known as criteria air pollutants [137]. In contrast to the United States EPA, which has six criteria pollutants, CARB has 10 criteria pollutants [138].

Table 74: Various Criteria Pollutants for CARB and EPA

CARB Criteria Pollutants		EPA Criteria Pollutants	
1.	Ozone	1.	Ozone
2.	Suspended PM (PM10)	2.	PM10
3.	Fine Suspended PM (PM2.5)	3.	PM2.5
4.	Carbon Monoxide	4.	Carbon Monoxide
5.	Nitrogen Dioxide	5.	Nitrogen Dioxide
6.	Sulfur Dioxide	6.	Sulfur Dioxide
7.	Sulfates		
8.	Lead		
9.	Hydrogen Sulfide		
10.	Visibility Reducing Particles		

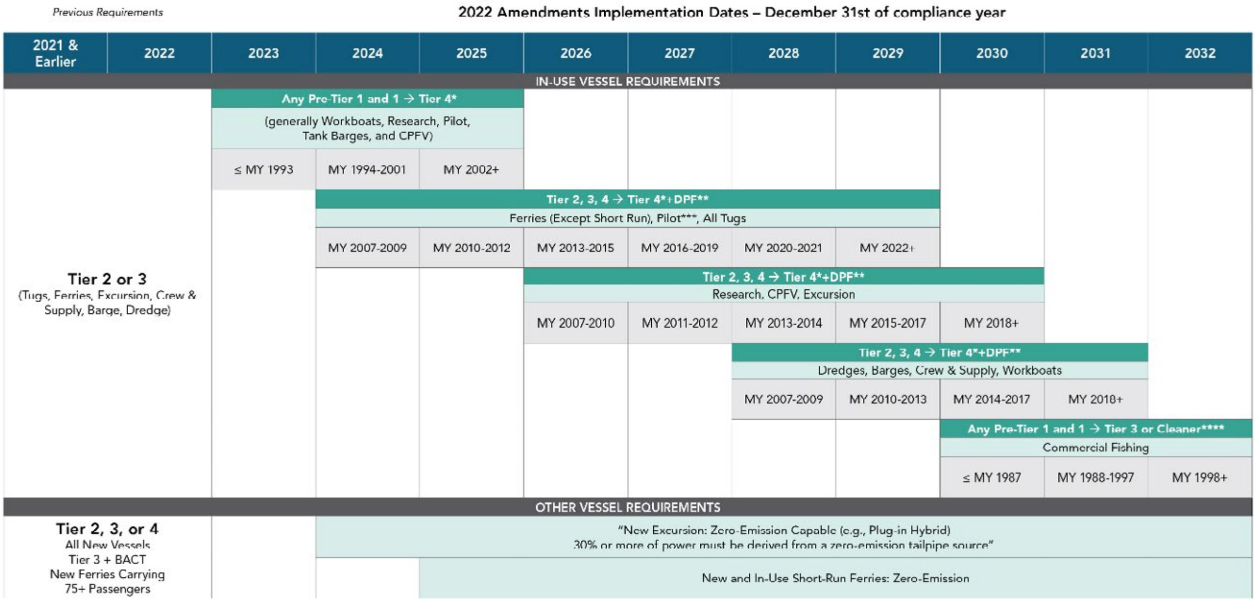
Since the original adoption of the CHC regulation in 2008 and its amendment in 2010, CHC vessel owners have replaced older engines with newer and cleaner engines, which reduced the emissions of air.

In 2022, a new set of amendments were adopted to expand the applicability of the regulation to more vessel types and require cleaner upgrades and newer technology [139]. The purpose of the CHC Regulation is to reduce emissions of diesel PM and oxides of NO_x from diesel engines used on CHC operated in California Regulated Waters. California Regulated Waters are all internal waters, estuarine waters, ports, and coastal waters within 24 nautical miles of the California coast [140].

On December 30, 2022, the California Office of Administrative Law approved amendments to the CHC Regulation, Section 2299.5, Title 13, division 3, chapter 5.1, and Section 93118.5, Title 17, chapter 1, subchapter 7.5 of the California Code of Regulations. The amended CHC Regulation went into effect January 1, 2023 [141].

Compliance dates for engine upgrades depend on the vessel category, and the model year (MY) of the engines are shown Figure 52 below .

Figure 52: CARB CHC Implementation Dates



Previous Requirements

2022 Amendments Implementation Dates – December 31st of compliance year

2021 & Earlier | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032

IN-USE VESSEL REQUIREMENTS

Tier 2 or 3
(Tugs, Ferries, Excursion, Crew & Supply, Barge, Dredge)

Any Pre-Tier 1 and 1 → Tier 4*
(generally Workboats, Research, Pilot, Tank Barges, and CPFV)
2023: ≤ MY 1993
2024: MY 1994-2001
2025: MY 2002+

Tier 2, 3, 4 → Tier 4*+DPF**
Ferries (Except Short Run), Pilot***, All Tugs
2024: MY 2007-2009
2025: MY 2010-2012
2026: MY 2013-2015
2027: MY 2016-2019
2028: MY 2020-2021
2029: MY 2022+

Tier 2, 3, 4 → Tier 4*+DPF**
Research, CPFV, Excursion
2026: MY 2007-2010
2027: MY 2011-2012
2028: MY 2013-2014
2029: MY 2015-2017
2030: MY 2018+

Tier 2, 3, 4 → Tier 4*+DPF**
Dredges, Barges, Crew & Supply, Workboats
2028: MY 2007-2009
2029: MY 2010-2013
2030: MY 2014-2017
2031: MY 2018+

Any Pre-Tier 1 and 1 → Tier 3 or Cleaner****
Commercial Fishing
2030: ≤ MY 1987
2031: MY 1988-1997
2032: MY 1998+

OTHER VESSEL REQUIREMENTS

Tier 2, 3, or 4
All New Vessels
Tier 3 + BACT
New Ferries Carrying
75+ Passengers

2023–2032: "New Excursion: Zero-Emission Capable (e.g., Plug-in Hybrid)
30% or more of power must be derived from a zero-emission tailpipe source"

2025–2032: New and In-Use Short-Run Ferries: Zero-Emission

*All engines >600 kW would be required to be certified to Tier 4. For engines <600 kW, a Tier 4 certified engine would be required if certified by U.S. EPA or CARB and available by the compliance date.

**Retrofit DPF requirements would apply to all Tier 3 and Tier 4 engines.

***Pilot vessels at Tier 2, 3, or 4 with MY 2007-2009 would not need to comply until December 31st, 2025

****Commercial Fishing Vessels at Tier 2 by January 1, 2023 require no additional compliance under the 2022 Amendments

Updated March 2023 to clarify compliance for Commercial Fishing

The marine emission standards outlined in 40 CFR Part 1042.605 permit the adaptation of land-based "off-road" engines for marine use if they comply with the standards specified in 40 CFR parts 85 and 86, or parts 89, 92, 1033, or 1039.

The U.S. EPA has established standards for marine compression-ignition engines, commencing with Tier 1 engines from MY 2004 and advancing to Tier 4 standards phased in until MY 2017. These standards vary based on factors such as MY, engine category, power output, and cylinder displacement. Marine Tier 1 and 2 standards are detailed in 40 CFR Part 94, while Marine Tier 3 and Tier 4 standards are specified in 40 CFR Part 1042. Notably, Tier 4 standards apply exclusively to engines with brake horsepower equal to or exceeding 600 kilowatts.

Engines are categorized into three main groups based on cylinder displacement, with emissions standards (Tier 1, 2, 3, and 4) for oxides of NO_x, CO, hydrocarbons (HC), and PM becoming progressively stringent as tier levels increase.

For compliance with USCG requirements, there are numerous overlapping vessel design requirements that require careful evaluation. These include adherence to relevant 46 CFR Subchapter regulations, ABS Marine Vessel Rules, and considerations regarding vessel stability, trim characteristics, buoyancy, and vessel structural design limits. Additionally, small passenger vessels must meet specifications outlined in 46 CFR Subchapter-T, 46 CFR 177 Subpart D 0 Fire Protection, 46 CFR 182.425 – Engine Exhaust Cooling, and 46 CFR 182.430 – Engine Exhaust Pipe Installation.

Moreover, when installing exhaust aftertreatment retrofit systems, factors such as exhaust temperature profiles and available space within the engine compartment must be considered. This is to determine the type of aftertreatment system required. Changes in vessel displacement tonnage may necessitate a review of vessel stability evaluation by the U.S. Coast Guard (USCG) Marine Safety Center (CG-MSC) or other approved entities.

Internationally, the IMO developed MARPOL, subsequently amended by the protocol of 1978, known as MARPOL 73/78. Annex VI of MARPOL 73/78, effective from May 19, 2005, targets air pollution from international shipping by regulating emissions of NO_x, SO_x, PM, volatile organic compounds (VOCs), and shipboard incineration emissions. Amendments made in 2008 introduced NO_x emissions control areas (ECAs) and mandated a reduction in fuel oil sulfur content to mitigate acid rain, effective January 1, 2020.

In California, certain vessels such as oceangoing tugboats, articulated tug and barge combinations (ATBs), and some international ferries are required to operate engines certified to both IMO and U.S. EPA standards. However, dual-certified marine diesel engines meeting Tier 4 and IMO III standards are not universally available in all power categories. Therefore, the USCG has issued an exemption pending the commercial availability of sufficient dual-certified marine engines, requiring engines to adhere to U.S. EPA standards in the interim.

It is important to note that while IMO III emission standards aim to reduce SO_x and NO_x pollution from larger Category 3 engines used in international shipping, they do not address the near-source health risks associated with PM emissions from harbor craft activity in coastal communities. Consequently, there is limited interest or opportunity for CARB to enforce additional control of PM emissions from engines certified to IMO standards operating in Regulated California Waters.

7 – 3. TECHNOLOGIES

7 – 3.1 HYBRID PROPULSION

A hybrid vessel propulsion system has two or more energy sources. They can be utilized individually or in combination to power the vehicle or vessel utilizing mechanical propulsion, electrical propulsion, or a combination of both.

Serial hybrid propulsion systems share similarities with diesel-electric propulsion systems in that they lack a direct mechanical linkage between the diesel engine and the propeller shaft. In contrast, parallel hybrid propulsion systems maintain the mechanical connection between the engine and the propeller.

The regulatory framework for a hybrid propulsion system is usually lacking at a state, federal, and international level. This is because there can be many permutations and combinations of designing a hybrid vessel. However, there has been an attempt by class societies to bring some uniformity in regulations like ABS, LR, BV, and CCS.

7 – 3.2 LITHIUM-ION BATTERIES

In marine applications, zero-emission and hybrid technologies often rely on lithium-ion batteries for storing energy on board. When installing marine-grade battery Energy Storage Systems (ESSs) in CHC, approval from the USCG Marine Safety Center (MSC) is necessary. These approved battery systems must undergo type classification by recognized organizations, including ABS, Lloyd's Register, DNV-GL, Bureau Veritas, and RINA.

Following an MSC-approved installation plan for a type-approved battery, ESS ensures compliance with safety regulations and vessel design standards. They guarantee safe operation with onboard battery systems. In October 2019, the USCG issued engineering policy letter CG-ENG-02-19 concerning the installation of lithium batteries. This letter cites relevant regulations from Title 46 of the Code of Federal Regulations, Subchapter J, and ASTM F3353-19, the Standard Guide for Shipboard Use of Lithium-Ion Batteries. Referencing these guidelines ensures adherence to USCG requirements for lithium-ion batteries and considerations for vessel design.

Table 75: Overview of USCG Lithium Battery Requirements [64]

USCG Requirement	Design Considerations
Testing Requirements: Battery design tests such as short circuit, impact, and overcharging	Batteries should be type-approved (by class society) and have met all class testing requirements.
Operating Environment: Control and monitoring of the shipboard battery operating environment	Battery room should be ventilated and air conditioned. Heating, ventilation, and air conditioning (HVAC) systems must be monitored remotely by crew.
Fire Safety: Measure to detect, contain, and mitigate emergency situation through battery temperature monitoring, structural fire protection, fire detection, and fire safety systems	Battery room should be insulated and equipped with fire detection and suppression. Insulation could be a combination of thermal and structural fire protection.
Battery System Design: Battery Management System (BMS) requirement	Batteries should have a BMS and be type-approved (by class society).
Testing and maintenance: Testing procedures for automation systems installed in vessel propulsion, ship service electrical, or emergency power applications	Batteries should be type-approved (by class society) and have met all class testing requirements.
System Verification and Maintenance: Maintenance manual including actions to be taken in emergency situations	Batteries should be type-approved (by class society) and have met all class testing requirements.

Marine-grade lithium-ion battery ESSs that are type-approved conform to rigorous international standards regarding vibration and shock loading. These standards, such as UNT 38.3, DNV 2.4, or IEC 60068-2-6, ensure the durability and reliability of these systems in maritime environments. Additionally, these ESSs are equipped with provisions for external air or liquid cooling systems to maintain optimal operating temperatures. Furthermore, they incorporate passive integrated safety features designed to prevent the escalation of thermal runaway incidents from one cell to adjacent cells, enhancing overall safety and reliability.

7 – 3.3 FUEL CELL TECHNOLOGIES

Fuel cells, particularly hydrogen fuel cells, play a pivotal role in Compound Hybrid Configuration propulsion systems, similar to batteries, by generating power through the flow of electrons. Unlike batteries that store chemical potential energy internally, fuel cells derive electricity from two external sources: the chemical energy stored in hydrogen fuel within external tanks and oxygen from the atmosphere. These react within the fuel cell to produce electricity as needed.

Hydrogen fuel cells can be complemented by a battery ESS to meet transient peak power demands of vessels. The power output of hydrogen fuel cells and the capacity of the battery ESS can be adjusted in various proportions to accommodate different Compound Hybrid Configurations. The electrical power generated by hydrogen fuel cells serves multiple purposes. Those include propelling electric propulsion systems, supplying auxiliary power, and charging onboard battery ESSs. They also include meeting vessel power requirements both in motion and when docked in areas lacking shore power for cold ironing.

Marine applications of hydrogen fuel cells represent an emerging technology, with the establishment of USCG requirements and design standards for all CHC regulatory classes still pending. A notable project sponsored by CARB involves the technology demonstration of a hydrogen fuel cell ferry vessel, namely the Switch Maritime Seachange. This vessel measures 70 feet in length and can accommodate 75 passengers. It features an electric propulsion system driven by two 300-kilowatt electric motors. The propulsion system is powered by 360 kilowatts of Proton Exchange Membrane (PEM) fuel cells and is supported by 100 kilowatt-hours of lithium-ion batteries. The vessel stores 240 kilograms of hydrogen in gaseous form on the top deck at a pressure of 250 bar. Having been completed, the Sea Change ferry is scheduled to commence operations in San Francisco in the fourth quarter of 2023.

ENERGY EFFICIENCY PROPULSION

CARB has excluded Enhanced Efficiency Propulsion (EEP) systems from the Zero-Emission and Advanced Technologies (ZEAT) credit category.

Most CHC in California, particularly those equipped with relatively large Category 1 diesel engines apart from harbor and escort tugs, lack a suitable duty cycle that exhibits adequate variation or a necessity for occasional high main engine power output over short durations. Vessels falling within categories that could potentially benefit less from EEP include those operating for prolonged periods at consistent high main engine loads. This includes high-speed ferries, low-speed ferries, most pilot run-boat vessels, most crew and supply vessels, and most workboats.

High-speed ferries, commonly found in areas like the San Francisco Bay Area, typically exhibit a bi-modal load profile. They are characterized by a significant portion of engine idle time and a need for very high power output similar to harbor and escort tugs. However, high-speed ferries sustain high engine output levels for extended periods while traveling at speeds ranging from 27 to 36 knots. So, they either idle or operate at 90 to 100% throttle.

A small fraction of time is spent on standby station-keeping while awaiting docking at passenger terminals, decelerating, accelerating, or maneuvering to enter or exit passenger terminals. Ferries may also engage in a dock-push mode to ensure passenger safety during embarkation/disembarkation in rough weather conditions.

The large main engines onboard high-speed ferries fall within the same displacement range as the Category 1 engines commonly used by harbor and escort tugs. However, ferries consistently operate their engines at high power levels. This results in efficient fuel consumption over extended periods compared to the occasional high power demand of tugboats. Opportunities for reductions lie in periods of low-power demand, such as idling and maneuvering.

Nevertheless, any additional weight from an EEP system installed on a high-speed ferry, aimed at reducing fuel consumption and emissions during low-power modes, would need to be borne by the main engines during high-speed transit. This could potentially increase fuel consumption and associated emissions to a greater extent than the savings achieved during low-power modes.

Furthermore, discussions with high-speed ferry operators suggest that power requirements during maneuvering/docking phases can constitute a significant proportion of main engine power. This is particularly true in adverse weather or tidal conditions. It is uncertain whether an EEP system could adequately provide the necessary power for safe vessel handling/maneuvering in all weather conditions.

The CHC Regulation stipulates that engines cannot idle for longer than 15 or 30 minutes. Consequently, the incremental benefits of employing enhanced efficiency technologies are primarily limited to reductions during maneuvering or transit phases.

7 – 4. CONCLUSIONS, RECOMMENDATIONS, AND KEY TAKEAWAYS

1. Robust state and federal regulatory frameworks are required:

   Most of the harbor craft covered under this study do not fall under the international regulatory framework or the frameworks developed by class societies. As of today, only international and class frameworks are available for most alternate fuels and technologies. If adoption of alternate fuels is to be accelerated, then robust state and federal regulatory frameworks are required for all alternate fuels. Without regulations in place, harbor craft face too much risk to become early adopters of these fuels.

2. Battery technology for appropriate use cases are immediate game changers:

   The regulatory framework for the adoption of battery technologies is advanced, and thus, can usher in an immediate transition for the right use cases.

3. Shore power regulations for CHC are lacking:

   Though there is a mighty push from CARB on Shore Power Regulations, these are principally aimed at oceangoing vessels (At-Berth Regulation). For harbor craft vessels to be brought into the fold, the requirements need to be adjusted and suitably adopted, which will accelerate the use of shore power in harbor craft.

4. Ammonia and hydrogen are rising stars:

   There could be significant challenges in the adoption of ammonia (primary concern: toxicity) and hydrogen (primary concern: flammability) due to lack of regulation across the board, even internationally at IMO. A large body of work and testing needs to be commissioned, as ammonia and hydrogen are perceived as rising stars in the alternate fuel space.

5. Regulatory incentives:

   It might appear that states, particularly California, are having a proclivity to pick winning and losing contenders in the alternate fuels race, such as incentivizing RD. This approach might hamper the adoption of non-incentivized alternate fuels in the short-term, such as synthetics and ammonia.

6. Tier 4 engine availability for CHC:

   Though CARB's regulation mandates the use of Tier 4 engines plus diesel particulate filters, there is an obvious void in the availability of lower powered Tier 4 engines (less than 600 kilowatts). Though this void is bridged partially by providing exemptions, the regulation as written requires the adoption of Tier 4 engines on availability. If there was a single Tier 4 engine available, then it would compel all harbor craft vessels in that power range to buy that engine.

7. Diesel Particulate Filter (DPF) availability for CHC:

   Diesel particulate filters are required by CARB, but these are currently not manufactured by engine manufacturers or third-party vendors. There are potential back-pressure issues when third-party DPF's are installed. It might void EPA EIAPP certificates and class certifications for some engines. This also requires USCG approval. This issue is currently being addressed by CARB but is a pain point for the community until DPF's for Tier 4 engines are widely available.

REFERENCES

8 REFERENCES

[1] International Maritime Organization, “Fourth IMO GHG Study 2020,” International Maritime Organization, London, 2021.

[2] California Air Resources Board, “2021 Update to the Emission Inventory for Commercial Harbor Craft: Methodology and Results,” 21 September 2021. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2021/chc2021/apph.pdf. [Accessed July 2024].

[3] Argonne National Laboratory, “R&D GREET,” Argonne National Laboratory, 2023. [Online]. Available: https://greet.anl.gov/index.php. [Accessed 26 January 2024].

[4] Y. Zhang and W.-T. Chen, “5 - Hydrothermal Liquefaction of protein-containing feedstocks,” Direct Thermochemical Liquefaction for Energy Applications, pp. 127-168, 2018.

[5] M. D. Kass, C. S. Sluder and B. C. Kaul, “Spill Behavior, Detection, and Mitigation for Emerging Nontraditional Marine Fuels,” US Department of Energy, Tennessee, 2021.

[6] California Department of Food & Agriculture, “California Agricultural Exports 2021-2022,” California Department of Food & Agriculture, 2022.

[7] K. Hede, “Biocrude Passes the 2,000-hour Catalyst Stability Test,” 25 March 2021. [Online]. Available: https://www.pnnl.gov/news-media/biocrude-passes-2000-hour-catalyst-stability-test.

[8] L. Grande, I. Pedroarena, S. Korili and A. Gil, “Hydrothermal Liquefaction of Biomass as One of the Most Promising Alternatives for the Synthesis of Advanced Liquid Biofuels: A Review,” Materials, Pamplona, 2021.

[9] Farm-Energy, “Energy in Soybean Crushing and Transesterification,” 3 April 2019. [Online]. Available: https://farm-energy.extension.org/energy-in-soybean-crushing-and-transesterification/#:~:text=Conversion%20of%20Soybean%20Oil%20into%20Biodiesel,-The%20conversion%20of&text=This%20process%20is%20called%20%E2%80%9Ctransesterification,%2C%20glycerin%2C%20an.

[10] E. C. Tan, K. Harris, S. Tifft, D. Steward and C. Kinchin, “Adopting Biofuels for the Marine Shipping Industry: A Long-Term Price and Scalability Assessment,” National Renewable Enrgy Laboratory, Golden, 2021.

[11] D. Barik, “Chapter 3 - Energy Extraction From Toxic Waste Originating From Food Processing Industries,” Energy from Toxic Organic Waste for Heat and Power Generation, pp. 17-42, 2019.

[12] California Governor’s Office of Business and Economic Development, Governor’s Office of Planning and Research, “Sustainable Woody Biomass Industry Development in California,” February 2022. [Online]. Available: https://business.ca.gov/wp-content/uploads/2022/02/GO-Biz-Interagency-Biomass-Market-Development-Framework.pdf.

[13] National Energy Technology Laboratory, “10.2. Fischer-Tropsch Synthesis,” [Online]. Available: https://www.netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/ftsynthesis.

[14] H. Aatola, M. Larmi, T. Sarjovaara and S. Mikkonen, “Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NOx, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine,” SAE International Journal of Engines, pp. 1251-1262, 2009.

[15] U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy, “Straight Vegetable Oil as a Diesel Fuel?,” December 2021. [Online]. Available: https://afdc.energy.gov/files/u/publication/straight_vegetable_oil_as_diesel_fuel.pdf.

[16] Lloyd’s Register, UMAS, “Techno-Economic Assessment of Zero-Carbon Fuels,” Lloyd’s Register & UMAS, London, 2020.

[17]	L. Carvalho, J. Lundgren, E. Wetterlund, J. Wolf and E. Furusjo, “Methanol Production via Black Liquor Co-gasification with Expanded Raw Material Base - Techno-economic Assessment,” Applied Energy, pp. 570-584, 2018.
[18]	Ship & Bunker, “Rotterdam Bunker Prices,” 15 5 2024. [Online]. Available: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#MEOH.
[19]	L. Pomaska and A. Michele, “Bridging the Maritime-Hydrogen Cost-Gap: Real options analysis of policy alternatives,” Transportation Research Part D, vol. 107, 2022.
[20]	“ww2.arb.ca.gov,” March 2021. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2021/chc2021/apph.pdf.
[21]	ABS, “ABS Requirements For Use Of Lithium-Ion Batteries In The Marine And Offshore,” ABS, 2022.
[22]	B. University, “Battery University,” [Online]. Available: https://batteryuniversity.com/article/bu-106-advantages-of-primary-batteries. [Accessed 2023].
[23]	B. University, “Battery University,” [Online]. Available: https://batteryuniversity.com/article/bu-107-comparison-table-of-secondary-batteries. [Accessed 2023].
[24]	ABS, “ABS advisory on Hybrid Electric Power Systems,” 2023.
[25]	batteryuniversity, “batteryuniversity,” [Online]. Available: https://batteryuniversity.com/article/bu-205-types-of-lithium-ion. [Accessed 2023].
[26]	G. Bhutada, “visualcapitalis,” [Online]. Available: https://www.visualcapitalist.com/breaking-down-the-cost-of-an-ev-battery-cell/. [Accessed 2022].
[27]	B. Schweber, “https://www.eetimes.com/,” [Online]. Available: https://www.eetimes.com/lithium-batteries-for-evs-go-nmc-or-lfp. [Accessed 2023].
[28]	“solartechadvisor.com,” [Online]. Available: https://solartechadvisor.com/lithium-titanate-batteries/. [Accessed 2021].
[29]	ABS, “Emerging Battery Technologies in the Maritime Industry,” ABS, 2021.
[30]	ABS, “ABS Requirements For Fuel Cell Power Systems For Marine And Offshore Applications,” ABS, 2019.
[31]	M. E. Solutions, “MAN Energy Solutions,” [Online]. Available: https://www.man-es.com/marine/solutions/hybrid-marine-propulsion-systems. [Accessed 2023].
[32]	A. Yachting, “Allied Yachting,” [Online]. Available: https://alliedyachting.com/faq/marine-propulsion-systems/. [Accessed 2023].
[33]	Twindisc, “twindisc.com,” [Online]. Available: https://twindisc.com/goelectric/marine/serial-hybrid-single-electric-motor-with-generator-power-energy-storage/. [Accessed 2023].
[34]	“twindisc.com/,” Twindisc, [Online]. Available: https://twindisc.com/goelectric/marine/serial-hybrid-single-electric-motor-with-generator-power-energy-storage/.
[35]	E. M. S. A. EMSA, “Shore-Side Electricity: Guidance to Port Authorities and Administrations,” 2022.
[36]	U. D. o. Engery, “energy.gov,” [Online]. Available: https://www.energy.gov/eere/solar/photovoltaics. [Accessed 2023].
[37]	B. Pilkington, “Solar Energy Management Systems on an Industry-First Vessel,” Azo Cleantech, 2022. [Online]. Available: https://www.azocleantech.com/article.aspx?ArticleID=1426.

[38]	N. H. Prevljak, “Industry firsts: Berge Bulk ship tests solar panels,” Offshore Energy, 2021. [Online]. Available: https://www.offshore-energy.biz/berge-bulk-ship-tests-solar-panels/.
[39]	GloMEEP, “Solar Panels,” GloMEEP, 2016. [Online]. Available: https://glomeep.imo.org/technology/solar-panels/.
[40]	J. Cherner, “This Sleek New Solar-Powered Ship Is a Game Changer in Fighting Climate Change,” Architectural Digest, 2022. [Online]. Available: https://www.architecturaldigest.com/story/sleek-new-solar-powered-ship-game-changer-fighting-climate-change.
[41]	Stillstrom, “stillstrom.com,” [Online]. Available: https://stillstrom.com/. [Accessed 2023].
[42]	AirSeas, “AirSeas,” AirSeas, 2023. [Online]. Available: https://airseas.com/en/.
[43]	S. Power, “SkySails Power,” SkySails Power, 2023. [Online]. Available: https://skysails-power.com/.
[44]	T. Casey, “Cargo Ships Reclaim Wind Power With High Tech Rigid Sails,” CleanTechnica, 2021. [Online]. Available: https://cleantechnica.com/2021/12/13/cargo-ships-reclaim-wind-power-with-high-tech-rigid-sails/.
[45]	Norsepower, “Norsepower Technology,” Norsepower, 2023. [Online]. Available: https://www.norsepower.com/technology.
[46]	Neoline, “The Neoliner Project,” Neoline, 2023. [Online]. Available: https://www.neoline.eu/en/the-project/#vision.
[47]	E. E. Division, “Eaton supercapacitors for marine,” 2023.
[48]	Skeleton, “www.skeletontech.com,” [Online]. Available: https://www.skeletontech.com/skeleton-blog/skeleton-is-developing-marine-certified-supercapacitors. [Accessed 2023].
[49]	ABS, “Use of Supercapacitors in the Marine and,” 2022.
[50]	Wavefoil, “Wavefoil,” Wavefoil, 2022. [Online]. Available: https://wavefoil.com/.
[51]	M. Executive, “Wave Energy Concept Ready for Ship Propulsion,” Maritime Executive, 2017. [Online]. Available: https://maritime-executive.com/article/wave-energy-concept-ready-for-ship-propulsion.
[52]	R. D. Caballar, “The revolutionary boat powered by the ocean,” BBC, 2020. [Online]. Available: https://www.bbc.com/future/article/20200718-the-revolutionary-electric-boat-powered-by-the-ocean.
[53]	M. Z. Weijia Yuan, “Superconducting Magnetic Energy Storage (SMES) Systems,” Wiley , 2015.
[54]	C. S. N. D. S. R. J. M. S. R. W. J. Cheung K.Y.C, “Large-Scale Energy Storage Systems,” Imperial College Londo, vol. ISE2, 2002/2003.
[55]	U. D. o. H. Secuity, “Design Guidance For Lithium-Ion Battery Installations,” 2019.
[56]	U. C. Guard, “U.S. Coast Guard Marine Safety Center Plan Review Guideline,” 2021.
[57]	L. D. Erik Emilsson, “Lithium-Ion Vehicle Battery Production Status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling,” IVL Swedish Environmental Research Institute, Stockholm, 2019.
[58]	N. Bullard, “This Is the Dawning of the Age of the Battery,” Bloomberg, 2020.
[59]	ABS, “Hydrogen as marine fuel whitepaper,” 2021.

[60]	M. G. X. M. Y. M. Dr Sze Jia Yin, “ELECTRIFICATION OF SINGAPORE HARBOUR CRAFT - Shore and Vessel Power System Considerations,” Nanyang Technological University, Singapore, 2020.
[61]	Weforum, “World Economic Forum,” [Online]. Available: https://www.weforum.org/agenda/2023/04/electricity-generation-solar-wind-renewables-ember/. [Accessed 2023].
[62]	California Air Resources Board, “Zero-Emission and Advanced Technologies (ZEAT) for New, Newly Acquired and In-Use Short-Run Ferries, and New and Newly Acquired Excursion Vessels,” CARB, 2022 December 2022. [Online]. Available: https://ww2.arb.ca.gov/resources/fact-sheets/chc-factsheet-zero-emission-advanced-technology-zeat-requirements. [Accessed 2 August 2024].
[63]	D. R. L. Russell, B. Welch and E. O’Neil, “Emissions from a Harbor Craft Vessel Using Retrofit Emission Control Technologies,” California Air Resources Board, Riverside, 2015.
[64]	California Air Resources Board, “Appendix E: Purpose and Rationale of Proposed Amendments for the Low Carbon Fuel Standard Requirements,” 2 January 2024. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2024/lcfs2024/lcfs_appe.pdf. [Accessed June 2024].
[65]	California Air Resources Board, “Airborne Toxic Control Measure for Diesel Engines on Commercial Harbor Craft Operated Within California Waters and 24 Nautical Miles of California Baseline,” 30 December 2022 . [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2007/chc07/rev93118.pdf. [Accessed June 2024].
[66]	A. Mahone, J. Kahn-Lang, V. Li, D. Ryan, D. Subin, D. Allen, G. D. Moor and S. Price, “Deep Decarbonization in a High Renewables Future,” California Energy Commission, San Francisco, 2018.
[67]	M. D. Kass, T. Hawkins, E. Tan, K. Ramasamy and B. Kaul, “Determination of the Feasibility of Biofuels in Marine Applications,” 22 March 2021. [Online]. Available: https://www.energy.gov/sites/default/files/2021-04/beto-01-peer-review-2021-sdi-kass.pdf. [Accessed June 2024].
[68]	California Air Resources Board, “The State of California’s Draft Priority Climate Action Plan,” The State of California, 2024.
[69]	H. Simpson and B. R. Vignesh, “Bakersfield Biodiesel and Glycerin Production Plant Expansion,” California Energy Commission, Bakersfield, 2019.
[70]	Biofuels International, “BDI-BioEnergy opens California’s largest biodiesel plant,” 19 April 2022. [Online]. Available: https://biofuels-news.com/news/bdi-bioenergy-opens-californias-largest-biodiesel-plant/. [Accessed June 2024].
[71]	G. Morris, “Biomass Energy Production in California: The Case for a Biomass Policy Initiative,” National Renewable Energy Laboratory, Golden, 2020.
[72]	E. Orozco, B. Springsteen, C. Darlington, C. Stevenson and P. Rogers, “Woody Biomass Gasification Technology in California,” Placer County Air Pollution Control District, 2022.
[73]	D. R. Seiser, D. R. Cattolica and M. Long, “Renewable Natural Gas Production from Woody Biomass via Gasification and Fluidized-Bed Methanation,” California Energy Commission, San Diego, 2020.
[74]	M. Bagtang, S. McCorkle and B. Scott, “The Generation of Synthetic Diesel and Other Synthetic Petroleum Products Through the Fischer-Tropsch Synthesis Process Via the Gasification of Dairy Manure Solids and Utilization of Biogas,” California Energy Commission, 2020.
[75]	California Department of Forestry and Fire Protection, “Pyrolysis Chapter Draft for Advisory Council Review,” California Department of Forestry and Fire Protection, 2019.
[76]	M. Francis and S. Hayati, “Almost all U.S. renewable diesel is consumed in California; most isn’t made there,” U.S. Energy Information Administration, 20 July 2023. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=57180. [Accessed June 2024].

[96]	M. A. K. 2. ,. A. M. 3. ,. M. H. A. 4. a. H.-S. C. 5. Syed Agha Hassnain Mohsan 1, “Enabling UnderwaterWireless Power Transfer towards Sixth Generation (6G)Wireless Networks: Opportunities, Recent,” Journal of Marine Science and Engineering, pp. 1, 29-30, 2022.
[97]	CARB, “CHC Regulatory Documents,” 1 January 2023. [Online]. Available: https://ww2.arb.ca.gov/our-work/programs/commercial-harbor-craft/chc-regulatory-documents. [Accessed 26 March 2024].
[98]	CARB, “Ocean Going Vessels At Berth Regulatory Documents,” 1 January 2021. [Online]. Available: https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessels-berth-regulation/ocean-going-vessels-berth-regulatory. [Accessed 26 March 2024].
[99]	J. Soone, “Sustainable maritime fuels “Fit for 55” package:The Fuel EC Maritime Proposal,” EPRS European Parliamentary Research Service, Nov 2023.
[100]	S. V. G. T. Jingjing Yu a, “Strategy development for retrofitting ships for implementing shore side electricity,” Science Direct, vol. 74, pp. 201-213, 2019.
[101]	IEEE, “ELECTRIFICATION OFFERS CLEANER MARITIME TRANSPORTATION,” IEEE, 2024. [Online]. Available: https://climate-change.ieee.org/news/maritime-transportation/. [Accessed 14 September 2023].
[102]	T. N. (.-S. D. G. (.-M. J. M. (.-M. C Bourne (RR-SSE), “Jon Morley (RR-MP),” DTI, 2001.
[103]	B. Parker, “Workboat Power: Alternatives Join Diesel to Power Current—and Future—Vessels,” Marine Link, 28 Dec 2023. [Online]. Available: https://www.marinelink.com/news/workboat-power-alternatives-join-diesel-510442. [Accessed 2 Jan 2024].
[104]	“Fuel cell systems for ships,” ABB, 2023. [Online]. Available: https://new.abb.com/marine/systems-and-solutions/electric-solutions/fuel-cell. [Accessed 29 September 2023].
[105]	“All American Marine,” All American Marine, [Online]. Available: https://www.allamericanmarine.com/hydrogen-vessel-launch/. [Accessed 29 September 2023].
[106]	P. V. A. K. V. Lindert van Biert, “Solid Oxide Fuel Cells for Marine Applications,” International Journal of Energy Research, vol. 2023 , no. 5163448 , 2023.
[107]	US Congress, Office of Technology Assessment, “Marine Applications for Fuel Cell Technology - A Technical Memorandum, OTA-TM-O-37,” U.S. Government Printing Office, Washington, DC, 1986.
[108]	E. T. J. P. Ioannis Kobougias, “PV Systems Installed in Marine Vessels: Technologies and Specifications,” Advances in Power Electronics, 2013.
[109]	The Maritime Executive, “Ports Employ Solar Power in Efforts to Improve Environment,” 18 Aug 2022. [Online]. Available: https://maritime-executive.com/article/ports-employ-solar-power-in-efforts-to-improve-environment.
[110]	ABS, “OFFSHORE WIND REPORT POSITIONING FOR U.S. EXPANSION: U.S. PORTS AND VESSELS INNOVATION,” ABS, Spring TX, 2021.
[111]	Offshore Wind California, “California Offshore Wind Industry Report,” Offshore Wind California, Menlo Park CA, November 2022.
[112]	“Headwind Propulsion for Articulated Two-Section Vessels,” The Maritime Executive, 23 Jul 2023. [Online]. Available: https://maritime-executive.com/editorials/headwind-propulsion-for-articulated-two-section-vessels. [Accessed 2 Jan 2024].
[113]	Energy.Gov, “DOE Awards $8.5 Million to Advance Promising Nuclear Technologies,” 18 November 2021. [Online]. Available: https://www.energy.gov/ne/articles/doe-awards-85-million-advance-promising-nuclear-technologies. [Accessed 2 Feb 2024].

[77]	California Department of Tax and Fee Administration, “Biofuels,” California Department of Tax and Fee Administration, [Online]. Available: https://www.cdtfa.ca.gov/taxes-and-fees/fuel-tax-and-fee-guides/diesel-fuel-and-motor-vehicle-fuel-tax/biofuels.htm#vegetable-oil-soy-raw-waste. [Accessed June 2024].
[78]	California Department of Tax and Fee Administration, “Biodiesel and California Tax,” March 2018. [Online]. Available: https://www.cdtfa.ca.gov/formspubs/pub96.pdf. [Accessed June 2024].
[79]	P. Marrin, O. Dixon and B. Yemane, “Ammonia as a Clean Energy Solution for Maritime Use,” Amogy, Houston, 2023.
[80]	J. P. Parker, T. Moot, S. McManus, S. Parvathikar and G. M. Wessler, “The Future of Ammonia in Maritime Decarbonization,” RTI International, 14 November 2023. [Online]. Available: https://www.rti.org/impact/green-ammonia-as-sustainable-maritime-fuel#:~:text=Ammonia%20has%20great%20potential%20as,fuels%20for%20heavy%20duty%20transportation. [Accessed June 2024].
[81]	“Harbor Craft (HC) Best Practices to Improve Air Quality,” 20 December 2022. [Online]. Available: https://www.epa.gov/ports-initiative/harbor-craft-hc-best-practices-improve-air-quality#:~:text=Harbor%20craft%20(HC)%20play%20an,%2C%20pilot%20boats%2C%20and%20barges..
[82]	“IEEE Xplore,” IEEE, 25 October 2021. [Online]. Available: https://ieeexplore.ieee.org/document/957058. [Accessed 14 Sep 2023].
[83]	“Climate Change IEEE: Enabling Innovation and Technology Solution,” IEEE, 2024. [Online]. Available: https://climate-change.ieee.org/news/maritime-transportation/. [Accessed 14 September 2023].
[84]	ABS, “Beyond the Horizon - View of the Emerging Energy Value Chains,” ABS, Spring TX, 2023.
[85]	ABS, “ABS Advisory on Hybrid Electric Power Systems,” ABS, Spring TX, 2017.
[86]	Y. L. &. Y. C. Dingchang Lin, “Reviving the lithium metal anode for high-energy batteries.,” Nat Nanotechnol, vol. 12, no. 3, pp. 194-206, 2017.
[87]	X. e. a. Cheng, “Toward Safe Lithium Metal Anode in Rechargeable Batteries: A Review,” Chem Rev, vol. 117, no. 15, pp. 10403-10473, 2017.
[88]	Ben Craig, “The Future of Batteries in the Marine Sector: What Lies Beyond the Horizon?,” University of Sout Hampton, Southamton, November 2020.
[89]	S.-T. M. a. Y.-K. S. Jang-Yeon Hwang, “Sodium-ion batteries: present and future,” no. 12, pp. 3485-3856, 21 June 2017.
[90]	N. Tapia-Ruiz, “J. Phys. Energy,” 2021 roadmap for sodium-ion batteries, no. 3, 2021.
[91]	W. C. a. A. Karmakar, “Cost Projections for Utility-Scale Battery Storage: 2023 Update,” National Renewable Energy Laboratory, Golden, CO, 2023.
[92]	“Shore-Side Electricity Guidance to Port Authorities and Administrations Part 1,” European Maritime Safety Agency, 2022.
[93]	L. K. K. K. Jagdesh Kumar, Technical design aspects of harbour area grid for shore to ship power: State, vol. 104, pp. 840-852, 2018.
[94]	X. Feng, “On maritime electrification – electrification technologies, charging infrastructure and energy management strategies,” Journal of Physics, vol. 2311, no. 012034, pp. 11-12, 2022.
[95]	Wartsila, “Wireless Charging,” Wartsila, 2018.

[114] “International Atomic Energy Agency,” 2023. [Online]. Available: https://www.iaea.org/topics/molten-salt-reactors. [Accessed 2 Feb 2024].

[115] N. E. Institute, “ADVANCED REACTOR ROADMAP PHASE 1: NORTH AMERICA,” EPRI, Palo Alto, California 94304-1338 USA, 2023.

[116] Joanne Liou, “What are Small Modular Reactors (SMRs)?,” International Atomic Energy Agency, 13 September 2023. [Online]. Available: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs. [Accessed 20 March 2024].

[117] “World Nuclear News,” 27 October 2022. [Online]. Available: https://world-nuclear-news.org/Articles/NucScale-and-Prodigy-announce-new-marine-based-SMR. [Accessed 2 Feb 2024].

[118] “Prodigy Clean Energy,” 2024. [Online]. Available: https://www.prodigy.energy/technology. [Accessed 2 Feb 2024].

[119] “Thorcon,” 2024. [Online]. Available: https://thorconpower.com/project/. [Accessed 2 Feb 2024].

[120] Ulstein, “Ship design concept from Ulstein can solve the zero emission challenge,” 26 April 2022. [Online]. Available: https://ulstein.com/news/ulstein-thor-zero-emission-concept. [Accessed 2 Feb 2024].

[121] Crowley, “Crowley, BWXT Debut Nuclear Power Generation Vessel Concept,” 20 September 2023. [Online]. Available: https://www.crowley.com/news-and-media/press-releases/crowley-bwxt-debut-nuclear-power-generation-vessel-concept/. [Accessed 2 Feb 2024].

[122] ABS, “Requirements for Use of Supercapacitors in the Marine and Offshore Industries,” ABS, Spring TX, 2022.

[123] ABS, “Requirements for Hybrid and All-Electric Power Systems in Marine and Offshore Applications,” ABS, Spring TX, 2024.

[124] Crowley, “Crowley, Port of San Diego Celebrate Groundbreaking for All-Electric Tugboat Charging Station,” Crowley, 9 August 2023. [Online]. Available: https://www.crowley.com/news-and-media/press-releases/crowley-port-of-san-diego-celebrate-groundbreaking-for-all-electric-tugboat-charging-station/. [Accessed 3 April 2024].

[125] Wartsila, “Full electric vessels,” Wartsila, 2024. [Online]. Available: https://www.wartsila.com/marine/products/ship-electrification-solutions/full-electric-vessels#:~:text=Already%2C%20some%20inland%20vessels%20such,are%20faster%20to%20re%2Dcharge.. [Accessed 3 April 2024].

[126] ABS, “HARVEY ENERGY: HOW A TRI-FUEL VESSEL IS SHAPING THE FUTURE OF SUSTAINABILITY,” ABS, Spring TX, 2021.

[127] K. Fehrenbacher, “The future of ferries is electric, too,” Green Biz, 5 June 2019. [Online]. Available: https://www.greenbiz.com/article/future-ferries-electric-too. [Accessed 21 December 2023].

[128] “Stena Line to order first fully electric ferry by 2025,” NIFERRYSITE, 4 Feb 2021. [Online]. Available: https://www.niferry.co.uk/stena-line-to-order-first-fully-electric-ferry-by-2025/. [Accessed 21 Dec 2023].

[129] “Cityland New York City,” New York Law School, 15 Dec 2023. [Online]. Available: https://www.citylandnyc.org/city-receives-over-10-million-in-grants-to-support-electrification-of-governors-island-ferry-operation-of-staten-island-ferry/. [Accessed 21 Dec 2023].

[130] W. W. S. Ferries, “Washington State Ferries 2040 Long Range Plan,” Olympia, 2019.

[131] U. E. I. Administration, “Levelized Costs of New Generation Resources in the Annual Energy,” U.S. Energy Information Administration, 2022.

[132] B. V. C. G. L. H. L. K. M. d. J. Alan Guengan, "Application Case 1 Offshore Support Vessel Deliverable D9.1," Holiship, 2020.

[133] ABS, "Insights Into Future OSV Designs and Operations," ABS, Spring TX, 2022.

[134] California Air Resources Board, "Final Regulation Order Commercial Harbor Craft Regulation," 30 December 2022. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2021/chc2021/chcfro.pdf. [Accessed 10 May 2024].

[135] California Air Resources Board, "Appendix D-2: Attachment A, Environmental And Regulatory Setting," 23 June 2023. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2021/chc2021/appd-2.pdf. [Accessed 10 May 2024].

[136] California Air Resources Board, "About," [Online]. Available: https://ww2.arb.ca.gov/about. [Accessed 15 May 2024].

[137] Environmental Protection Agency, "Criteria Air Pollutants," 30 July 2024. [Online]. Available: https://www.epa.gov/criteria-air-pollutants. [Accessed 1 August 2024].

[138] California Air Resources Board, "Maps of State and Federal Area Designations," 2024. [Online]. Available: https://ww2.arb.ca.gov/resources/documents/maps-state-and-federal-area-designations. [Accessed 15 May 2024].

[139] California Air Resources Board, " Commercial Harbor Craft," 2024. [Online]. Available: https://ww2.arb.ca.gov/our-work/programs/commercial-harbor-craft. [Accessed 15 May 2024].

[140] California Air Resource Board, "Compliance Guidelines for the Commercial Harbor Craft Regulation," February 2017. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/2020-07/complianceguidelines021017.pdf. [Accessed 15 May 2024].

[141] California Air Resources Board, "Commercial Harbor Craft (CHC) Regulation Updates and Deadlines," June 23 2023. [Online]. Available: https://members.wto.org/crnattachments/2023/TBT/USA/23_10608_00_e.pdf. [Accessed 15 May 2024].

[142] Bunker Oil, "Our Products," 27 March 2024. [Online]. Available: https://www.bunkeroil.no/en/category/fuel#:~:text=Marine%20gas%20oil%20(MGO)&text=Marine%20Gasoil%20is%20used%20as,0855%2C%20Sulfur%20max%201000%20ppm..

[143] M. B. Vermeire, "Everything You Need to Know About Marine Fuels," August 2021. [Online]. Available: https://www.chevronmarineproducts.com/content/dam/chevron-marine/fuels-brochure/Chevron_Everything%20You%20Need%20To%20Know%20About%20Marine%20Fuels_v8-21_DESKTOP.pdf.

[144] The Engineering Toolbox, "Fossil vs. Alternative Fuels - Energy Content," 2008. [Online]. Available: https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html.

[145] J. Xu, J. Jiang, W. Dai, T. Zhang and Y. Xu, "Bio-Oil Upgrading by Means of Ozone Oxidation and Esterification to Remove Water and to Improve Fuel Characteristics," ACS Publications, 2011.

[146] P. Mehta and K. Anand, "Estimation of a Lower Heating Value of Vegetable Oil and Biodiesel Fuel," ACS Publications, 2009.

[147] The Engineering Toolbox, "Fuels Higher and Lower Calorific Values," 2003. [Online]. Available: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html.

[148] IEC, IEC TS 62600-4 Technical Specification - Marine energy – Wave, tidal and other water current converters – Part 4: Specification for establishing qualification of new technology, Geneva Switzerland: IEC Central Office, 2020.

[149] I. M. Organization, "FOURTH IMO GREENHOUSE GAS STUDY," IMO, 2020.

[150] Danish Environmental Protection Agency, “4. Fuel Oils - General Aspects,” 1998. [Online]. Available: https://www2.mst.dk/udgiv/Publications/1998/87-7909-173-3/html/kap04_eng.htm.

[151] ABS, “Sustainability Whitepaper Ammonia as Marine Fuel,” ABS, Houston, 2020.

[152] D. S. Wittrig, “Ammonia Fuel Opportunities, Markets, Issues,” 10 September 2015. [Online]. Available: https://arpa-e.energy.gov/sites/default/files/Wittrig_Ammonia_TransportationFuels_Workshop.pdf.

[153] M. Cheliotis, E. Boulougouris, N. L. Trivyza, G. Theotokatos, G. Livanos, G. Mantalos, A. Stubos, E. Stamatakis and A. Venetsanos, “Review on The Safe Use of Ammonia Fuel Cells in the Maritime Industry,” MDPI, Basel, 2021.

[154] DNV GL, “Handbook for Hydrogen-Fuelled Vessels,” MarHySafe , Hovik, 2021.

[155] European Maritime Safety Agency, “Potential of Hydrogen as Fuel for Shipping,” EMSA, Lisbon, 2023.

[156] L. E. Klebanoff, J. W. Pratt, R. T. Madsen, S. A. Caughlan, T. S. Caughlan, J. T. B. Appelgate, S. Z. Kelety, H.-C. Wintervoll, G. P. Haugom and A. T. Teo, “Feasibility of the Zero-V: A Zero-Emission, Hydrogen Fuel-Cell, Coastal Research Vessel,” Sandia National Laboratories, Livermore, 2018.

[157] V. V., D. S. D. and Z. O., “Vegetable Oils as Alternative Fuel for a New Generation of Diesel Engines. A Review,” in Scientific Proceedings XXIV International Scientific-Technical Conference, St. Petersburg, 2016.

[158] M. Kass, Z. Abdullah, M. Biddy, C. Drennan, T. Hawkins, S. Jones, J. Holladay, D. Longman, E. Newes, T. Theiss, T. Thompson and M. Wang, “Understanding the Opportunities of Biofuels for Marine Shipping,” U.S. Department of Energy, Oak Ridge, 2018.

[159] ABS, “Sustainability Whitepaper Biofuels as Marine Fuel,” ABS, Houston, 2021.

[160] N. L. Panwar and A. S. Paul, “An overview of recent development in bio-oil upgrading and separation techniques,” Environmental Engineering Research, Udaipur, 2020.

[161] C. L. Williams, T. L. Westover, R. M. Emerson, J. S. Tumuluru and C. Li, “Sources of Biomass Feedstock Variability and the Potential Impact on Biofuels Production,” Bioenergy REsearch, pp. 1-14, 2015.

[162] I. Kariim, H. Swai and T. Kivevele, “Bio-Oil Upgrading over ZSM-5 Catalyst: A Review of Catalyst Performance and Deactivation,” International Journal of Energy Research, 2023.

[163] R. McGill, W. Remley and K. Winther, “Alternative Fuels for Marine Applications,” IEA, Paris, 2013.

[164] Lloyd’s Register, “Engine Retrofit Report 2023: Applying Alternative Fuels to Existing Ships,” Lloyd’s Register, London, 2023.

[165] M. M. Wright, J. A. Satrio, R. C. Brown, D. E. Daugaard and D. D. Hsu, “Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels,” National Renewable energy Laboratory, Golden, 2010.

[166] A. M. Rizzo and D. Chiaramonti, “Blending if Hydrothermal Liquefaction Biocrude with Residual Marine Fuel: An Experimental Assessment,” Energies, vol. 15, no. 2, 2022.

[167] “twindisc.com,” Twindisc, [Online]. Available: https://twindisc.com/goelectric/marine/parallel-hybrid-diesel-single-electric-motor-with-energy-storage/.

[168] W. N. Association, “www.world-nuclear.org,” [Online]. Available: https://www.world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx. [Accessed 2023].

[169]	O. o. N. Energy, “www.energy.gov,” [Online]. Available: https://www.energy.gov/ne/articles/advantages-and-challenges-nuclear-energy.
[170]	R. N. K. V. J. H. R.D. Geertsma, “Design and control of hybrid power and propulsion systems for smart ships: A review of developments,” Applied Energy, vol. 194, pp. 30-54, 2017.
[171]	Wattsup Power, “Flywheel,” Wattsup Power, [Online]. Available: https://wattsuppower.com/flywheel/. [Accessed 4 April 2024].
[172]	ABS, “Technology Trends - Exploring the Future of Maritime Innovation,” ABS, Spring TX, 2022.
[173]	ABS, “EMERGING BATTERY TECHNOLOGIES IN THE MARINE INDUSTRY,” ABS, Spring TX, 2021.
[174]	California Air Resources Board, “Appendix E Technical Support Document and Assessment of Marine Emission Control Strategies, Zero-Emission, and Advanced Technologies for Commercial Harbor Craft,” 21 September 2021. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2021/chc2021/appe.pdf. [Accessed 10 May 2024].

COMBINED APPENDICES

9 COMBINED APPENDICES

WORKSTREAM 1 APPENDIX

DATA IMPUTATION

Missing BHP/KW values	• Identified that there were 5 tugs with missing engine BHP/KW values among vessels with a gross tonnage of less than 1200. • Grouped the tugs into 10 bins based on their gross tonnage. • Calculated the mean BHP for each bin using the available data for the tugs in that bin. • Filled the missing BHP values for the 5 tugs using the corresponding mean BHP value from their respective bins. • Filled the missing KW values using the formula: *1 metric horsepower=0.735499 kw*
Missing Main Engine count	• Identified missing main engine count for certain vessels. • Explored different machine learning models such as random forest and gradient boosting to impute the missing values. • Utilized the predictors 'Gross tonnage', 'Draft', 'Net Tonnage', 'LOA', and 'BHP'. • Split the data into training and test sets. • Trained the random forest model and the gradient boosting model on the training set. • Evaluated the models on the test set using Mean Squared Error (MSE) and R-squared metrics. The test set MSE was 0.308, and the test set R-squared was 0.587 for the random forest model. • Determined that the random forest model provided the best results based on the evaluation metrics.
Missing Aux Engine count	• Identified missing aux engine count for certain vessels. • Considering that only 61 out of 238 vessels had aux engine entries and the majority of those had ‘2’ aux engines, filled the missing aux engine count with the value ‘2’ for the remaining vessels.

AIS POSITION HISTORY

The LLI API’s **‘aispositionhistory’** endpoint was utilized to retrieve the travel history of each vessel for the year 2020. This endpoint provides access to the vessel’s AIS (Automatic Identification System) position data, which includes latitude, longitude, position timestamp, operational status, vessel speed (instantaneous speed), and vessel draft (instantaneous draft).

By querying the **‘aispositionhistory’** endpoint with the appropriate parameters, such as LLI vessel ID or MMSI (Maritime Mobile Service Identity) and specifying the desired time range for the year 2020, the API returned the vessel’s position data for that specific period.

It’s important to note that the LLI API’s **‘aispositionhistory’** endpoint requires appropriate authentication and authorization to access the data. The specific parameters and authentication methods used may vary depending on the implementation and access privileges.

INSTANTANEOUS DRAFT – AIS DRAFT

To enhance the accuracy of the draft data retrieved from the LLI API position history endpoint, an additional step was taken to update and refine the existing values. A function was applied to the dataset to check if the existing value was either missing, equal to zero, or greater than the design draft value. If any of these conditions were met, the function replaced the existing draft value with the design draft value, effectively enhancing the accuracy of the data. In cases where no update was necessary, the function retained the draft value retrieved from the endpoint.

GEOFENCING

The **geopandas** library was utilized to create a Geo data frame from the AIS position history data frame. The Geo data frame was constructed by assigning the geometry column with the geographical points created from the Longitude and Latitude columns of the AIS data frame. The coordinate reference system (CRS) was set to 'epsg:4326', which corresponds to the standard WGS84 coordinate system commonly used for latitude and longitude coordinates.

This transformation facilitated the representation of the AIS data as geospatial objects, allowing for spatial operations and analysis.

To determine if the vessels were operating within specific geographic areas, a geofencing approach was employed. The **geopy** library was used to calculate the circumference points around predefined center points, each with a 1 nm radius. The predefined center points were obtained from **Marinetraffic.com** and represent the coordinates of various ports. The **shapely** library was utilized to create buffer zones around these circumference points, resulting in a collection of polygons.

The **geodesic** function from geopy.distance was employed to calculate the destination points along the circumference of each defined radius, based on the center points and bearing angles. These destination points were converted to **Point** geometries using the longitude and latitude coordinates.

Next, a list of buffered polygons was generated by applying a buffer of 1 nm / 60 (to convert from nautical miles to degrees) around each destination point using the **buffer** method from **shapely.geometry**.

The buffered polygons were then merged using the cascaded_union function from shapely.ops, resulting in a single polygon representing the combined geofence.

Finally, the **within** spatial operation from **shapely** was utilized to check if the vessel's geographic coordinates fell within the geofence polygon. The results were assigned to a new column named 'geofence' in the data frame, indicating whether the vessel was inside or outside the defined geofenced areas. The Boolean values were then mapped to '**In**' or '**Out**' for clarity. The static map in Figure 20 portrays a vessel's movements, with points marked in red indicating when the vessel enters the geofence.

By applying this geofencing approach, it became possible to classify vessels based on their operational location, providing valuable insights into their spatial distribution and adherence to predefined operational boundaries.

DISTANCE TRAVELLED

The Haversine formula is a mathematical equation used to calculate the distance between two points on the surface of a sphere, such as Earth. It considers the curvature of the Earth and provides an accurate approximation of the distance between two coordinates given their latitude and longitude values.

The AIS position history dataset provides a record of the vessel's latitude and longitude coordinates at different timestamps. To calculate the distance traveled, the Haversine formula is applied iteratively to each pair of consecutive coordinates in the AIS position history. The latitude and longitude values are extracted from the dataset, and the Haversine formula is used to calculate the distance between each pair of coordinates. The distances obtained are then added to determine the total distance traveled by the vessel during the specified time.

WORKSTREAM 2 APPENDIX

PORT SURVEY

1. Port Information

Category	Survey Question	Response
Contact	Port you are representing	
	Name	
	Email	

2. Port Size

Category	Survey Question	Response
Port Size	How many terminals are there in the overall port?	
	What is the tonnage volume for the overall port? (example: X tons per year)	
	How much berth space is available on Port-Authority owned property? (example: feet / meters)	
	How much berth space do you have available for the overall port? (example: feet / meters)	
	Include any additional information you deem pertinent regarding port size.	

3. Fuels Bunkered

Category	Survey Question	Response
MDO/MGO	Do you have MGO/MDO available for bunkering at your port?	
	What MGO/MDO bunkering modes are available at your port?	
	Current MDO/MGO Storage Capacity	
	Current MDO/MGO bunkering rate (cubic feet per minute)	
	How is your MDO/MGO storage capacity replenished?	
HFO	Do you have HFO available for bunkering at your port?	
	What HFO bunkering modes are available at your port?	
	Current HFO Storage Capacity (e.g. 5,000 tonnes)	
	Current HFO bunkering rate (cubic feet per minute)	
	How is your HFO storage capacity replenished?	
LFO	Do you have LFO available for bunkering at your port?	
	What LFO bunkering modes are available at your port?	
	Current LFO Storage Capacity	
	Current LFO bunkering rate (cubic feet per minute)	
	How is your LFO storage capacity replenished?	

Category	Survey Question	Response
LNG	Do you have LNG available for bunkering at your port?	
	What LNG bunkering modes are available at your port?	
	Current LNG Storage Capacity	
	Current LNG bunkering rate (cubic feet per minute)	
	How is your LNG storage capacity replenished?	
Methanol	Do you have Methanol available for bunkering at your port?	
	What Methanol bunkering modes are available at your port?	
	Current Methanol Storage Capacity	
	Current Methanol bunkering rate (cubic feet per minute)	
	How is your Methanol storage capacity replenished?	
Other Bunkering Fuels	Do you have any other fuels available for bunkering at your port? If so, please list all of them	
	What bunkering modes are available for any other fuels at your port?	
	Current "Other" Storage Capacity (or Capacities)	
	Current bunkering rate for any other fuels (cubic feet per minute)	

4. Additional Bunkering Infrastructure

Category	Survey Question	Response
Additional Bunkering Infrastructure	Include any additional information you deem pertinent regarding bunkering capacities at your port.	

5. Natural Gas Infrastructure

Category	Survey Question	Response
Natural Gas Infrastructure	How many natural gas lines do you have entering your port?	
	Please enter the line parameters for each natural gas line (diameter, pressure, and access locations (i.e. dock, offices, etc.))	
	Include any additional information you deem pertinent regarding natural gas infrastructure.	

6. Electrical Infrastructure

Category	Survey Question	Response
Electrical Infrastructure	How many points of connection are there with the utility grid?	
	What is the total electrical capacity at the port (kW)?	
	What is the typical percentage of capacity utilized? (i.e. 75% of capacity on average)	

7. Electrification Infrastructure

Category	Survey Question	Response
Electrification Infrastructure	Please provide information on any wind turbine projects/capacities as applicable.	
	Please provide information on any solar panel projects/capacities as applicable.	
	Please provide information on any backup generator projects/capacities as applicable.	
	Include any additional information you deem pertinent regarding electrical infrastructure.	

8. Shore Power

Category	Survey Question	Response
Shore Power	Do you currently have shore power capabilities at your port?	
	How many shore power berths does your port currently have?	
	Do you have high-voltage shore connection (HVSC), low-voltage shore connection (LVSC), or both at your port?	
	Current shore power maximum capacity (MW)	
	What is your current average annual Shore Power usage at your port (MWh)?	

9. Future Initiatives

Category	Survey Question	Response
Future Initiatives	Please discuss or provide links to any future initiatives for your port regarding shore power, electrification, or alternative fuel use.	

WORKSTREAM 3 APPENDIX

FUEL PROPERTIES

Table 76: Fuel Properties

Fuel Type	Density (g/ml)	Gravimetric Energy Density (MJ/kg)	Volumetric Energy Density (MJ/L)	Reference
MGO	0.85 - 0.89	45.9	39.20	[142], [143]
Biocrude	0.97 - 1.04	45.60	38.55	[5]
Biodiesel	0.82-0.88	40.20	35.62	[5]
Bio-oil	1.10 - 1.30	30.40	39.52	[5]
FT-Diesel	0.80	45.5	36.20	[144]
Pyrolysis Oil	0.92 - 0.94	41.00	39.36	[145]
Renewable Diesel	0.77 - .80	46.80	36.42	[5]
Straight Vegetable Oil	0.91 - 0.95	37.00	35.15	[5], [146]
Ammonia	$0.80*10^{-6}$	22.50	$1.80*10^{-5}$	[5], [147]
Methanol	0.79	23.00	18.20	[5], [147]
Hydrogen	$0.09*10^{-6}$	141.80	$1.32*10^{-5}$	[5], [147]

FULL SUITABILITY TABLE

Table 77: Full Suitability Table

See table in Alt-Fuels Project.xlsx for original.

Fuel Pathway	Process	Feedstock	Storage	Cost Competitiveness	Feedstock Availability	Technological Readiness	Compatibility	Bunkering Capability	GHG Emissions	Safety	Environmental Risks (Spill)	Overall Viability
Biocrude	Hydrothermal Liquefaction	Manure	3	3	5	4	2	4	5	5	1	4
	Hydrothermal Liquefaction	Sludge	3	3	5	4	2	4	5	5	1	4
Biodiesel	Transesterification	Soybean	4	5	3	5	5	5	3	5	2	4
Biooil	Fast Pyrolysis	Woody Biomass	1	4	5	5	3	1	4	5	1	3
	Fast Pyrolysis	Woody Biomass, Pt/TiO2	2	4	5	4	4	2	5	5	1	4
	Fast Pyrolysis	Woody Biomass, ZSM5	3	4	5	4	5	3	5	5	1	4
FT-Diesel	Fischer-Tropsch	Biomass	5	1	5	2	5	5	5	5	2	4
	Fischer-Tropsch	Biomass & Coal	5	2	5	2	5	5	1	5	2	4
	Fischer-Tropsch	Biomass & Natural Gas	5	2	5	2	5	5	2	5	2	4
	Fischer-Tropsch	Natural Gas	5	2	5	2	5	5	1	5	2	4
	Fischer-Tropsch	Waste CO2 & Electricity	5	1	2	2	5	5	5	5	2	4
Pyrolysis Oil	Pyrolysis	Biomass	3	2	5	2	5	4	5	5	1	4
Renewable Diesel	Hydrotreating	Yellow Grease	4	5	3	5	4	5	4	5	5	5
Straight Vegetable Oil	Oilseed Oil Extraction	Soybean	3	3	3	5	2	4	3	5	5	4
Ammonia	Steam Methane Reforming & Haber Process	Natural Gas	1	1	5	3	1	3	1	1	1	2
	Hydrolysis & Haber Process	Water & Electricity	1	1	1	3	1	3	5	1	1	2
Methanol	Gasification & Methanol Synthesis	Black Liquor	2	3	3	5	3	4	3	5	2	3
	Gasification & Methanol Synthesis	Coal	2	3	5	5	3	4	1	5	2	3
	Gasification & Methanol Synthesis	Forest Residue	2	3	5	5	3	4	5	5	2	4
	Methanol Synthesis	Natural Gas	2	3	5	5	3	4	2	5	2	3
	Methanol Synthesis	Renewable Natural Gas	2	2	1	5	3	4	4	5	2	3
	Methanol Synthesis	Waste CO2 & Electricity	2	2	1	5	3	4	5	5	2	3
	Methanol Synthesis	Waste Industrial Gas	2	2	1	5	3	4	5	5	2	3
Hydrogen	Steam methane reforming	Fossil Fuel or Natural Gas	1	1	5	4	1	1	1	4	5	3
	Steam methane reforming with CC	Fossil Fuel or Natural Gas	1	1	1	4	1	1	3	4	5	3
	Hydrolysis w/ renewable energy	Water & renewable natural gas	1	1	1	4	1	1	5	4	5	3
	Fuel Cell	Hydrogen	2	1	1	4	1	1	5	4	5	3
Full-Electric	Batteries	Grid-Electric	1	3	5	5	1	5	3	5	1	3
	Batteries	Renewable	1	2	2	5	1	5	5	5	1	3

WORKSTREAM 4 APPENDIX

EVALUATION OF POWER OPTIONS

Table 78: Evaluation of power options

	Lithium-Ion Batteries	Fuel Cell	Hybrid power system	Shore Power	Solar PV	Wind Power	Hydroelectric/ Wave Power	Other(i)
Technical Readiness	5	4	5	4	4	4	3	2
Infrastructure Readiness	3	3	5	3	5	5	3	1
Cost Competitiveness	2	2	3	3	4	4	3	1
Safety Performance	3	3	3	5	5	5	5	1
Emission Reduction Potential	3	3	2	5	5	5	5	5
Regulatory Conformance	5	5	5	5	5	5	5	1

DESCRIPTION OF EVALUATION SCALE FOR POWER OPTIONS

General Notes:

i. For the “Other” column, refer to the power sources presented in section 3.7.

ii. The colors depicted in Table 78 are denoted as shown in Table 79 below. Each evaluation category was transformed into a five-point scale.

Table 79: Five-point evaluation scale for power options

Color Indicators					
Scale	1	2	3	4	5
Description	Very Poor	Poor	Average	Good	Very Good

iii. The mapping of each evaluation category to the five-point scale is as defined below:

  a. Technical readiness and compatibility of engines and fuel Systems are based on TRLs. (TRL Source: NASA): TRL 1-2 is red, TRL 3 is light red, TRL 4-6 is yellow, TRL 7 is light green, and TRL 8-9 is green.

  b. Infrastructure readiness and cost competitiveness are based on commercial readiness indices (CRI) for renewable energy sectors. (CRI source: Australian Renewable Energy Agency): CRI 1-2 is red, CRI 3-4 is yellow, CRI 5-6 is green.

  c. Safety includes safety of life, property, and environment. This includes flammability, corrosion and toxicity and is categorized as: High risk is red, medium risk is yellow, low risk is green.

  d. Emissions reduction potential is taken on a life cycle assessment (LCA) approach basis and compared to HFO (with sulfur 0.50% m/m in line with IMO global sulfur cap) on a CO_2 equivalent level: LCA emissions > HFO is red, LCA emissions = HFO is yellow, LCA emissions < HFO is green.

  e. Regulatory conformance: Neither international nor regional regulations exist is red, no international regulations exist but regional regulations exist is yellow, and international regulations exist is green.

iv. All the above-listed allocations for red, orange, yellow, blue and green in this section of general notes are for preliminary guidance. Also, the listed selection criteria are not an exhaustive list. The weightage of each of the factors may vary and the final evaluation is based on a mix of qualitative and quantitative factors.

WORKSTREAM 6 APPENDIX

DEFINITION OF INTEGRATION READINESS LEVELS

Table 80: Definition of Integration Readiness Levels (IRL) [148]

IRL	Description
1	An interface (i.e. physical connection) between technologies has been identified with sufficient detail to allow characterisation of the relationship
2	There is some level of specificity to characterise the interaction (i.e. ability to influence between technologies through their interface)
3	There is compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact
4	There is sufficient detail in the quality and assurance of the integration between technologies
5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration
6	The integrating technologies can accept, translate and structure information for its intended application
7	The integration of technologies has been verified and validated with sufficient detail to be actionable
8	Actual integration completed and mission qualified through test and demonstration, in the system environment
9	Integration is mission-proven through successful mission operations