Ocean Conservancy®

Reducing Greenhouse Gases in the Maritime Sector: Approaches for Decarbonizing the U.S. Fleet

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Prepared for Ocean Conservancy by:

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Acronyms and Abbreviations

AIS	Automatic Identification System
ARF	United States Academic Research Fleet
BIL	Bipartisan Infrastructure Law
CAPEX	Capital expenditures
CBP	U.S. Customs and Border Patrol
CCS	Carbon capture and storage
CH_3OH	Methanol
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DME	Dimethyl ether
DOD	Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DWT	Deadweight tons
EERA	Energy and Environmental Research Associates
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FAME	Fatty acid methyl ester
FOGs	Fats, oils and greases
FT diesel	Fischer-Tropsch diesel
g	Grams
GHG4	Fourth IMO Greenhouse Gas Study
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model
GT	Gross tonnage
GWh	Gigawatt-hour
H_2	Hydrogen
H_2O	Water
HFO	Heavy fuel oil
HP	Horsepower
HVO	Hydrotreated renewable diesel
IEA	International Energy Agency
ILULC	Indirect land use land cover change
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
ITB	Integrated tug/barge
IWG-FI	Interagency Working Group on Facilities and Infrastructure
JAF	Jones Act Fleet
kg	Kilogram
kt	Knot (equal to a distance traveled of 1 NM per hour)
kWh	Kilowatt-hour

L	Liters
LH_2 - FC	Liquid hydrogen fuel cell
Li-ion	Lithium ion
LNG	Liquefied natural gas
m^3	Cubic meter
MARAD	U.S. Maritime Administration
MDO	Marine diesel oil
MeOH	Methanol
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil (0.1% sulfur by mass)
MJ	Megajoule (1,000,000 Joules)
MSC	Military Sealift Command
MSP	Maritime Security Program
MT	Metric tonne (1,000 kg)
MV	Merchant vessel
MW	Megawatt
MWh	Megawatt-hour
N_2	Nitrogen
NH_3	Ammonia
NM	Nautical mile (1.1508 statute miles)
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen oxides
NREL	National Renewable Energy Laboratory
NS	Nuclear Ship
NSF	National Science Foundation
O-D	Origin - Destination
O_2	Oxygen
OGV	Oceangoing vessel
OPEX	Operational expenditures
OSTP	National Ocean Council's Office of Science and Technology Policy
OSV	Oceangoing self-propelled vessel
PIDP	Port Infrastructure Development Program
PM	Particulate matter
Ro-Ro	Roll-on/roll-off vessel
RRF	Ready Reserve Fleet
RV	Research vessel
SCR	Selective catalytic reduction
SMR	Steam methane reformation
SOx	Sulfur oxides
TEU	Twenty-foot equivalent unit
TtW	Tank-to-Wake
U.S.	United States
UNOLS	University National Oceanographic Laboratory System

USACE	United States Army Corps of Engineers
USD	U.S. dollars
USNS	United States Naval Ship
VISA	Voluntary Intermodal Sealift Agreement
VLSFO	Very low sulfur fuel oil
WtT	Well-to-Tank
WtW	Well-to-Wake
WWII	World War II

Executive Summary

This research identifies opportunities for decarbonizing the oceangoing Jones Act and U.S. flagged fleet, and federally owned and operated research vessel fleets (i.e., the "Federal Fleet"). Jones Act Fleet vessels are potentially "low-hanging fruit" in decarbonization efforts. These vessels are typically much older, less fuel-efficient, and more energy- and greenhouse gas (GHG)-intensive than comparable vessels participating in international trade. Efforts to decarbonize these vessels have the potential to result in greater relative GHG reductions. Moreover, Jones Act Fleet vessel routes involve U.S. point-to-U.S. point voyages on shorter routes, leading to the potential to develop U.S. infrastructure supporting zero-carbon fueling and electrification infrastructure, and to act as a test bed to demonstrate and mature technologies. Based on detailed analysis of vessel characteristics, movements, and energy use, this work provides a comprehensive analysis of approaches to achieve emissions reductions.

This work analyzes the movements and carbon abatement potential of 153 large oceangoing cargo vessels in the Jones Act and U.S. flagged fleet in 2019. These vessels include tanker, container, roll-on/roll-off (Ro-Ro), bulk, and general cargo vessels. These vessels are generally older, with a fleetwide median age of 15.5 years. Among these vessels, containerships and Ro-Ro vessels have a median age of 19 years and tankers have a median age of 13 years. This work also analyzes the so-called Federal Fleet of vessels operated by U.S. Federal Agencies and the Federal Oceanographic Fleet, which consists of around 31 vessels that support Federal agency operations and support oceanographic research. This fleet is aging and estimated to decline to 18 vessels by 2030.

In total, Jones Act and U.S. flagged fleet vessels saw nearly 8,300 entrances at U.S. ports in 2019, with the most frequent port pairs being Jacksonville, FL-San Juan, PR; Tacoma, WA-Anchorage, AK; and the San Pedro Bay Ports (Los Angeles and Long Beach)-Honolulu, HI. Total estimated energy for the Jones Act and U.S. flagged fleet is 4,000 gigawatt hours (GWh) in 2019, equivalent to around 337,900 metric tonnes (MT) of marine gas oil (MGO) fuel, or around 1.5% of global domestic navigation, as estimated by the fourth International Maritime Organization (IMO) Greenhouse Gas Study. Total well-to-wake (WtW) life cycle GHG emissions are estimated at around 1.37 million MT carbon dioxide equivalent (CO_2e). In total, of the 153 large oceangoing cargo vessels studied, tankers accounted for the greatest energy use, consuming 43.1% of estimated energy, followed by containerships at 32.1% and Ro-Ro vessels at 22.8%.

The top ten vessels account for just over 25% of total estimated energy consumption, and just 35 vessels account for over half of total estimated energy. Results show significant energy consumption along routes from central and southern California ports to Hawaii, accounting for six of the top 10 Origin-Destination (O-D) pairs by total energy consumption, followed by connections from the Puget Sound to Alaska, and Houston, TX, to Elizabeth River, VA. Just 35 vessels account for the top 50% of energy consumption, following a similar pattern to the fleet as a whole, with connections between California and Hawaii accounting for five of the top 10 connections by energy consumption.

Though their missions may extend far offshore, Federal Fleet vessels typically depart from and return to the same port. Total energy consumption by Federal Fleet vessels is estimated at around 280 GWh in 2019, or around 8.2% of the energy consumption of the Jones Act and U.S. flag fleets. Taking the Federal Fleet as a whole, 50% of voyages are less than 600 nautical miles, take less than 10.5 days, and consume less than 0.35 GWh. Three vessels account for nearly 22% of energy consumption among the Federal Fleet vessels, and vessels generally return to their home port, rather than calling at alternate ports.

Vessel operators and ports have a range of alternative low- and zero-carbon fuels identified as potential opportunities for decarbonization. Each of these fuels comes with differing benefits and costs specific to the fuel properties, availability, and potential applicability in marine vessels.

Ammonia is an efficient energy carrier and may be used in engines that are similar to current marine diesel engines. Ammonia may be transported by pipeline, and existing transportation infrastructure for ammonia is mature, due to its widespread use as an agricultural fertilizer. Ammonia is currently typically produced via carbon intensive pathways (brown/grey ammonia), and under current conditions does not offer the potential for well-to-wake GHG abatement. With carbon capture and storage (blue ammonia), the GHG benefits of ammonia become clearer, though the well-to-wake abatement potential is strongly dependent on the efficiency of carbon capture and storage technology. Well-to-wake GHG abatement with blue ammonia ranges from 18-76%. Green ammonia, produced using renewable energy sources, potentially offers up to around 74% - 88% GHG abatement. While the GHG benefits of ammonia, particularly green ammonia, are clear, fuel costs for brown and blue ammonia are 1.39-1.86x the cost of MGO for the equivalent energy content, and green ammonia is up to 4.3x the cost of MGO. Furthermore, ammonia requires cooling and pressurization, and so the larger fuel system and storage tanks must be designed accordingly. Ammonia engine costs are potentially up to $5.3 million higher than the cost of equivalent marine diesel engines.

Biofuels have the potential to be used as drop-in fuels, with limited modifications to existing engines and fuel systems, providing GHG abatement of around 66-98% but requiring larger storage tanks due to lower energy density. Biofuel costs vary broadly depending on the production pathway. Dimethyl ether (DME) biofuels, which also offer the greatest abatement potential, are 0.66-0.90x the cost of MGO, while fatty acid methyl ester (FAME) ranges from 1.43-2.14x the cost of MGO, and Fischer-Tropsch (FT) diesel is 1.81-4.53x the cost. FT diesel and DME biofuels offer the greatest GHG abatement potential, at 95.6% and 97.8%, respectively. Biofuels contain no sulfur but are indicated to produce nitrogen oxides (NOx), particulate matter and black carbon emissions. Considering the life cycle of the fuel, if feedstocks are not sustainably harvested or gathered then land use and land cover changes associated with biofuels may be deleterious to the environment.

Hydrogen may be used on-board in a variety of forms, including dual fuel engines, turbines, and fuel cells. Fuel cells are among the most widely studied applications to date and are the focus of the hydrogen section of this report. Grey hydrogen, derived from natural gas, offers well-to-wake GHG abatement of around 34%, while blue and green hydrogen offer much higher abatement potential at around 89% and 97% respectively. To be used efficiently on-board vessels, hydrogen must be stored cryogenically, and the fuel tanks and system together require nearly 8x as much space as MGO fuel. Grey and blue hydrogen are potentially lower in cost, on a per unit energy basis, than MGO, ranging from around 0.4x-1x and 0.6x-1.5x, respectively. Green hydrogen costs range from on par with MGO to as much as 2.16x. Hydrogen is a promising marine fuel for new build vessels, but fuel volume constraints, limited availability in the U.S., and high capital cost barriers need to be overcome before widespread adoption may occur.

Methanol may be used in existing two- and four-stroke engines with minor modifications to the injection, storage, and fuel handling systems. Methanol may be used in existing fuel storage, transportation, and bunkering infrastructure, and the IMO has identified all aspects of methanol storage, bunkering, and handling as mature. From a safety standpoint, methanol fires are not visible to the naked eye and require specialized fire detection systems. Brown methanol, derived from coal, increases life cycle GHG emissions compared to MGO, whereas grey methanol, derived from natural gas, offers up to around 40% GHG abatement. Bio-methanol offers nearly 98% GHG abatement, and E-methanol offers near total GHG abatement. Though lower in cost per unit energy, brown methanol is not a feasible fuel for decarbonizing shipping. Grey methanol fuel costs range from around 0.24x-0.54x MGO, and bio-methanol costs range from round 0.8x to 1.7x MGO costs.

Existing alternative fuel infrastructure may be more limited at Federal Fleet ports as they are typically smaller ports. All but three of the top ten Federal Fleet ports list fertilizer facilities at their ports, two list chemical and chemical product facilities, and only Pascagoula, MS, lists ammonia facilities. As with oceangoing JAF and U.S. flagged vessels, all of the top ten ports are within 500 miles of hydrogen production facilities, and so bunkering of liquid hydrogen using tanker trucks is possible.

There are significant efforts at the IMO and within the U.S. federal government to decarbonize oceangoing vessels. Despite these efforts, a diverse array of hurdles remains before widespread adoption and operation of low- and zero-carbon vessels in the U.S. fleet. Significant efforts are required to fund technical research and development to ensure availability of safe, efficient fuels and propulsion systems. Clean and green electricity grids are essential to producing low-carbon hydrogen, methanol, ammonia, and biofuels. Without the funding and incentives to drive land-side energy systems toward greener solutions, the life cycle emissions of alternative marine fuels will remain high. Furthermore, without lowering green electricity costs through widespread adoption and deployment of renewable energy, low-carbon fuels will not be economically viable without significant subsidy.

The maritime industry has historically been slow to adopt new technologies, which come at a cost premium. There is currently no clear frontrunner in the case of low- and zero-carbon fuels. Firms may be unwilling to invest large sums of money in alternative fuel technologies and risk ending up with stranded assets or the need to retrofit vessels ahead of schedule due to the lack of fuel availability, bunkering infrastructure, or poor fuel performance. Jones Act and U.S. flagged vessels may use engine and propulsion components manufactured overseas, enabling access to the global market of low-carbon systems. In the short term, drop-in fuels like methanol and biofuels may be preferred as bridge fuels in the fleet until research and development can advance hydrogen and ammonia technologies to the point where engines are cost-competitive, fuels are widely available and economically viable, and renewable electricity grids mean well-to-wake emissions are low.

Introduction

International and domestic shipping are responsible for annual emissions of over 1 billion metric tonnes of carbon dioxide (CO_2).[1] The International Maritime Organization (IMO) has a goal of reducing emissions from ships by 50% in terms of total emissions and 70% in terms of transport work by 2050 compared to the 2008 baseline.[2] The range of plausible scenarios in the *Fourth IMO Greenhouse Gas Study* (GHG4) (Faber et al. 2020) projects CO_2 emissions to increase from about 90% of 2008 levels in 2018 to 90-130% of 2008 levels by 2050. That is, GHG4 demonstrates a high likelihood that IMO's own 2050 emission reduction goals will not be met.

In 2021, the United States (U.S.) announced that it is working with Denmark and Norway to develop green maritime technologies, with a goal of 5% of the global deep sea shipping fleet running on well-to-wake (WtW) zero emission fuels by 2030 (by fuel consumption).[3] India, Morocco, the United Kingdom, Singapore, France, Ghana, and South Korea are also supporting the initiative. However, the roadmap and timeline for how the U.S. will meet these goals are not yet clearly outlined.

The purpose of this research is to identify opportunities for decarbonizing the U.S. flagged fleet and federally owned and operated research vessel fleets (i.e., the "Federal Fleet"). Based on detailed analysis of vessel characteristics, movements, and energy use, this work provides a comprehensive analysis of approaches to achieve emissions reductions.

This report discusses both the Jones Act Fleet and the Federal Fleet. The report begins with a literature review (Section 0) and discussion of the Jones Act and its influence on the U.S. shipping industry. This report then provides an overview of selected alternative maritime fuels that have been identified as likely candidates for decarbonizing shipping (Section 0). Section 4 of the report presents vessel data, followed by Section 0, which provides information on fleet activity. Section 0 presents a technology assessment for decarbonization-related technologies, and lastly, Section 0 provides an analysis of policies and case studies to help inform future directions for policymakers and other stakeholders.

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[1] *Fourth IMO GHG Study* is available at https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx
[2] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx
[3] https://www.reuters.com/business/sustainable-business/us-joins-norway-denmark-advance-zero-emissions-ship-fuels-2021-06-11/

Literature Review

1.1 The Jones Act

The Jones Act—Section 27 of the Merchant Marine Act of 1920—requires that U.S.-flagged vessels making domestic waterborne shipments (from U.S. point to U.S. point) be: 1) built in the U.S.; 2) crewed by at least 75% U.S. citizens (including master, all officers, and 75% of remaining crew); and 3) U.S.-owned, and where a corporation owns the vessel, at least 75% of shares must be held by U.S. citizens (John Frittelli 2019; Rutherford 2021).

The Jones Act was intended to support the U.S. shipyard industry to ensure that the U.S. retained domestic shipbuilding and repair capacities in the interest of national defense. The Jones Act was also intended to ensure that the U.S. had a functioning, high-quality, reliable, and safe Merchant Marine that could be called upon in the event of war, national emergency, or other situations requiring activities in the interest of national defense. Certain vessels covered by the Jones Act, termed here the *Jones Act Fleet*, or JAF, may be used to transport equipment, supplies, fuel, and cargo to support Department of Defense strategy and tactical efforts in these situations.

Though there are recognized national defense and security benefits of the Jones Act, the act has also been subject to much scrutiny. The intended effect of the Jones Act on U.S. shipyards and shipbuilding capabilities has been put into question (Grabow, 2019). The number of U.S. shipyards, shipyard employees, and capabilities and efficiency of U.S. shipyards has declined over time—and lags behind foreign-owned shipyards. Foreign yards are often able to build, repair and reconstruct ships far more cost-effectively and far more efficiently (in terms of time to produce and number of ships built and repaired, etc.) than U.S. shipyards; for example, the cost of U.S.-built vessels can reach six to eight times the cost of foreign-built-vessels to build (Bonello et al. 2022).

Also, some argue that the Jones Act has increased operational costs of domestic U.S.-flag shipping through increased costs of ship construction and higher relative labor costs (Bonello et al. 2022). Additionally, the Jones Act may result in increased negative environmental impacts by diverting U.S. waterborne shipments to rail and truck—or to imports using foreign-flag vessels—due to these higher costs. As a result of the protectionist measures of the Jones Act and the high costs imposed on shippers, Jones Act vessels are generally much older and less efficient than comparable foreign-flag vessels, calling into question both the safety and environmental impacts of the requirements (J. Frittelli 2017; Bonello et al. 2022; Helton 2021; Grabow 2019; Fitzgerald 2020).

The U.S. has recently recognized the importance of decarbonizing the marine shipping sector and has demonstrated this priority by (among other efforts) rejoining the Paris Agreement in January 2021, signing the Clydebank Declaration in November 2021, and committing, along with 21 other nations, to developing green (zero-emission) shipping corridors (Bonello et al. 2022; Blinken 2021; Stockbruegger 2021).

Jones Act Fleet vessels have been recognized as a potential opportunity or "low-hanging fruit" in decarbonization efforts (Rutherford 2021). These vessels are typically much older than comparable vessels participating in international trade. Older vessels tend to be less fuel efficient and more energy- and GHG-intensive, and so efforts to decarbonize these vessels have the potential to result in greater relative GHG reductions. Moreover, Jones Act Fleet vessel routes involve U.S. point-to-U.S. point voyages on shorter routes, leading to the potential to develop U.S. infrastructure supporting zero-carbon fueling and electrification infrastructure, and to act as a test-bed to demonstrate and mature technologies (Rutherford 2021; Fitzgerald 2020; Helton 2021; Bonello et al. 2022).

Currently, JAF vessels are not only older, and thus tend to be less efficient by design, but also do not support the fuels, systems, and equipment needed for decarbonization efforts, such as zero-carbon fuels and electrification. Current fuel systems rely on marine diesel oil (MDO), heavy fuel oil (HFO), and a small amount of liquid natural gas (LNG). As a result, efforts toward decarbonizing the JAF will require ship construction, reconstruction, rebuild, and retrofits. This creates an opportunity to revive the demand for and capabilities of U.S. shipyards and employees, encouraging this industry to grow and innovate, and to be first-movers in the global efforts toward decarbonization of the marine shipping sector (Bonello et al. 2022; Rutherford 2021).

Given the unique restrictions and opportunities surrounding JAF vessels, however, the potential for, and practical feasibility of, decarbonizing these vessels may be a function of the many policies affecting these vessels. The policies include both those that may present barriers to decarbonization, and those that may support or encourage these efforts.

1.2 Requirements of Jones Act Fleet Vessels

1.2.1 Determination of U.S.-Built and Permissible Foreign-Built Components

The U.S. Maritime Administration (MARAD) administers programs related to the merchant marine (e.g., the Maritime Security Program, or MSP), but Jones Act enforcement authority and responsibility falls to the U.S. Coast Guard and U.S. Customs and Border Control (CBP) (Goldman, 2021). Among the U.S. Coast Guard authorities and responsibilities are determining and enforcing whether vessels and voyages are Jones Act compliant; a key aspect of this involves whether a vessel meets the "U.S.-built" requirement.

According to the U.S. Coast Guard interpretation, "U.S.-built" vessels can be assembled using many foreign-built components, given that the vast majority (>98.5%) of the "major components" of the vessel—the hull and superstructure—are fabricated in the U.S., and the vessel is assembled in the U.S., as well (Frittelli 2019; Papavizas 2017). One potential concern surrounding the decarbonization of JAF vessels may be whether the necessary retrofits, modifications, and key system components and designs required in decarbonization efforts are available or manufactured in the U.S.

Specifically, components that do not impact U.S.-build determination include "propulsion systems (the ship's [main and auxiliary] engine), other machinery, small engine room equipment modules, consoles, wiring, piping, certain mechanical systems and outfitting" (Frittelli 2019). These components are permitted as they do not affect the integrity of the hull, or how watertight the vessel is. As such, U.S. shipyards import various ship components, including ship engines, rudders, propellers, watertight enclosures, stern and bow sections, and other components that can be attached to the ship in the U.S. The steel products used in ship components can also be imported, without limit, as long as the shaping, molding, cutting and design take place in a U.S. shipyard (Frittelli 2019).

Shipyards often inform the U.S. Coast Guard of the foreign-built components to be included in a vessel and seek "Determination Letters" from the Coast Guard, detailing the foreign-built components that are permissible, and to what extent/in what capacity they are allowed (Frittelli 2019). U.S. shipyards have sued the Coast Guard with respect to their interpretation of "U.S. built" vessels, which allows for not only foreign-built components, but also vessel designs. In 2007, shipyards brought a suit in response to a Philadelphia shipyard's partnership with a South Korean shipbuilder to build Jones Act tankers; the partnership involved the use of the South Korean firm's vessel designs and other procurement services. The U.S. Court sided with the Coast Guard, and the partnership continues (and has subsequently expanded to container ships). A San Diego firm has also partnered with a South Korean shipbuilding firm with respect to ship designs, engineering services and materials used in producing Jones Act carriers. (Frittelli 2019).

The "U.S. build" requirement refers not only to initial ship construction but also to rebuilding, retrofitting, and reconditioning. Similarly, the U.S. Coast Guard allows for certain components and systems to be replaced, retrofitted, and otherwise built or manufactured by foreign firms, if these changes meet the requirements in terms of changes to the hull and superstructure: i.e., if a "a new, separate and completely-constructed unit, built separate from and added to the vessel" weighs less than 1.5% of the weight of the hull or superstructure; and if a repair conducted in a foreign shipyard does not exceed 7.5% of the steel-weight of the vessel (Papavizas 2017; Washburn 2017; Committee on Transportation and Infrastructure, 110th Congress 2008).

Our review indicates that the risk of the US-built requirement being a barrier for decarbonization efforts of JAF vessels may be less than expected. Many key system components—including engine and propulsion system, piping, and "certain mechanical systems and outfitting"—which may be of relevance in decarbonizing efforts (whether shipbuilding or retrofitting)—may not be required to be produced in the United States to meet Jones Act requirements. If and when these components and systems are not produced or available in the U.S.—or until they are—this interpretation may increase the availability of technologies, components, systems, and designs required for decarbonization of vessels, and may reduce the costs of required technologies and systems for the Jones Act Fleet, while also allowing for the legality of changes leading to decarbonization.

1.2.2 Sealift Requirement of Jones Act Fleet Vessels

With respect to JAF vessels, "sealift" involves the use of privately-owned U.S.-flag commercial marine merchant vessels (that is, the Jones Act Fleet) by the U.S. military to transport and deploy equipment, supplies, fuel, and personnel for strategic or tactical purposes. A primary purpose of the Jones Act was to ensure the availability and suitability of commercial vessels for sealift in the event of war—and the U.S.-owned, -operated and -built requirement was intended to ensure the safety, reliability, and availability of these vessels for military purposes (Frittelli 2019).

Most JAF oceangoing, self-propelled vessels (OSV) of 1,000 gross tons or more (77 out of 96 vessels as of November 2021) are considered *Militarily Useful*; however, "during execution any vessel offered for sealift may be considered" (MARAD 2022). To be considered "Militarily Useful," vessels must meet certain requirements, including a minimum cruising speed of 12 knots. Dry cargo ships over 2,000 deadweight tons (DWT) (including containerships, Ro-Ro, breakbulk, and heavy lift vessels) should be able to carry equipment, ammunition, and supplies without requiring significant modification, and tankers should have capacity to carry 2,000 to 100,000 DWT of petroleum, oils, and lubricants (MARAD 2022). Over time, specialization in commercial vessels, including changes in vessel configuration and equipment on JAF, means that modern vessels may not meet military needs (Frittelli 2019).

The JAF is not the only reserve fleet used by the military for sealift purposes. The U.S. military has access to several reserve fleets for sealift, all of which have been established in the time since the Jones Act was enacted (1920). These include: MARAD's National Defense Reserve Fleet of approximately 100 vessels, of which the Ready Reserve Force (RRF—est. 1976), a government-owned fleet of 41 standby cargo (and other) vessels is a subset; vessels enrolled in the Maritime Security Program (MSP—established in 1996 and also administered by MARAD), which consists of 60 privately-owned U.S.-flag ships (not necessarily Jones Act vessels), each of which receive ~$5 million in annual operating subsidies; vessels operating under MARAD's Voluntary Intermodal Sealift Agreement (VISA–established in 1950), under which participants are given preference for Department of Defense (DOD) cargo shipments during peacetime; and the Military Sealift Command (MSC—established in 1949)—a government-owned fleet of ~125 ships, maintained by the DOD as a division of the U.S. Navy.[4] Additionally, a new Cable Security Fleet (2 cable vessels capable of installing, repairing, and maintaining submarine cables) was funded in the 2020 NDAA (Frittelli 2019; MARAD 2020b; 2021a; 2022; U.S. Navy 2021; Goldman 2021; MARAD 2021b).

While JAF vessels are required to be U.S.-built, most vessels in government-operated sealift fleets are foreign-built and comparatively less expensive (Frittelli 2019). The JAF vessels are used in commercial operations and must compete in the marketplace, while government-owned military vessels operate outside of the market, where minimizing costs is not as crucial to regular operations and viability (Frittelli 2019).

1.2.3 Relevance to Decarbonizing Jones Act Fleet Vessels

JAF vessels are required to meet certain standards in order to be considered safe and useful for military sealift operations, if and when they are needed. A potential concern may be that modifications/retrofitting of JAF vessels to meet decarbonization goals could alter these vessels so that they are no longer considered militarily useful, or so that their safety or reliability is in question—ultimately defeating the purpose of the Jones Act. For example, if the energy content of alternative (or zero-carbon) fuels is far lower than that of MDO or HFO, and thus limits the range and reliability of the vessels, this may present a concern or barrier to implementation of decarbonization in JAF vessels.

[4] https://www.maritime.dot.gov/national-security/strategic-sealift/voluntary-intermodal-sealift-agreement-visa and https://www.federalregister.gov/documents/2018/01/31/2018-01851/voluntary-intermodal-sealift-agreement-changes-to-the-open-season-enrollment-period

Another potential concern of the use of zero-carbon fuels or technologies (e.g., electrification) in JAF vessels used for sealift may be that infrastructure to fuel and/or power vessels may be unavailable at foreign (or other destinations) where sealift is required, as may be adequate maintenance and repair facilities, so the use of these vessels in war or emergencies will be impractical if not impossible. These concerns may hold for all oceangoing vessels, including those engaged in international trade. Therefore, addressing these concerns where possible for the JAF may potentially enable broader decarbonization in the shipping sector beyond this fleet. In the case of the JAF, however, the locations and situations where sealift will be required for military applications are largely unknown until the time they are needed—which are often emergency situations, and in areas abroad—whereas in the case of vessels used for international trade, decarbonized vessels could potentially be dedicated for certain routes and origin-destination (O-D) pairs where appropriate fuel and/or infrastructure were readily available. Solutions that support decarbonization fuels and technologies but do not require fixed infrastructure and facilities (e.g., portable fueling, electrification, or maintenance and repair solutions) may help to address this barrier for both JAF vessels and vessels engaged in international trade.

1.2.4 Jones Act Exemptions and Exceptions

Congress has granted exemptions and exceptions to the Jones Act for a number of reasons, including:

1. When finding there were no Jones Act-qualified operators who had an interest in or capability to serve a specific market—such as passenger travel between Puerto Rico and other U.S. ports (P.L. 98-563) and liquefied natural gas (LNG) domestic service;
2. In response to a sharp increase in demand for—and resulting shortage of—Jones Act-qualified vessels, similar to the increased demand for iron ore shipments on the Great Lakes experienced during WWII;
3. When JAF vessels were required for key efforts, such as oil spill cleanups in 1989 and 1996;
4. Waivers for specific voyages where legs of the voyage would otherwise fall under the Jones Act, such as shipments of empty containers between U.S. ports; and
5. Waivers “in the interest of national defense,” such as expediting transportation of fuel in times of emergency (e.g., hurricane response or drawdown of Strategic Petroleum Reserve in 1991 and 2011) (Frittelli 2019).

As this list demonstrates, Jones Act exemptions and waivers have tended to be for certain *voyages*—allowing the use of foreign-flag vessels between U.S. points in emergencies—rather than waivers for the U.S.-built requirement or other requirements of JAF *vessels*—and so the history of waivers and exemptions does not suggest the likelihood or possibility of exemptions or exceptions being made for JAF vessels for decarbonization efforts, including shipbuilding and retrofits.

As waivers have been granted "in the interest of national defense," this suggests there may be an opportunity for waivers or exemptions related to decarbonization of JAF vessels, if and when decarbonization efforts would serve the interests of national defense. The "national defense" standard is a high standard to meet, according to the U.S. Customs and Border Patrol (CBP), and should not be used for economic or commercial reasons (Frittelli 2019). However, the effects of climate change are increasingly seen as a threat to national defense. In 2021, the Department of Defense (DOD) issued a Climate Risk Analysis report to the National Security Council that highlights the threats and risks to United States defense posed by climate change, including increased demand for defense support of civil authorities, and altered, limited, or constrained environment for military operations (U.S. DOD 2021). In summary, *to the extent that climate change mitigation strategies, such as decarbonization, are seen by the DOD as critical to national security in the future, there may be the potential for decarbonization efforts to qualify for waivers or exemptions*.

Low and Zero Carbon Maritime Fuels

In 2018, the IMO adopted their *Initial Strategy* for the reduction of GHG emissions from ships. The Initial Strategy specifies a reduction in total annual GHG emissions of 50% by 2050 compared to 2008 levels. The Initial Strategy was adopted at the MEPC (Marine Environment Protection Committee) 72 meeting. In April 2021, the U.S. announced that they would join an international effort to reduce GHG emissions from global shipping to zero by 2050. In the announcement, the U.S. Special Envoy for Climate John Kerry stated, "The technologies that we need to decarbonize shipping are known to us, so they need investment, and they need to be scaled up." This section discusses the suite of alternative marine fuels and technologies either in use or being considered by industry to meet IMO's 2050 greenhouse gas emission goals, and the more ambitious goals of the zero emissions international effort.

Throughout this section, reference will be made to the terms brown, grey, blue, and green when discussing low- and zero- carbon fuels. While these definitions may differ slightly across fuels, *brown* and *grey* fuels are generally derived from fossil fuel sources, with no capture of GHG emissions. Brown and grey fuels have the highest GHG emissions and often represent the status quo. *Blue* fuels are also generally produced from fossil fuel feedstocks, such as natural gas, but with carbon capture and sequestration processes capturing some greenhouse gas emissions from the process. Blue fuels may have moderate up- and downstream emissions of carbon and other GHGs associated with their production. Other GHGs may include methane (CH_4), which has a much greater global warming effect than CO_2 in the short term and so is of particular concern. *Green* fuels are generally derived using renewable energy sources and sustainable feedstocks and have the lowest greenhouse gas emissions throughout their life cycle.

This section examines four alternative fuels that are commonly discussed in the literature as potential pathways to reducing GHG emissions from the shipping sector. These fuels are ammonia, biofuels, hydrogen, and methanol. From a life cycle perspective, Very Low Sulfur Fuel Oil (VLSFO) and Marine Gas Oil (MGO), the two most commonly used conventional ship fuels, have WtW emissions of 4.12 and 4.04 kg CO_2e per kg fuel, respectively (Comer and Osipova 2021; Kramel et al. 2021).[5] A summary of the life cycle emissions of these fuels, considering peer-reviewed and other estimates, can be found at the end of this section.

1.3 Ammonia

Ammonia (NH_3) has been touted as one of the most promising alternative shipping fuels (IRENA 2021; Englert and Losos 2021). Ammonia has been commercially produced since 1913 using the Haber-Bosch process (Figure 1), which converts Nitrogen Gas (N_2) and Hydrogen (H_2) into NH_3. Ammonia is used widely as a fertilizer in the agricultural sector, chemical feedstock, and refrigerant and is an essential component of selective catalytic reduction (SCR) systems designed to reduce emissions of nitrogen oxides (NOx) from combustion systems.

Ammonia is a colorless gas under room temperatures and pressures, and a liquid when stored at temperatures below -33.4℃ at atmospheric pressure, or at room temperature (25℃) and at a pressure of 9.9 atmospheres. Ammonia has very similar boiling pressures as propane. Ammonia is hazardous to inhale but can be rapidly detected by its odor without special equipment. Under theoretical combustion in air, ammonia forms only nitrogen and water, as shown below.

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O + \text{Heat}$$

Under typical conditions, however, combustion of ammonia leads to the secondary formation of NOx particles, and it is also possible for non-combusted ammonia to escape in exhaust gasses (Kojima

[5] Carbon dioxide equivalent, or CO_2e is a measure of the total global warming potential (GWP) of greenhouse gas emissions, including carbon dioxide, which has a GWP of 1, methane (CH_4), which has a 100-year GWP between 26 and 36, and nitrous oxide (N_2O), which has a GWP of 265 to 298.

2018). Combustion of ammonia also leads to the formation of nitrous oxide (N_2O), a potent greenhouse gas (Li et al. 2021).

Ammonia has an energy content of 18.6 MJ/kg (lower heating value, LHV) and an energy density of 14,100 MJ/m^3 (Kim et al. 2020). Ammonia is an effective carrier of hydrogen, with a higher volumetric energy density and lower storage costs (0.54 \$/kg-H_2 for NH_3 vs. 14.95 \$/kg-H_2 for H_2 over 182 days (Kojima 2018)). Accordingly, ammonia may be used as either a long-term energy carrier, or directly as a zero-carbon fuel. Notably, combustion of ammonia does lead to NOx formation, which is regulated by the IMO, under Regulation 13,[6] and is an ozone precursor and thus requires exhaust gas controls to limit emissions.

Due to its long history of production, transport, storage, and use in a variety of systems, ammonia is potentially a cost-efficient alternative to conventional maritime fuels in terms of fuel price and the availability of existing infrastructure (Kim et al. 2020). Ammonia may be used in a range of propulsion technologies on board vessels. It may be burned in internal combustion engines or combined cycle gas turbines, similar to conventional marine fuels and LNG, but is most efficient when partially decomposed to release hydrogen. Ammonia may also be used in fuel cells, including proton exchange membrane and alkaline fuel cells after cracking, and directly in solid oxide fuel cells, where it is reacted with oxygen to produce electricity (The Royal Society 2020).

While ammonia offers a carbon-free tank-to-wake (TtW) emissions profile, production of ammonia is predominantly achieved through steam reformation of methane (CH_4) to produce hydrogen, which is then combined with nitrogen through the Haber-Bosch process. Currently, production of ammonia is highly energy intensive, consuming around 1.8% of annual global energy output and carbon emissions (The Royal Society 2020). The energy content of ammonia is around 5.17 MWh/MT, requiring 8-12 MWh of energy per MT produced.[7] If the production of ammonia is not decarbonized, then the upstream carbon emissions can offset downstream savings on a life cycle basis.

Brown ammonia production uses fossil fuel feedstocks. Hydrogen is produced through steam reformation of fossil fuels and may emit 1.6 - 3.8 tonnes CO_2 per ton of ammonia, depending on the feedstock used (The Royal Society 2020). Total life cycle emissions of carbon associated with brown ammonia production range from 2.1 - 3.6 MT CO_2e per MT NH_3, with emissions using coal gasification ranging from 6.1 - 7.8 MTCO_2e per MT NH_3 (Liu, Elgowainy, and Wang 2020; Zhang et al.

[6] https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-–-Regulation-13.aspx
[7] https://www.ammoniaenergy.org/articles/round-trip-efficiency-of-ammonia-as-a-renewable-energy-transportation-media/

2013). In the U.S. the average CO_2 emissions from ammonia production are 2.1 MT CO_2e per MT NH_3.[8] The costs of brown ammonia are estimated to be around $550 - $600 per metric ton NH_3 ($0.030-$0.032 per MJ)) (IEA 2019). Notably, the cost of brown ammonia production is linked to the cost of the feedstock. At the end of 2021, when natural gas prices rose significantly, the price of ammonia also rose to $1,120 per MT in Europe,[9] with similar prices seen in the U.S. ($1,022 in October 2021).[10]

Blue ammonia uses blue hydrogen, generated also through steam reformation, but with carbon capture and storage (CCS) systems used to capture CO_2 emissions. Using CCS systems raises the cost of hydrogen by around $0.53/kg-$H_2$ per the International Energy Agency (IEA).[11] Despite the use of CCS systems, production of blue hydrogen captures only around 60-85% of CO_2 emissions and fugitive methane emissions remain an issue (Howarth and Jacobson 2021), and so does not represent a zero carbon pathway. Levelized costs of blue ammonia range from around $600 - $800 per MT ($0.032 - $0.43 per MJ) (IEA 2019).

Green ammonia uses green hydrogen, generated through electrolysis of water using renewable energy forms. Nitrogen is obtained using an air separation unit, constituting 2-3% of the process energy used, and renewable energy is used to power the Haber-Bosch process. Green ammonia pathways, studied by Liu et al (2020) show life-cycle emissions of between 0.22 and 0.45 MT CO_2e per MT NH_3, depending on the pathway, with renewable electrolysis methods producing the lowest life cycle emissions. The levelized costs of green ammonia, that is the net present cost over the lifetime of the facility, range from around $1,600 - $1,850 per MT ($0.086-$0.099 per MJ) (IEA 2019).[12]

Current global ammonia production is about 176 million tonnes per year (The Royal Society 2020), predominantly through steam methane reformation (SMR) to produce hydrogen, which is then fed into the Haber-Bosch process to synthesize ammonia. Ammonia is often blended with methane to improve the combustion characteristics of the fuel (Li et al. 2021), but doing so can lead to issues of

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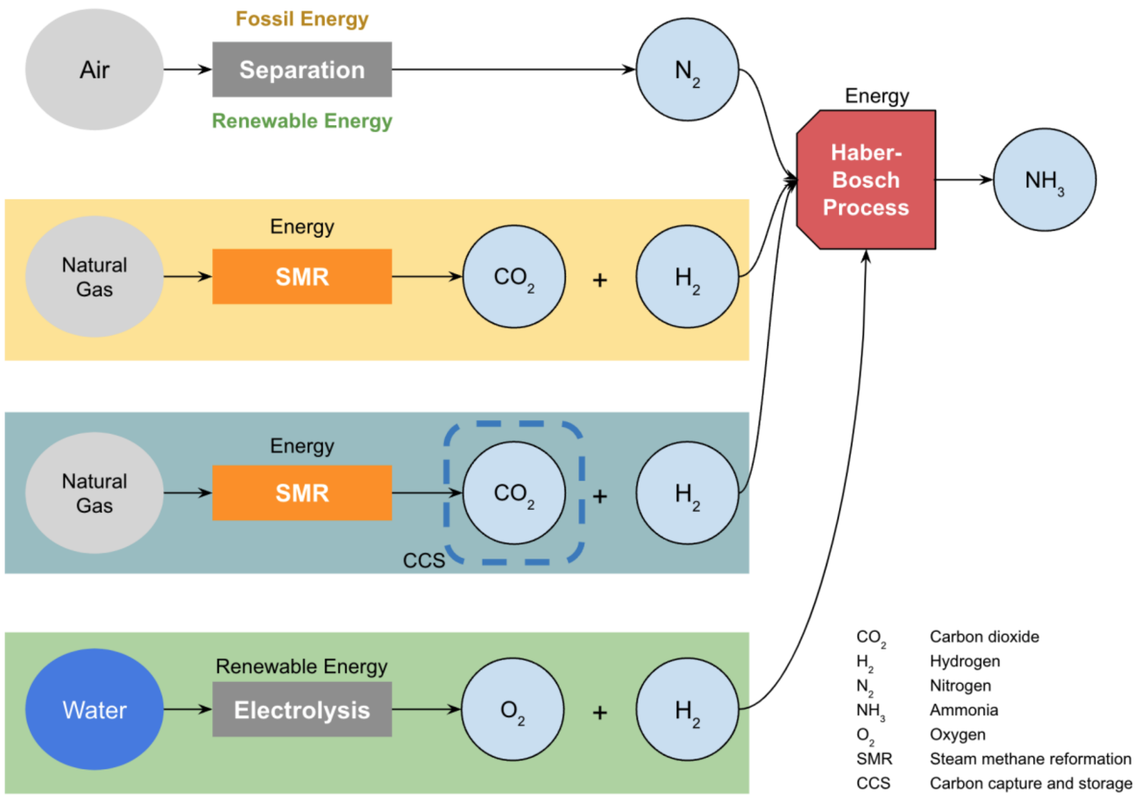
[8] https://www.eia.gov/naturalgas/weekly/archivenew_ngwu/2021/04_01/
[9] https://www.spglobal.com/commodity-insights/en/market-insights/latest-news/energy-transition/121621-global-ammonia-prices-surge-on-european-natural-gas-cost-push
[10] https://www.agweb.com/news/crops/corn/natural-gas-prices-only-account-15-run-anhydrous-ammonia-prices-shows-new-texas-am
[11] International Energy Agency. 2019 The Future of Hydrogen. See https://www.iea.org/hydrogen2019/
[12] 1 MT NH_3 contains around 5.2 MWh of energy, for a cost of $310 - $359/MWh. The levelized cost of energy for energy generation using a diesel reciprocating engine is from $154 - $327/MWh, meaning the levelized cost of green ammonia is up to double the levelized cost of diesel engines. https://www.lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf

methane slip. Ammonia production, storage, and transportation, including maritime transport, are mature sectors, with existing port and shipping infrastructure able to enable first-movers.

Figure 1: Schematic diagram of the formation of ammonia via brown, blue, and green pathways



U.S. ammonia production is estimated at 14 million metric tons in 2021, with significant growth up 21% from 11.6 million metric tons in 2017.[13] Ammonia is produced at 35 plants in 17 states in the U.S. with domestic production outpacing demand. Hydrogen synthesized using SMR accounts for 95% of all hydrogen produced in the U.S. (IEA 2021). The majority of ammonia production is co-located with natural gas reserves, with around 60% of production capacity in Louisiana, Oklahoma, and Texas.[14] The U.S. has over 10,000 ammonia storage facilities, predominantly serving agricultural markets in the Midwest, 88% of domestic consumption is for fertilizer use,[15] but with significant capacity at a number of U.S. ports[16] (The Royal Society 2020). The U.S. also has a network of ammonia pipelines, with the Kaneb pipeline connecting the Midwest from Nebraska to Indiana with the Gulf at New Orleans via a 2,000-mile 6–8-inch carbon steel pipeline.

[13] https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nitrogen.pdf
[14] Ibid.
[15] Ibid.
[16] EERA evaluated facility-level information available from the U.S. EPA under the facility reporting service (https://www.epa.gov/frs) and the USACE Master Docks lists

1.4 Biofuels

Biofuels are created from biomass that has been converted into liquid fuel.[17] Most biofuels are created from plant-based sugars, oils, and terpenes, although some are derived from other sources such as animal fat waste (Hsieh and Felby 2017). See Figure 2 for an overview of various biofuels production pipelines. Biofuels are able to blend with current petroleum fuels, and some are able to be used as drop-in fuels in order to reduce GHG emissions.[18] According to the EIA, the U.S. annual production capacities of biodiesel and renewable diesel/other biofuels were 2,244 million gallons and 1,106 million gallons, respectively, in 2021,[19] up 27.6% over biodiesel production capacity in 2008 (1,759 million gallons).[20]

Biofuels are classified into different generations depending on their feedstock. In total, there are four different generations of biofuels, all with different characteristics. First-generation biofuels are derived from food crops, such as wheat, sugarcane, and soybean (Sikarwar et al. 2017). First-generation biofuels are comparable to marine gas oil (MGO) when comparing life cycle GHG emissions and are therefore not a suitable alternative for reducing GHG emissions from ships (Zhou et al. 2021). Second-generation biofuels are derived from lignocellulosic biomass including wood, forestry and organic wastes, and agricultural residues. These fuels provide large GHG reductions, cutting WtW GHG emissions between 70% and almost 100% when compared to MGO (Zhou et al. 2021). Third- and fourth-generation biofuels are derived from algae/microbes and genetically engineered algae, respectively (Sikarwar et al. 2017). Alalwan et al. (2019) state that "more investigations are needed to achieve higher yields and more cost-effective production processes" when it comes to third- and fourth-generation biofuels. These fuels are currently in early developmental stages and are therefore less viable to replace maritime fuels in the near term. For this reason, this section will focus on first- and second-generation biofuels.

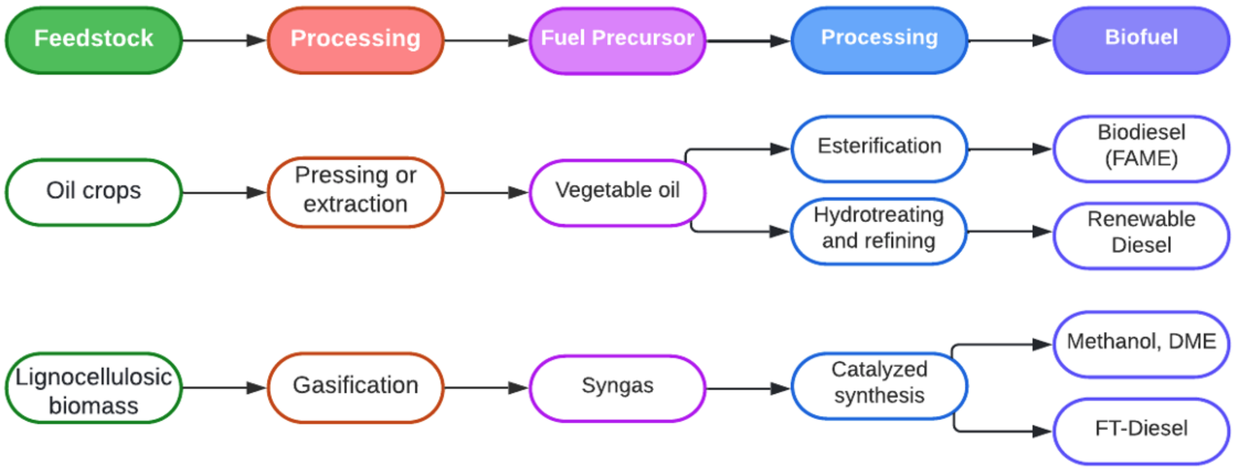
This report will focus on the five biofuels selected by the International Council on Clean Transportation (Zhou et al. 2021) that appear to be the most viable when aiming to reduce life cycle GHG emissions. These fuels are fatty acid methyl ester (FAME), hydrotreated renewable diesel, Fischer-Tropsch (FT) diesel, dimethyl ether (DME), and methanol (covered separately).[21]

FAME, or biodiesel, is produced by transesterification, which occurs when oils are converted into methyl esters (Hsieh and Felby 2017). FAME falls into both the first- and second-generation biofuel categories depending on its feedstock (first-generation if produced from food crops and second-generation if produced from waste fats, oils, and greases (FOGs)). FAME has already established a wide distribution network and is relatively easy to produce. First-generation FAME is not a viable option for GHG reductions due to its indirect land-use change (ILUC) emissions, but second-generation FAME has potential for GHG reductions in current marine engines by blending with conventional marine fuels (Zhou et al. 2021). When used as a neat fuel with second-generation feedstocks, FAME outputs around 25.09 gCO_2e/MJ in WtW emissions, derived from the GREET

[17] https://www.energy.gov/eere/bioenergy/biofuel-basics
[18] Drop-in fuels are functionally equivalent to petroleum-derived fuels and allow for the ability to fully replace these fuels in current engines.
[19] https://www.eia.gov/biofuels/update/table1.pdf
[20] https://www.eia.gov/biofuels/biodiesel/production/archive/2009/2009_12/table1.pdf
[21] Methanol has its own dedicated section later in the paper.

model (Zhou et al. 2021). For reference, MGO outputs around 92.10 gCO_2e/MJ in WtW emissions, derived from the GREET model (Pavlenko et al. 2020).

Figure 2: Feedstock conversion routes for the marine biofuels analyzed (adapted from Hsieh and Felby (2017)).



Currently, blends containing 20% FAME with petrodiesel are common in the diesel fuel market since these fuels don't require any engine modifications. In 2021, BP successfully completed a trial where they used 30% FAME blended with VLSFO (0.5% S m/m) without having to make any adjustments to their vessel engines.[22] At present, the most common biodiesel blend is B20, which contains 6% - 20% biodiesel, and can be used in current engines without modification.[23] Technically, 100% FAME fuels are possible but would require engine adjustments for efficient operations, including biodiesel-compatible lines and gaskets, and more frequent filter cleaning with initial operations. FAME is seen as an alternative to MDO and MGO in low- to medium-speed diesel engines but is more commonly utilized as a fuel additive (Hsieh and Felby 2017). The estimated production cost for FAME is about USD 0.75-USD 1.25 per liter, making it typically 1.3-2.2 times the price of MGO (Brown et al. 2020; Zhou et al. 2021). The global market for FAME is increasing; the market was estimated at USD 16.7 billion in 2020, but is projected to climb to USD 21.2 billion by 2026.[24] The U.S. produced 1,817 million gallons of pure biodiesel in 2020.[25] Although this market is increasing, feedstock supply is not unlimited and demand for FAME from other sectors, such as road transport and heating oil, indicate that it is unrealistic for this biofuel to be produced in large quantities solely for the purpose of marine fuel (Hsieh and Felby 2017).

Hydrotreated renewable diesel (HVO)[26] is produced from FOGs and does not require engine modifications to run in current engines, making it an ideal drop-in fuel to cut GHG emissions. Similar to FAME, HVO is a viable option for cutting GHG emissions only in its second-generation, when waste FOGs are used in production. The process of hydrotreatment necessary to produce HVOs first involves the deoxygenation of the feedstock and the saturation of its double bonds in order to form

[22] https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-and-maersk-tankers-carry-out-successful-marine-biofuel-trials.html
[23] https://afdc.energy.gov/fuels/biodiesel_blends.html
[24] https://www.prnewswire.com/news-releases/global-fatty-acid-methyl-esters-fame-market-to-reach-21-1-billion-by-2026--301305914.html
[25] https://www.eia.gov/biofuels/biodiesel/production/table1.pdf
[26] Hydrotreated renewable diesel is also known as hydrotreated vegetable oil, resulting in the HVO acronym.

alkanes, and then the isomerization and cracking of these alkanes. Current oil refineries have the ability for hydrotreatment, which adds to the benefits of this biofuel (Hsieh and Felby 2017). When used as a neat fuel with second-generation feedstocks, HVO outputs less CO_2 than FAME at around 15.5 gCO_2e/MJ in WtW emissions, derived from the GREET model (Zhou et al. 2021). The estimated production cost of HVO is USD 0.84-USD 1.38, which is slightly higher than FAME (Zhou et al. 2021). Approximately 5 million tonnes of HVO were produced globally in 2017, with this number estimated to reach 6-7 million tonnes in 2020 (Brown et al. 2020).

Overall, the cost of production is typically more expensive than FAME, but the drop-in benefits of HVO may outweigh this cost downside. Also, when HVO is produced, oxygen is removed from vegetable oils, which increases the efficiency of the fuel and increases the shelf life by reducing the possibility of fuel oxidation. HVO's ability to be either blended or used neat allows for greater versatility than some of the other biofuels. Although this is the case, blended HVO will have to be utilized for the foreseeable future, seeing as volume requirements for shipping are too high for solely HVO fuel (Hsieh and Felby 2017). Also, competition for HVO from land uses will affect its availability for marine usage.

FT-diesel is produced through the FT process which encompasses a group of chemical reactions. Hydrogen and carbon monoxide serve as feedstocks for FT and are produced from the gasification of coal, natural gas, or biomass, although production pathways involving such feedstocks as natural gas do not reduce GHG emissions. These gasses are then converted into liquid hydrocarbons. FT-diesel is currently not as technologically ready as other biofuels but has potential to be a viable long-term maritime fuel (IRENA 2021). Production pathways utilizing lignocellulosic biomass as the fuel's feedstock produce fuels lower in carbon, and output no or sometimes negative ILUC emissions (Zhou et al. 2021). With these feedstocks, neat FT-diesel outputs around 2.83 gCO_2e/MJ in WtW emissions, derived from the GREET model (Zhou et al. 2021).This feedstock is widely available in agricultural residues and municipal solid waste. Also, FT-diesel can be utilized as a drop-in fuel or blended without any issues in current engines.

Due to FT-diesel's more recent entrance as a viable biofuel option, high costs are associated with this technology. FT-diesel was around three times more expensive than MGO in 2019 (Zhou et al. 2021). FT-diesel's production cost was estimated to be about USD 0.85-USD 2.36, making it the most expensive biofuel analyzed (Brown et al. 2020; Zhou et al. 2021). Also, these diesels tend to be less energy dense and may hold more impurities than natural gas, resulting in emissions of criteria pollutants (Hsieh and Felby 2017). Current production numbers for FT-diesel in the US were unavailable.

DME can be produced by gasifying lignocellulosic feedstocks, and then converting this syngas into DME first through a reaction producing methanol, and then through a methanol dehydration reaction that produces DME.[27] DME can also be produced through direct synthesis when methanol synthesis and dehydration are combined into the same process. DME is typically a colorless gas under normal conditions and must be maintained at about 75 psi in order to be in liquid form.[28] DME is a high-quality fuel, and its engines have energy efficiency and power ratings comparable to those of diesel

[27] https://www.etipbioenergy.eu/images/AllBiofuelFactsheets2016.pdf
[28] https://afdc.energy.gov/fuels/emerging_dme.html

engines. When used as a neat fuel with second-generation feedstocks, DME has the lowest gCO_2e/MJ of the studied biofuels, outputting only around 1.77 gCO_2e/MJ in WtW emissions, derived from the GREET model (Zhou et al. 2021). Although the use of DME is typically inexpensive when using natural gas as a feedstock, the utilization of lignocellulosic biomass as a substitute is an emerging technology and requires higher costs. Between 2016 and 2020, the spot prices of DME in China ranged between USD 0.27 and USD 0.40 per liter, although these prices are associated with first-generation feedstocks.[29]

This biofuel requires a compression ignition engine specific to DME. A 40% blend of DME has been tested on a vessel, but engine modifications were necessary (IRENA 2021). The ability of DME to be used in large engines is still in question. As of 2020, there were no examples of DME being used commercially as marine fuel (Zhou et al. 2021). Current production numbers for DME in the U.S. were unavailable.

1.5 Hydrogen

Hydrogen (H_2) has been identified as a promising energy carrier and fuel for decarbonizing shipping (Englert and Losos 2021). When consumed in a fuel cell hydrogen produces only energy and water. Hydrogen is a versatile energy carrier and may be converted to different forms, including liquefied and compressed for transport, as well as serving as a feedstock for other fuels.

At room temperature and pressure hydrogen is a clear and colorless gas. 1 kg of H_2 is equivalent in energy content to 1 gallon of gasoline, around 33.3 kWh/kg-H_2.[30] When used as a fuel hydrogen is typically transported and consumed in compressed or liquid form. Storage of compressed hydrogen gas requires high-pressure tanks (5,000-10,000 psi), while liquid storage requires cryogenic temperatures (H_2 boiling point = -252.8℃ at atmospheric pressures).[31] Hydrogen is flammable in all states and should be handled using appropriate safety considerations. Cryogenic conditions mean that liquid hydrogen can cause cold burns, and while biologically inert, if released in high volumes may displace oxygen.

Hydrogen can be produced by a range of processes, including thermal processes, electrolytic processes, and solar driven processes. At present, around 95% of all hydrogen is produced through steam methane reformation of natural gas, so called grey hydrogen. Though hydrogen is a clean fuel when considering tailpipe emissions, production pathways can lead to GHG and criteria pollutant emissions from hydrogen production.

Grey hydrogen uses fossil fuel feedstocks, mainly natural gas, which contains methane, that is reacted with high temperature (700℃ - 1,000℃) steam under pressure (3-25 bar) in the presence of a catalyst to produce hydrogen, carbon monoxide, and small amounts of CO_2. Subsequently, in the water-gas shift reaction, carbon monoxide and steam are further reacted in the presence of a catalyst to produce CO_2 and more hydrogen. CO_2 is then removed from the gas stream. The set of general equations is below.

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[29] https://www.ceicdata.com/en/china/china-petroleum--chemical-industry-association-petrochemical-price-organic-chemical-material/cn-market-price-monthly-avg-organic-chemical-material-dimethyl-ether-990-or-above
[30] https://afdc.energy.gov/files/u/publication/fuel_comparison_chart.pdf
[31] https://www.energy.gov/eere/fuelcells/hydrogen-storage

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2 + \text{heat}$$

While the tank-to-wake stack GHG emissions of grey hydrogen are zero, the SMR process generates criteria and greenhouse gas pollutants, and methane leakage associated with natural gas drilling and transportation infrastructure is a concern. Using the global average grid mix, life cycle emissions of GHGs associated with hydrogen production are on the order of 9.2-11 kgCO_2e per kg H_2, depending on the energy source and country.[32] Review of SMR-related CO_2 emissions at U.S. facilities found a ratio of 9.13 kg CO_2 per kg H_2, and a range of 7.5-10 kg CO_2 per kg H_2 (0.063-0.083 kg CO_2e per MJ fuel) in the literature (Sun et al. 2019). Note that this estimate is not for the full life cycle emissions, but only for the SMR-related emissions. GREET's WtW calculator is largely in agreement with the upper end of the Sun et al. estimate, accounting for CO_2e, at 0.096 kg CO_2e per kg H_2 from natural gas via SMR without CCS.[33]

Blue hydrogen is produced using the same processes as grey hydrogen, but GHGs produced during SMR are captured and stored before they can be emitted to the atmosphere. Per a 2021 assessment from the Hydrogen Council,[34] blue hydrogen life cycle emissions are estimated to range from 1.2-1.5 kg CO_2e per kg H_2 with a Norwegian natural gas feedstock to 3.9 kgCO_2e per kg H_2 (0.01-0.033 kg CO_2e per MJ) with a Russian natural gas feedstock, as the Norwegian grid mix contains a large fraction of renewable hydropower and other renewable sources,[35] compared to the Russian grid, which is dominated by natural gas and coal.[36] The GREET WtW analysis for hydrogen produced from natural gas via SMR with CCS is 0.040 kg CO_2e per MJ.[37] The rate of CCS efficiency has a significant effect on the WtW CO_2e associated with blue hydrogen pathways (Howarth and Jacobson 2021).

Hydrogen can also be produced through electrolysis of water, where an electric current is passed through water, separating it into hydrogen and oxygen. When renewable energy sources are used to provide the energy for electrolysis, the resulting hydrogen is termed green hydrogen. Using renewable energy resources (wind, solar, geothermal, hydro) for energy production for electrolysis can result in virtually zero greenhouse gas and criteria pollutant process emissions. Considering the life cycle of renewable energy generation resources, it is expected that there would be some GHG emissions associated with infrastructure development and manufacturing. NREL estimate that life cycle emissions associated with hydrolysis of water using energy derived from wind resources is around 0.97 kgCO_2e per kg H_2 produced[38] with 78.1% of those CO_2e emissions coming from the manufacturing and installation of wind turbines and foundations. Life cycle emissions of hydrogen

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[32] https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf
[33] https://greet.es.anl.gov/results
[34] https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf
[35] 98% of electricity production in Norway is from renewable sources, https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/
[36] https://www.iea.org/countries/russia
[37] https://greet.es.anl.gov/results
[38] https://www.nrel.gov/docs/fy04osti/35404.pdf

produced using photovoltaic-generated electricity range from 0.7-6.6 $kgCO_2e$ per kg H_2 produced, depending on the life cycle assumptions associated with photovoltaic electricity generation (Kanz et al. 2021). A 2021 report by the Hydrogen Council estimates 2030 GHG emissions associated with green hydrogen production are lower than those found by Kanz et al., varying from 0.3 $kgCO_2e$ per kg H_2 with a renewable hydro energy source to 1.0 kg CO_2e per kg H_2 with a renewable solar energy source.

In order to be used to power oceangoing vessels, vessels may need to be equipped with hydrogen fuel cells to convert hydrogen into electricity for propulsion energy. While hydrogen fuel cells have a lengthy history of powering smaller mobile systems, they have not been applied to powering large oceangoing vessels. Sandia National Laboratories have developed a series of analyses that show that liquid hydrogen fuel cell propulsion systems are feasible across a range of vessel types and sizes, from small fishing trawlers to large oceangoing vessels. The limit of stored energy for the Emma Maersk, a 170,794 GT 14,770+ TEU vessel is around 9,000 MWh, assuming hydrogen storage density of 1.3 kWh/L, enough for a 5,005 NM voyage from Tanjung Pelepas, Malaysia, to Port Said, Egypt.[39] These results are supported by desktop feasibility studies for container shipping between the U.S. and China, and Alaskan fishing and cargo vessels.[40]

The U.S. currently produces around 10 million metric tons of hydrogen each year.[41] Primary demand for hydrogen is for petroleum refining and ammonia production, but hydrogen use is expanding across multiple sectors, including chemical and industrial processes and as a transportation fuel. The U.S. Department of Energy (DOE) has identified the biggest challenge to hydrogen production as cost. Depending on the production pathway, the cost of hydrogen is \$2.50 - \$6.80/kg-H_2.[42] Analysis by KPMG, an accounting and consulting firm, shows differences in the levelized cost of hydrogen produced by different pathways, with grey hydrogen ranging from around \$1-\$2.75/kg-H_2, blue hydrogen from around \$1.50 - \$4.10/kg-H_2 and green hydrogen from around \$2.5 - \$6.0/kg-H_2 as shown in Figure 3.[43] In order to help drive hydrogen costs lower, DOE launched The First Hydrogen Shot in June 2021, with the goal of reducing the cost of hydrogen by 80% to \$1 per 1 kg in 1 decade.[44]

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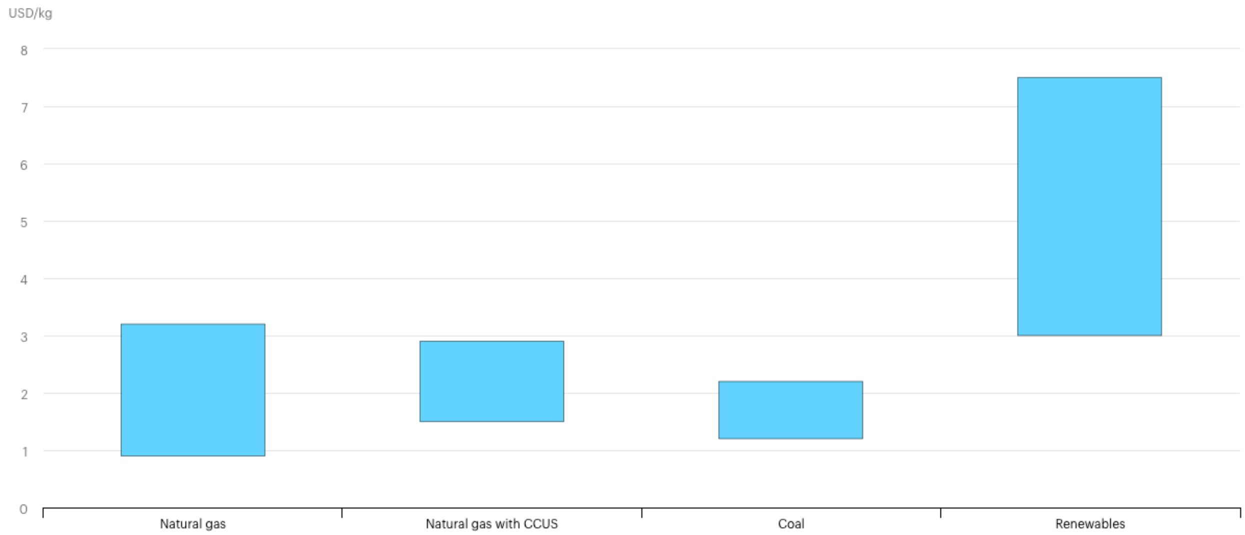
39 https://energy.sandia.gov/wp-content/uploads/2017/12/SAND2017-12665.pdf
40 https://theicct.org/publication/refueling-assessment-of-a-zero-emission-container-corridor-between-china-and-the-united-states-could-hydrogen-replace-fossil-fuels/
https://theicct.org/publication/marine-us-aleutians-hydrogen-jun22/
41 https://www.energy.gov/eere/fuelcells/hydrogen-production
42 https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf
43 https://home.kpmg/xx/en/home/insights/2020/11/the-hydrogen-trajectory.html
44 https://www.energy.gov/eere/fuelcells/hydrogen-shot

Figure 3: Levelized cost of hydrogen produced by grey (natural gas), blue (natural gas w. CCUS), brown (coal), and green (renewable) pathways. (Source: IEA[45])



1.6 Methanol

Methanol (CH_3OH, or MeOH) has a low carbon-to-hydrogen ratio compared to conventional liquid marine fuels and has been increasingly considered as an alternative shipping fuel (IRENA 2021). Methanol is a clear, colorless, flammable, volatile liquid under room temperature and pressure conditions. It is soluble in water, as well as with many organic solvents due to the alcohol group. Methanol freezes at -97.6°C. Methanol can be transported and stored using existing oil and gas infrastructure, with low-cost modifications to fuel lines and gaskets to accommodate methanol. The fuel properties of methanol are similar to ethanol, with 1 gal MeOH = 0.5 gallons of gasoline equivalent.[46]

Methanol may be used directly as a fuel in diesel engines, either with a small amount of diesel pilot fuel or through engine modifications to improve ignition conditions. Methanol is currently used as a road transportation fuel in China, which consumes 4.8 million metric tons per year.[47] DNV-GL report that there are currently more than 20 large ships that are either on order or operational that run on methanol[48] and the investment cost for new build vessels to run on methanol is similar to conventionally fueled vessels. The Stena Germanica, a large 50,000 GT, 32,000 HP ferry was retrofitted in 3 months to run economically on methanol. Methanol is currently available in over 100 major ports and can utilize existing bunkering infrastructure.[49] When burned in marine engines, methanol produces zero SOx, near zero PM, and low NOx. However, conventional combustion of methanol does produce CO_2 emissions, as shown in the equation below, meaning that the pathway of methanol synthesis is critical to methanol being used as a zero or low net carbon fuel.

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[45] https://www.iea.org/data-and-statistics/charts/hydrogen-production-costs-by-production-source-2018
[46] https://afdc.energy.gov/fuels/properties
[47] https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol
[48] DNV-GL Alternative Fuel Insights via https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol
[49] https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

$$2CH_3OH + 3O_2 \rightarrow 2\ CO_2 + 4H_2O$$

Currently most methanol is derived from coal or natural gas feedstocks, but it may also be produced from biogenic feedstocks, including agricultural and forest waste to produce bio-ethanol. Methanol is a common industrial feedstock, used in producing other chemicals like formaldehyde, acetic acid, and plastics.[50]

The most common method for methane synthesis is through using natural gas and/or coal to produce syngas, a mixture of CO, H_2, and CO_2, through gasification or SMR, which is then conditioned and converted to methanol through a catalytic process. Similar to the production of hydrogen, methanol produced from hydrogen derived from coal gasification method is called brown methanol, and methanol from natural gas reformation is grey methanol. Brown methanol produced from coal has estimated life cycle emissions from 170.8-262 gCO_2e/MJ. The energy density of methanol is 15.6 MJ/L,[51] therefore CO_2 emissions per L of brown methanol are around 2.66-4.09 kg CO_2e per L (2.11-3.24 kg CO_2e per kg MeOH).[52] Methanol produced from grey hydrogen has estimated life cycle emissions ranging from 1.42-1.58 kg CO_2e per L (1.12-1.25 kg CO_2e per kg MeOH).

Methanol may also be produced using methods with lower carbon intensity, including using low carbon and renewable energy to reform natural gas, and biogenic feedstocks. Methanol produced from biomass feedstocks, including biogas, municipal solid waste, forestry, and agricultural wastes is typically termed bio-methanol. Life cycle emissions for bio-methanol from 0.05-0.54 kg CO_2e per L (0.04-0.43 kg CO_2e per kg MeOH), per IRENA (2021). Additionally, methanol synthesized using green hydrogen and CO_2 produced using renewable energy sources is generally termed e-methanol. Life cycle emissions for e-methanol range from 0.001-0.52 kg CO_2e per L (0.001-0.41 kg CO_2e per kg MeOH).

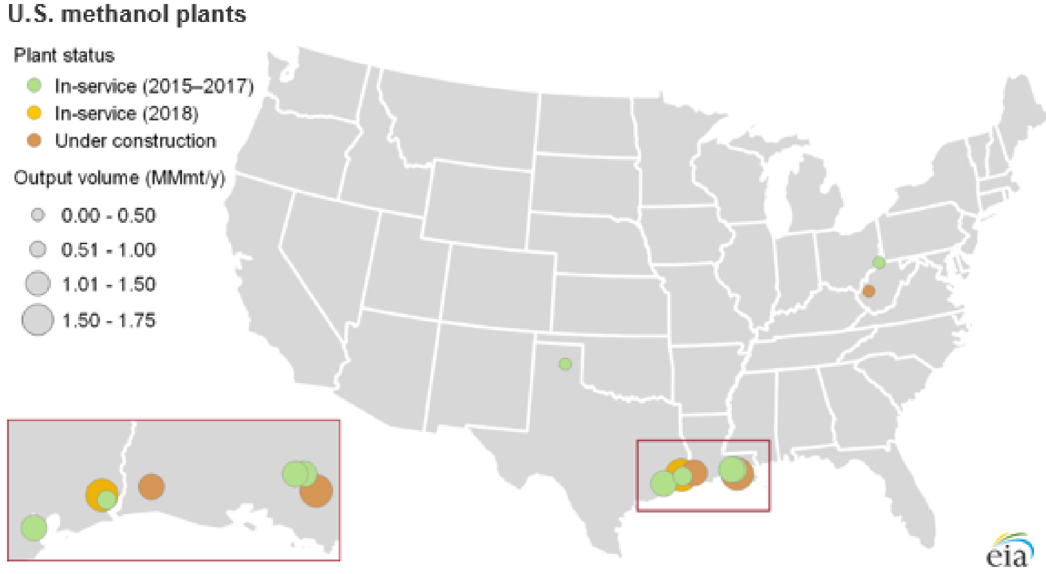
At present, global production of methanol stands at around 100 million metric tons (~125 billion L), with around 65% of methanol synthesized from natural gas feedstocks, around 35% from coal, and less than 1% from biomass and renewables.[53] The nameplate capacity of methanol plants in the U.S. stands at around 9.4 million metric tons per year, as of 2020.[54] The majority of methanol production in the U.S. is in the Gulf Coast region, in Texas and Louisiana, co-located with abundant fossil resources (Figure 4). Bio-methanol and e-methanol are chemically identical to grey and brown methanol, with significantly lower life cycle GHG emissions. If methanol is to become a commonly used fuel in the shipping industry, it is imperative that vessels use bio-methanol or e-methanol.

The cost of brown and grey methanol is in the range \$100 - \$250 per metric ton, while bio-methanol ranges from \$320 - \$770 per metric ton, and e-methanol ranges from \$800 - \$1,600 per metric ton. With process improvements IRENA estimates that bio-methanol costs may fall to \$220 - \$560 per metric ton. E-methanol costs are driven by the cost of green hydrogen, IRENA estimates that with

[50] https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol
[51] Energy density of gasoline =33 MJ/L
MeOH density = 0.792 kg/L
[52] https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol
[53] https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol
[54] https://www.eia.gov/todayinenergy/detail.php?id=38412

anticipated decreases in renewable energy prices, e-methanol costs may fall to $250 - $630 per metric ton by 2050.

Figure 4: Location, status, and capacity of U.S. methanol plants. (Source: EIA[55])



1.7 Other Alternative Fuels

In addition to the four alternative fuels discussed above, this section will also discuss the case for battery-hybrid technologies on board vessels and provide an overview of nuclear fuels for ship propulsion.

1.7.1 Battery-Electric

Batteries are increasingly being deployed for maritime uses. The Maritime Battery Forum lists 441 vessels with battery systems as of 2021, up from 13 in 2010 and 104 in 2016.[56] Vessel battery systems work by charging the vessels using shore-based systems, sometimes supplemented with on board energy systems such as solar. Large batteries held on board the vessel are then used to power electric drive motors, in a manner similar to electric vehicles, albeit on a larger scale. Batteries may also be used alongside conventional 2-stroke engines to provide hybrid power, supplementing the main engine and reducing CO_2e emissions.[57]

The most common battery technologies being employed for propulsion are lithium-ion (Li-ion) batteries. In Li-ion batteries, the cathode is composed of a lithium compound, typically containing a combination or subset of cobalt, nickel, manganese, and phosphate.[58] Individual Li-ion cells, with voltages typically between 3.2 and 3.9 V, are connected in series to achieve desired system voltage.

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[55] https://www.eia.gov/todayinenergy/detail.php?id=38412
[56] https://www.maritimebatteryforum.com/ship-register
[57] https://www.man-es.com/docs/default-source/marine/tools/batteries-on-board-oceangoing-vessels.pdf
[58] Ibid.

An important consideration with Li-ion batteries is degradation over time. Battery degradation is governed by two primary factors, temperature and battery power cycles. Optimal cell temperatures are between 15°C and 30°C,[59] meaning thermal management of the battery system may be necessary when ambient or operational conditions fall outside that range. Charging the battery to a very high level or discharging to a very low level can increase the rate of battery aging, as well as the rate of discharge. Typically, battery systems impose operational thresholds to limit battery charging or discharging at rates that accelerate aging of the battery. All of these factors taken together contribute to an expected lifetime of 10 years for battery systems in the marine environment.[60]

While modern Li-ion batteries are lighter than their lead-acid counterparts (most commonly encountered in conventional car batteries), consideration should be given to space, cooling, and weight limitations of the systems. Table 1 reports the system-level (cells + thermal management, wiring, etc.) weight, volume, and cost of marine battery systems, reported by MAN, a marine equipment manufacturer.[61]

Table 1: Comparison of Weight, volume, and cost parameters for marine battery systems (Source: MAN, 2019)

	System Level
Specific weight (kg/kWh)	11-30
Specific volume (l/kWh)	12-38
Specific price ($/kWh)	500
Energy density (MJ/L)	0.54
Energy density (HFO) (MJ/L)	36.6

As shown in Table 1, the energy density of battery systems falls well below the energy density of HFO bunker fuels. In fact, a battery energy system containing the same amount of energy as a conventional HFO fuel system would take up around 68x as much space to store and deliver the equivalent amount of energy, resulting in concerns about tradeoffs between battery storage capacity and cargo payload. Costs of battery systems have been falling as technology develops but are subject to fluctuations in commodity prices. Li-ion battery pack prices were above $1,200/kWh in 2010 and have dropped by nearly 90% in real terms to $132/kWh in 2021.[62]

Because of the space and energy constraints that accompany marine battery electric propulsion systems, most of the applications of battery systems to date have been on smaller vessels, operated in constrained environments along well-defined routes, such as tugs, offshore supply vessels, and RoPax ferries.[63] The MV Yara Birkeland is the world's first fully battery electric, and ultimately fully autonomous (self-driving and navigating), container ship. She has a capacity of 120 TEU, powered by a 7-9MWh battery pack. The vessel is designed to sail between 3 Norwegian ports, with a maximum

59 Ibid.
60 Ibid.
61 Ibid.
62 https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite
63 DNV-GL via https://safety4sea.com/352-confirmed-ships-are-using-battery-installations/

voyage distance of around 30 nautical miles.[64] The MV Yara Birkeland is anticipated to move to fully autonomous operations in 2022.

In the U.S., Washington State Ferries is undertaking a plan to move toward a zero emissions fleet. Hybrid-electric vessels will be equipped with diesel generators to provide redundancy in the case of unavailable battery power. Washington State is moving ahead with converting their three Jumbo Mark II class ferries, the largest in the fleet,[65] to hybrid-electric propulsion. Washington State Ferries estimate that they consume over 18 million gallons of diesel each year, and the electrification of the ferry system will lead to an estimated diesel fuel reduction of 75-95%.[66]

While the downstream (TtW) CO_2e emissions, i.e., from the battery, are zero, life cycle analysis of batteries for marine propulsion must consider two additional factors. First, consider the emissions associated with electricity generation by the grid. If the generation mix does not include a large share of renewable and low carbon generation sources, then the electricity generated and used for propulsion will still have significant levels of CO_2e associated with it. At present, the U.S. generation mix produces around 373 kg CO_2e/MWh, with significant variation between states depending on the fraction of renewables that contribute to the grid mix.[67]

Second, batteries require significant raw materials and processing during the manufacturing process. Mining and extraction of raw materials, production of battery cells, transport of batteries, operations on board ship, and end of life recycling and reuse all contribute to the life cycle emissions associated with batteries. Analysis by DNV for the Maritime Battery Forum examined two use cases: a platform supply vessel, and a ferry, and estimated emissions of 285 kg CO_2e/kWh battery and 273 kg CO_2e/kWh battery for the upstream (WtT) emissions of the projects, respectively (DNV 2016). These results should be interpreted slightly differently to other life cycle estimates discussed, as they describe the emissions per kWh of battery capacity, not per unit fuel. Another study found WtW emissions of 79.74 kg CO_2e per nautical mile for an existing diesel-engine ferry, compared to 25.77 kg CO_2e per nautical mile for the equivalent battery powered vessel, where 92% of emissions were released during electricity generation and 8% emitted during battery manufacturing (Percic et al. 2020).

1.7.2 Nuclear

Nuclear fuel offers very low GHG and criteria air pollutant emissions and high-power density. On board nuclear-powered vessels, small nuclear reactors heat water to generate steam, which in turn drives steam turbines to generate electricity.

The U.S. Navy has over 50 years of experience safely operating nuclear powered vessels. At present, the U.S. Navy's Naval Nuclear Propulsion Program, known as Naval Reactors, operates 98 reactors. The U.S. Navy has 11 nuclear powered aircraft carriers and 68 submarines. In total the U.S. Navy built 230 nuclear-powered vessels, with a combined 7,100 reactor-years and 166 million miles

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[64] https://www.kongsberg.com/maritime/support/themes/autonomous-ship-project-key-facts-about-yara-birkeland/
[65] https://wsdot.com/ferries/vesselwatch/Vessels.aspx
[66] https://wsdot.wa.gov/sites/default/files/2021-11/WSF-SystemElectrificationPlan-December2020.pdf
[67] https://www.epa.gov/egrid

steamed. The first naval vessel to be powered using nuclear fuel was the USS Nautilus, launched in 1954, becoming the first submarine to travel to the North Pole in 1958.[68]

Nuclear power on board vessels provides for extended periods of operation away from port, with limited support needs compared to fossil-fueled vessels, allowing for greater mobility and operational security. Furthermore, nuclear fuel is very energy dense, which combined with propulsion plants eliminates the need for large-volume liquid or gas fuel tanks.

A single fossil-fuel powered aircraft carrier consumes approximately 500,000 barrels of oil per year under normal operations, generating around 240,000 metric tons of CO_2. Considering the U.S. Navy has 11 aircraft carriers and 68 submarines, by using nuclear fuels these vessels avoid emissions of 4.8 million metric tons of CO_2 per year.[69]

The Nuclear Ship Savannah, launched in 1962, was the world's first nuclear powered merchant ship. She sailed until 1970, traveling 454,675 miles on 163 pounds of uranium fuel. Were she powered by fossil fuels, Savannah would have burned nearly 29 million gallons of fuel.[70] NS Savannah is a registered National Historic Landmark, currently being decommissioned by MARAD, under license from the U.S. Nuclear Regulatory Commission.

The only operational nuclear-powered merchant vessel in 2022 is the Russian vessel Sevmorput. Typically operating on the Northern Sea Route, Sevmorput has a thermal output of 135 MW, with a total capacity of 1,328 TEUs.[71] However, the Sevmorput experiences restrictions and limitations in the ports it can visit, due to safety concerns (Balcombe et al. 2019).

Tank-to-wake emissions from nuclear powered vessels are zero, and when considering the total life cycle emissions of nuclear power, estimates range from 3.5-11.5 gCO_2e per kWh (equivalent to 12.6-41.4 gCO_2e per MJ) (Pehl et al. 2017). Costs of maritime nuclear operations are generally not available due to their classified military nature. The levelized cost of land-based nuclear is around $131-$204 / MWh,[72] with the expectation that mobile maritime systems would be more costly. While not directly comparable, the energy content of one metric tonne of MDO is around 11.9 MWh.

Though nuclear propulsion does have a range of benefits, particularly in military applications, including climate benefits,[73] the complex reactor system is costly to build and maintain and requires extensive specialized training in order to be operated safely and efficiently. Furthermore, the radioactive nature of the fuel raises significant safety concerns in a commercial maritime

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[68] https://www.energy.gov/sites/default/files/2021-07/2020%20United%20States%20Naval%20Nuclear%20Propulsion%20Program%20v3.pdf

[69] Ibid.

[70] https://cms.marad.dot.gov/sites/marad.dot.gov/files/docs/subdoc/116/maradnssavannahhistoryfsfinal051619.pdf

[71] https://www.maritime-executive.com/article/russia-s-nuclear-powered-cargo-ship-makes-arctic-voyage

[72] https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/

[73] https://www.navy.mil/Portals/1/Documents/Department%20of%20the%20Navy%20Climate%20Action%202030.pdf

environment, both for the fuel in use and the waste products, which must be handled by specially trained personnel with the proper equipment in adherence with strict protocols.

1.8 Summary of Life Cycle Well-to-Wake Emissions

Life cycle analysis considers the environmental impacts associated with all life stages of a product, from extraction and processing of raw materials, through manufacturing, transportation, use stages, and disposal. When considering fuels, a common approach is to set the boundaries of the life cycle analysis to focus on well-to-wheels (in the case of land-based transport) and well-to-wake, or WtW, (in the case of ships) analyses. This approach accounts for emissions from the upstream well-to-tank (WtT) phase, and downstream tank-to-wake (TtW) phase. WtT emissions include upstream fuel extraction, refining, production, and transportation. In many instances of low- or zero-carbon fuels, the TtW emissions, that is CO_2e emissions from the fuel system, engine, and stack, are zero or net zero. However, zero emissions fuels at the stack, often have upstream emissions associated with production of the fuel that are essential to consider when analyzing and comparing the benefits of alternative fuels.

Table 2 shows the low- and zero-carbon fuels considered in this report, comparing the WtW CO_2e emissions per unit of fuel, allowing for like-to-like comparisons of the fuels, their CO_2e differences, and their costs. Conversion tables are included in the Appendix.

Production of hydrogen is central to the production of all of the fuels studied. Specifically, developing green hydrogen for use in ships, either in its elemental form, or as a feedstock for other alternative fuels is critical to developing zero emissions pathways to decarbonizing shipping. While the fuels discussed in this report are to be used on board oceangoing vessels, without clean green land-side infrastructure and energy, the life cycle emission benefits of these fuels are diminished. The data presented here showcase the critical importance of greening the grid and electricity generation infrastructure alongside developing zero carbon fuels. Without a decarbonized grid, the benefits of zero-carbon fuels cannot be fully realized.

Table 2: Summary of well-to-wake CO_2e emissions and costs by fuel and fuel type

Fuel	Fuel Type	Well-to-Wake (kg CO_2e per kg Fuel)	Well-to-Wake (kg CO_2e per MJ Fuel)	Costs ($/MT)	Costs ($/MJ)
MGO		**4.023**	**0.094**	**$890 - $990 / MT**	**0.021-0.023**
Ammonia (NH_3)	Brown	2.1-3.6	0.113-0.194	$550 - $600 / MT	0.030-0.032
	Blue	0.42-1.44	0.023-0.077	$600 - $800 / MT	0.032-0.043
	Green	0.22-0.45	0.012-0.024	$1,600 - $1,850 / MT	0.086-0.099
Hydrogen (H_2)	Grey	7.5-10.0	0.063-0.083	$1,000 - $2,750 / MT	0.008-0.023
	Blue	1.2-3.9	0.010-0.033	$1,500 - $4,100 / MT	0.013-0.034
	Green	0.3-1.0	0.003-0.008	$2,500 - $6,000 / MT	0.021-0.050
Biofuels*	FAME	0.94	0.025	$860-1,430 / MT	0.030-0.049
	HVO	0.68	0.016	$1,080 - $1,770 . MT	0.037-0.061
	FT-Diesel	0.12	0.003	$1,090 - $3,030 / MT	0.038-0.105
	DME	0.06	0.002	$400 - $600 / MT**	0.014-0.021
Methanol (CH_3OH)	Brown	2.11-3.24	0.106-0.163	$100 - $250 / MT	0.005-0.013
	Grey	1.12-1.25	0.056-0.063	$100 - $250 / MT	0.005-0.013
	Bio-methanol	0.04-0.43	0.002-0.022	$320 - $770 / MT ($220 - $560 / MT proj.)	0.016-0.039
	e-Methanol	0.001-0.41	0-0.021	$800 - $1,600 / MT ($250 - $630 / MT proj.)	0.040-0.080
Nuclear			0.0126-0.0414	$131-$204 / MWh	

* Biofuel estimates assume second generation feedstocks and unblended fuels.
** Based on first generation feedstock costs.

Vessel Data and Fleet Characterization

This report focuses on vessel activity in two specific groups of vessels. First, we focus on large, privately owned Jones Act and other U.S. flagged vessels, as identified in the U.S. Maritime Administration (MARAD) dataset. MARAD lists 180 oceangoing vessels that are privately owned, greater than 1,000 gross tons, and are U.S. flagged.[74]

Next, we focus on the so-called Federal Fleet, which consists of 30+ vessels that are owned and operated by U.S. Federal Agencies, not including military vessels. In many cases, Federal Fleet vessels are part of the academic research fleet, operated by universities and research institutions in support of various scientific and policy missions.

1.9 Jones Act and U.S. Flagged Fleet

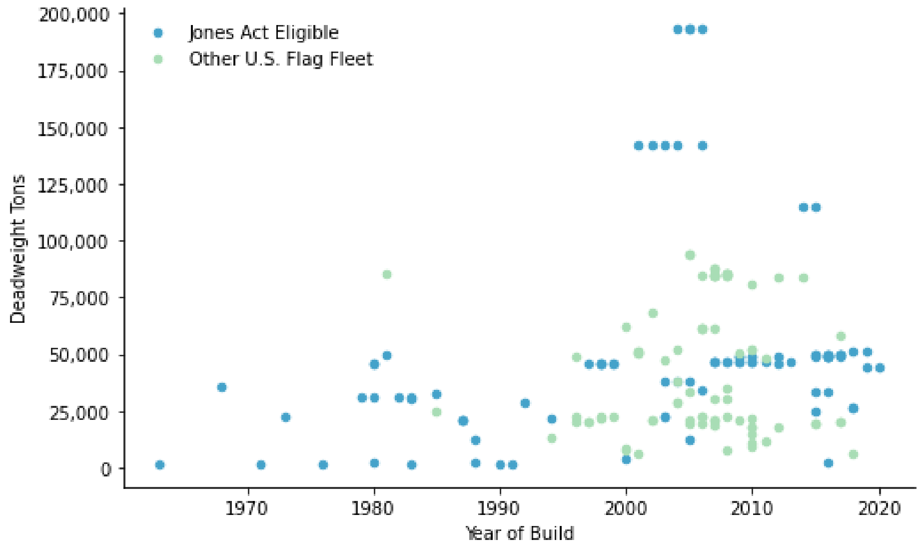
MARAD maintains data on the current JAF and other U.S.-flagged vessels that are privately-owned, oceangoing, self-propelled, larger than 1,000 gross tons, and carry cargo from port to port.[75] While there are thousands of other vessels covered by the Jones Act in the U.S. vessel database, including Great Lakes vessels, fishing vessels, tugs, offshore service vessels, and ferries, among others (Bonello et al. 2022), this analysis focuses on the large oceangoing cargo vessels identified in the MARAD dataset.

We refer to the JAF and other U.S.-flagged vessels together as the U.S. fleet. There are currently 180 vessels in the U.S. fleet. There are 96 vessels in the JAF and another 84 vessels in the U.S. flag fleet that are not Jones Act vessels; that is, they are U.S. flagged but may have been built or partially built overseas and may be in operation transporting cargo internationally.

The distribution of JAF and non-JAF U.S.-flagged fleet vessels is shown in Figure 5. As shown, there is a greater density of vessels built after 2000 than before. The median year of build for JAF vessels is 2006, and 2007 for non-JAF U.S.-flagged fleet vessels. Though the median year of build for the JAF is 2006, there are 31 Jones Act vessels built before the year 2000, that is, 32% of the JAF is over 22 years old. The oldest vessel, the general cargo/reefer vessel Coastal Trader, was built in 1963. The most recent addition to the JAF is the container ship Matsonia, built in 2020.

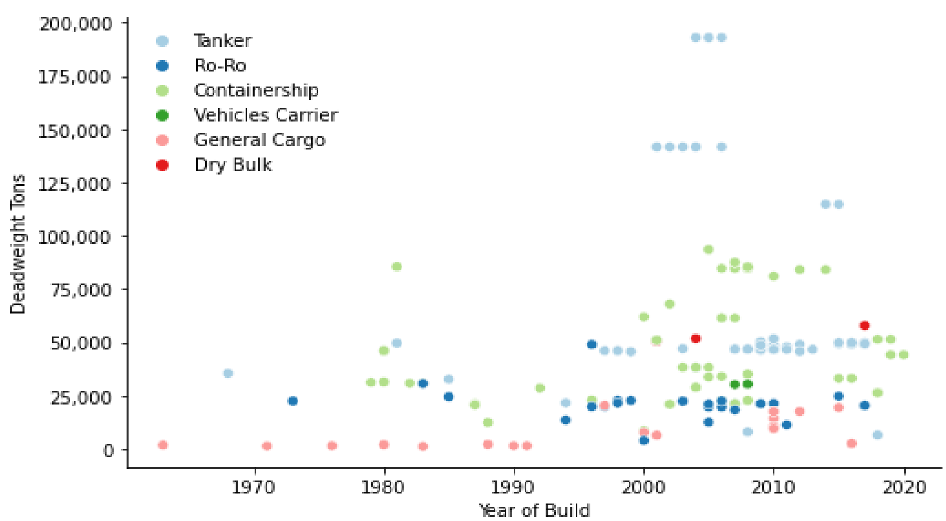
[74] https://www.maritime.dot.gov/sites/marad.dot.gov/files/2021-12/DS_USFlag-Fleet_2021_1014_Bundle_0.pdf
[75] https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics

Figure 5: JAF and other U.S. Flag Fleet oceangoing vessels by year of build and deadweight tonnage



The MARAD dataset groups vessels into six categories, shown in Figure 6 and described Table 3. The majority of JAF vessels are either tankers (59%) or container ships (24%). By tonnage, tankers account for 67% of the JAF, and containers account for 23%. Roll-on/Roll-off (RORO) vessels account for 9% of JAF tonnage, and General Cargo the remaining 1%. The distribution of vessels and tonnage is different for the other U.S. flagged vessels, with containers accounting for 56% of tonnage, followed by RORO vessels (27%). Among the non-JAF, container ships account for 46.4% of the vessels and 56.3% of the DWT. RORO vessels account for an additional 22.6% of the vessels, and 26.8% of the DWT.

Figure 6: JAF and non-JAF U.S. Flag Fleet oceangoing vessels by year of build, deadweight tonnage, and vessel type

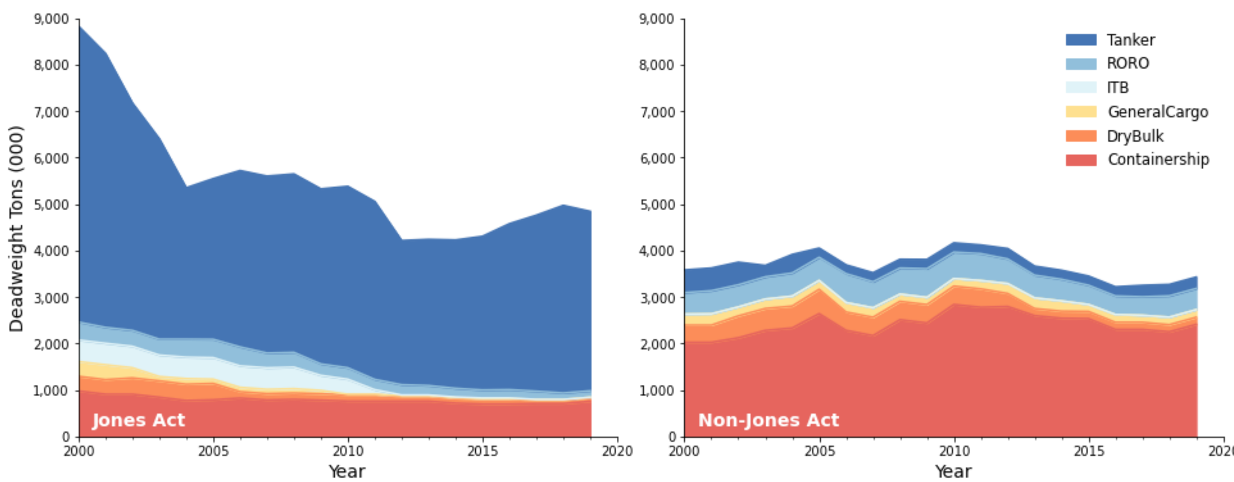


The ten largest vessels in the JAF are all tankers, with the four largest vessels operated by Alaska Tanker Co,[76] and the next five largest operated by Polar Tankers.[77] Taking the JAF as a whole, five firms account for over half the vessels in the fleet,[78] and four firms account for 54.4% of the total deadweight tonnage.[79]

Table 3: Jones Act and other U.S. flag vessel counts by vessel type

Vessel Type	Jones Act	Non-Jones Act
Containership	23	39
Dry Bulk	0	4
General Cargo	9	11
Ro-Ro	7	19
Tanker	57	8
Vehicles Carrier	0	3
Total	**96**	**84**

Figure 7: Change in deadweight tonnage over time in the Jones Act (left) and Non-Jones Act (right) fleets



The capacity of the JAF, measured by deadweight tonnage (DWT), declined by 45.1%, or 3.98 million DWT from 2000 to 2019 due to retirement of older vessels (Figure 7). While the largest percent reductions in DWT were seen in general cargo vessels (-95.3%) and dry bulk vessels (-64.1%), the largest absolute reductions in tonnage were seen in tankers, where capacity reduced by 2.51 million

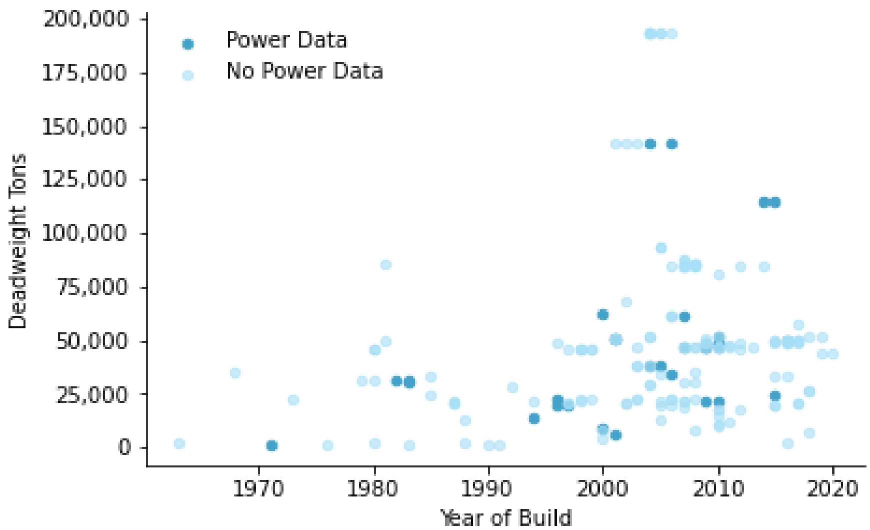
[76] Alaskan Explorer, Alaskan Frontier, Alaskan Legend, Alaskan Navigator
[77] Polar Resolution, Polar Enterprise, Polar Endeavor, Polar Discovery, Polar Adventure
[78] JAF Vessels: Matson Navigation Co (16.7%), Crowley Petroleum Service (12.5%), OSG Ship Management (10.4%), Pasha Hawaii Holdings (6.3%), Polar Tankers (5.2%)
[79] JAF Tonnage: Alaska Tanker Co. (16.1%), Polar Tankers (14.8%), Crowley Petroleum Service (12.2%), Matson Navigation Co. (11.4%)

DWT and integrated tug/barge (ITB) vessels, where capacity reduced by 462,000 DWT from 2000 to 2019.

The capacity of the non-JAF fleet is around 71% of the JAF and has remained somewhat stable since 2000. Overall, tonnage is down by 150,000 DWT (-4.2%). While the Non-JAF container fleet has grown by 386,000 DWT (19.1%), the total capacity of all other vessel types declined over the same period.

We analyzed vessel power data available from Lloyd's Register. We used partial extracts of the total Lloyd's fleet and therefore do not match every vessel. We found matches for 89 vessels, and non-zero power data for 33 of the U.S. flag fleet (Figure 8); summary statistics are shown in Table 4.

Figure 8: Vessels for which main engine power data were available



Data in existing EERA datasets show the mean main engine power for containerships for which there was a data match was 23,861 kW. The mean DWT for containerships that had power data matches is 39,028 DWT. Similar summary statistics are provided for those vessel categories where we were able to match power data. When comparing the data shown in Table 4 with the average DWT and main engine power estimates from GHG4 (Table 35), we find strong agreement between the two data sources when considering DWT and main engine power.

Table 4: Summary statistics for available main engine power data

Ship Type	Count	Mean (DWT)	Mean (kW)	Std (kW)	Min (kW)	Median (kW)	Max (kW)
Containership	11	39,028	23,861	9,707	7,200	22,214	43,070
General Cargo	2	3,893	2,344	2,794	368	2,344	4,320
Ro-Ro	7	21,610	17,743	8,243	12,330	13,320	30,000

Ship Type	Count	Mean (DWT)	Mean (kW)	Std (kW)	Min (kW)	Median (kW)	Max (kW)
Tanker	13	72,877	14,679	17,736	6,570	8,100	54,600

Analysis of the MARAD data shows that the JAF is generally older, with a fleetwide median age of 15.5 years. The median ages for containerships and ro-ro vessels are each 19 years and general cargo vessels have a median age of 39 years. Tankers have a median age of 13 years. With over half of the current JAF being more than 15 years old, many of the vessels operate using older, less efficient technologies that are higher emitting than those found in newer vessels. Accordingly, those vessels may be prime for either replacement or retrofit, with the potential to be first-movers toward low- and zero-carbon fuels, providing they are supported with the appropriate land-side infrastructure. With low- and zero-carbon infrastructure potentially in place to serve JAF, U.S. flagged, and the Federal Fleet, the barriers to decarbonization can be removed or reduced for the broader fleets that call on the U.S. and around the world.

1.10 Federal Fleet

The Federal Fleet is used to describe vessels that are owned and operated by U.S. Federal agencies, not including military vessels. The Federal Oceanographic Fleet, which consists of around 31 vessels supports critical Federal agency operations and supports oceanographic research. Federal Fleet vessels operate all over the world, with capability to operate in all oceans, including polar environments. The Federal Fleet is estimated to decline to 18 vessels by 2030 absent investment (IWG-FI 2016). Following the work of the Interagency Working Group on Facilities and Infrastructure (IWG-FI) under the National Ocean Council's Office of Science and Technology Policy (OSTP), this work focuses on the United States Academic Research Fleet (ARF), National Oceanic and Atmospheric Administration (NOAA) research and survey vessels, and U.S. Coast Guard polar icebreakers and vessels chartered by the National Science Foundation (NSF).

The set of vessels in the Federal Fleet is shown in Table 5. These vessels operate on the Great Lakes and around the world, supporting data gathering, surveying, and research used by a broad spectrum of stakeholders. Furthermore, the *USCGC Healy* and *USCGC Polar Star* provide critical ice-breaking capabilities. Sixteen of these vessels support NOAA's Office of Marine and Aviation Operations,[80] and the U.S. EPA operates the *R/V Lake Guardian* on the Great Lakes, and the *OSV Bold*, formerly the United States Naval Ship (USNS) Bold, which was transferred to EPA in 2004 and was EPA's only oceangoing and coastal monitoring vessel until around 2015, when it entered dry-dock. The primary U.S. Federal agencies that deploy vessels for ocean observing are NOAA and the National Science Foundation (NSF).

A 2017 report by the National Academies of Sciences, Engineering, and Medicine stresses that the research vessels in the Federal Fleet are critical to the ocean observing system (National Academies of Sciences, Engineering, and Medicine 2017). There are three classes of vessels—global class, which have a global range; ocean class, which operate within ocean basins and do not travel

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[80] https://www.omao.noaa.gov/learn/marine-operations/ships

globally; and regional class vessels, which operate more in coastal waters. The National Academies' report finds that the decreasing number of global and ocean class vessels is creating a shortfall in the research and observing abilities of the agencies that operate them (National Academies of Sciences, Engineering, and Medicine 2017), with a need to tailor the size of the fleet to meet existing budget, research, and survey needs.

In 2012, the University National Oceanographic Laboratory System (UNOLS) sponsored the first "Greening the Fleet Initiative" workshop.[81] The goals of this initiative relevant to decarbonization are to promote environmental sustainability and develop guidelines for construction, operation, and recycling of UNOLS vessels. The most recent workshop in 2018[82] reported three key findings relevant to decarbonization. These are

1. Sail-assist may be used for specific operations on smaller vessels
2. Hybrid power systems and new technologies should be considered for future vessels
3. Biofuels and bio lubricants are appropriate on some vessels and can reduce the vessel's overall environmental impact.

The 2016 NOAA Fleet Plan[83] notes that by 2028 the agency will see eight vessels reach the end of their service lives if additional capital investments are not made. While the agency lists a set of six strategies to mitigate the impact of the loss of these vessels, the strategy of integrating emerging technologies is most relevant to decarbonization of the NOAA fleet. While NOAA projects losing eight vessels, their analysis indicates that the best option for replacing capacity would be to build two Class A vessels, designed for oceanographic monitoring, research, and modeling. The 2016 NOAA Fleet Plan reports incremental improvements in efficiency and green initiatives, but that large efficiency gains are limited by the existing mechanical systems. Specific technologies and approaches to low and zero carbon technologies and fuels are not reported.

[81] https://www.unols.org/ships-facilities/unols-vessels/greening-fleet-initiative
[82] https://www.unols.org/sites/default/files/2018inm_6_Corliss_Bruce_VesselOp_101818_0.pdf
[83] https://www.omao.noaa.gov/sites/default/files/documents/The%20NOAA%20Fleet%20Plan_Final_31OCT.pdf

Table 5: Federal Fleet vessels, class, age in 2022, and days at sea

Vessel Name	Class	Age	Days at Sea
Atlantis	*G*	24	300
*Healy**	*G*	21	235
*Joides Resolution**	*G*	33	235
Knorr	*G*	51	300
*Laurence M. Gould**	*G*	24	235
Marcus G. Langseth	*G*	30	300
Melville	*G*	52	300
*Nathaniel B. Palmer**	*G*	29	235
*Polar Star**	*G*	45	235
Roger Revelle	*G*	25	300
Ronald H. Brown	*G*	25	235
Sikuliaq	*G*	7	300
Thomas G. Thompson	*G*	30	300
Atlantic Explorer	*O*	39	180
Bell M. Shimada	*O*	13	235
Endeavor	*O*	45	230
Fairweather	*O*	54	235
Gordon Gunter	*O*	32	235
Henry B. Bigelow	*O*	16	235
Hi'ialakai	*O*	37	235
Kilo Moana	*O*	19	280
Nancy Foster	*O*	31	235
Oceanus	*O*	46	210
Okeanos Explorer	*O*	33	235
Oscar Dyson	*O*	18	235
Oscar Elton Sette	*O*	34	235
New Horizon	*O*	43	230
Pisces	*O*	14	235
Rainier	*O*	54	235
Reuben Lasker	*O*	9	235
Thomas Jefferson	*O*	30	280
Ferdinand R. Hassler	*R*	12	235
Hugh R. Sharp	*R*	16	230
Oregon II	*R*	54	235
Point Sur	*R*	40	180

* NSF chartered vessel

1.11 Port and Dock Facilities

The United States Army Corps of Engineers (USACE) maintains the Master Docks Plus Public Extract,[84] which lists 41,782 unique "navigation units" corresponding to dock locations in the U.S., of which 34,236 are currently active. Of these docks, 604 (1.8%) list bunkering or fueling as a service, 4,526 list handling of petroleum products, 451 list handling of chemicals, and 1,655 list handling of fertilizers. Navigation units listing these commodities were selected as they are likely to have infrastructure that may be similar to the needs of alternatively fueled vessels. Chemicals often require special handling, including temperature and pressure management, which is needed for hydrogen and ammonia storage and transportation. Ammonia is commonly used as a fertilizer in the U.S., 87% of anhydrous ammonia in the U.S. is used as fertilizer,[85] so including facilities with experience handling fertilizers is likely to capture the subset of facilities that handle ammonia. Biofuels and ammonia may be stored and handled in a similar manner to liquid petroleum products, so by identifying the set of facilities that handle those products we have identified the set of facilities that may also be adapted to handle biofuels and methanol. The locations of these facilities are shown in

Figure 9.

Bunkering, petroleum product, chemical product, and fertilizer handling facilities can be found on all coasts and the Great Lakes, as well as throughout the heartland along the inland rivers and waterways.

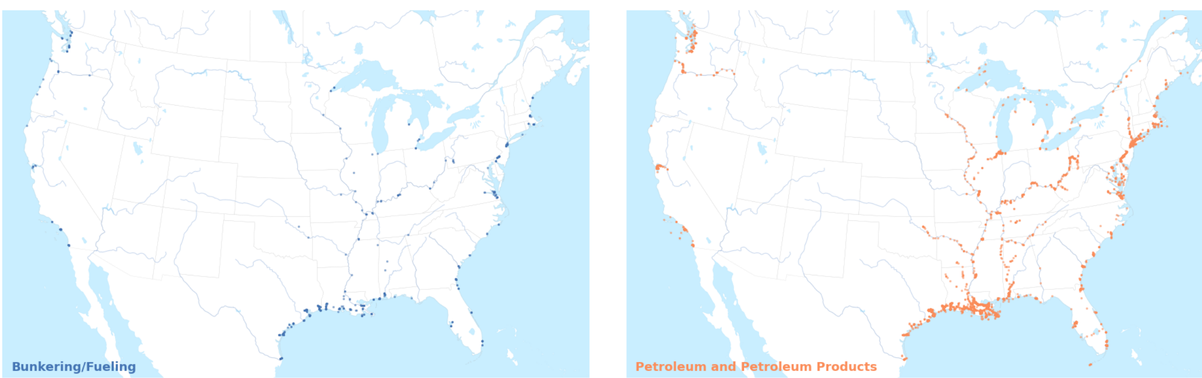
There are 53 docks that include "ammonia" in the "PURPOSE" field of the navigation unit data. At present, there is one facility on the East Coast located in Wilmington, North Carolina. There are five inland ammonia docks on the west coast, two in California (Stockton and Sacramento), one in Portland, OR, and two in Washington state. There are 23 docks in the Gulf states, with only one of those docks being located inland, and the remaining 24 docks are located on the inland rivers connecting to the Mississippi River throughout the heartland (

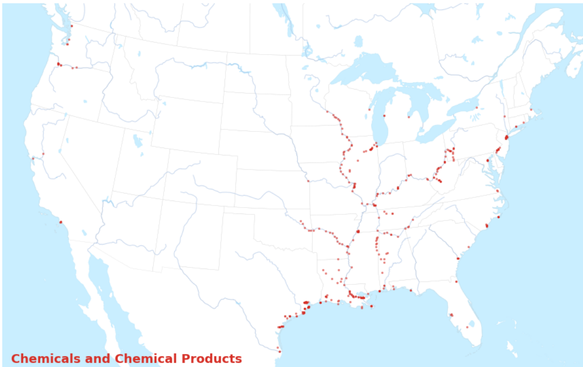
84 https://publibrary.planusace.us/document/8994a6c0-0e57-4182-be2c-66211af5c9b8

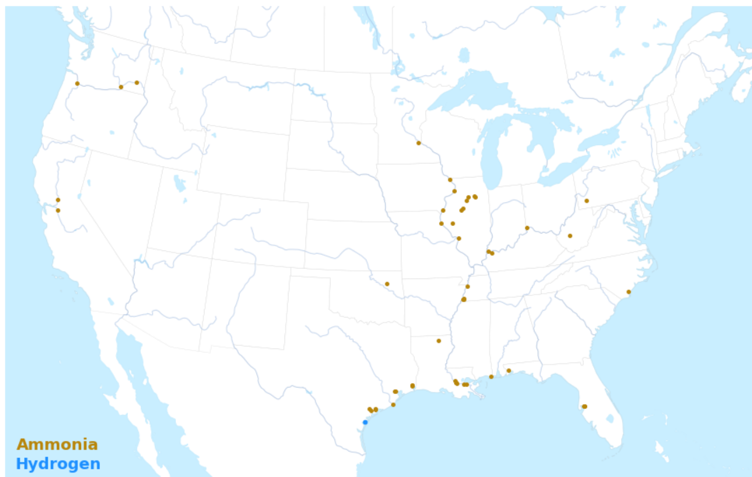
85 https://www.reuters.com/article/us-usa-explosion-ammonia/factbox-types-of-fertilizer-their-uses-and-hazards-idUSBRE93H11S20130418

Figure 9). There are no ammonia facilities located on the Great lakes. A single facility, at the Port of Corpus Christi, Texas, lists receipt and shipment of hydrogen chloride.

Figure 9: Locations of bunkering/fueling (top left), petroleum and petroleum product (top right), chemical and chemical product (center left), fertilizer (center right), ammonia (bottom), and hydrogen docks (bottom) in the continental U.S. Large format versions of these maps are available in the Appendix.







Vessel Activity

1.12 Vessel Activity Background

Understanding the positions and speeds of vessels in the JAF and U.S.-flagged fleets and the Federal Fleet allows for analysis of energy consumption and port calls. By understanding energy consumption by vessel and route, we can then identify which routes may be prime candidates for alternative fuels.

Automatic Identification System (AIS) data from the Marine Cadastre[86] contained vessel movements for 153 of 180 vessels in the JAF and U.S.-flagged fleet and 30 vessels in the Federal Fleet. EERA processed all AIS data for 2019, which served as the base year of analysis, with operations unaffected by the global Covid-19 pandemic that disrupted vessel movements and port operations beginning around March 2020. AIS data coverage is available for vessels on the U.S. East, West, Gulf, and Alaskan coasts, as well as vessels calling on ports in Hawaii and Puerto Rico.

[86] https://marinecadastre.gov/ais/

Note that this analysis is based on observed AIS positions. Where vessels traveled outside of range of the AIS transceivers, those positions are not recorded, and we rely on calculating the difference in time and distance between consecutive observations for each vessel. As such, the estimates in this study may undercount the energy needs of vessels traveling out of AIS transceiver range, which extends approximately 200 NM from the U.S. coastline (including territories).

AIS data, which contained billions of positions, was processed to focus on hourly positional data for the vessels included in this study. Vessel operational mode was determined based on positional speed and distance from port, following EPA's 2021 port inventory guidance. The parameters for establishing operating mode are shown in Table 6.

Port calls were identified based on operating mode, and entrances were identified based on the position at which the vessel first entered hoteling mode at a given port. Clearances were identified as the position at which the vessel first left hoteling mode en route to the next port. Entrances and clearances by vessel are used to identify the most frequently called on ports and port pairs.

Table 6: Operating mode defined by geography and speed criteria

Mode	Geography	Speed
Transit	Outside breakwater	> 3kts
Maneuvering	In port (≤ 1 NM from berth) Outside port (> 1 NM from berth)	> 1kt and ≤ 3kts
Hoteling	At dock	≤ 1kt
Anchorage	At anchorage	≤ 3kt

The power requirements of the vessel, in kWh, are estimated based on the positional data contained in the AIS, including speed over ground ("sog"), draft, and the time difference between successive vessel positions using the Admiralty Formula, in accordance with EPA guidance.[87] Engine load is calculated using the Admiralty Formula as follows

$$Load = \left(\frac{V_{obs}}{V_{design}}\right)^{3} * \left(\frac{D_{obs}}{D_{max}}\right)^{0.66} * \text{SM}$$

Where V_{obs} and V_{design} are the observed positional speed and the vessel design speed, respectively; D_{obs} and D_{max} are the observed positional draft and the maximum observed vessel draft; and *SM* is the sea margin, a scaling factor of 1.1 or 1.15 to account for wind, wave, and current resistance in coastal and offshore environments, respectively.

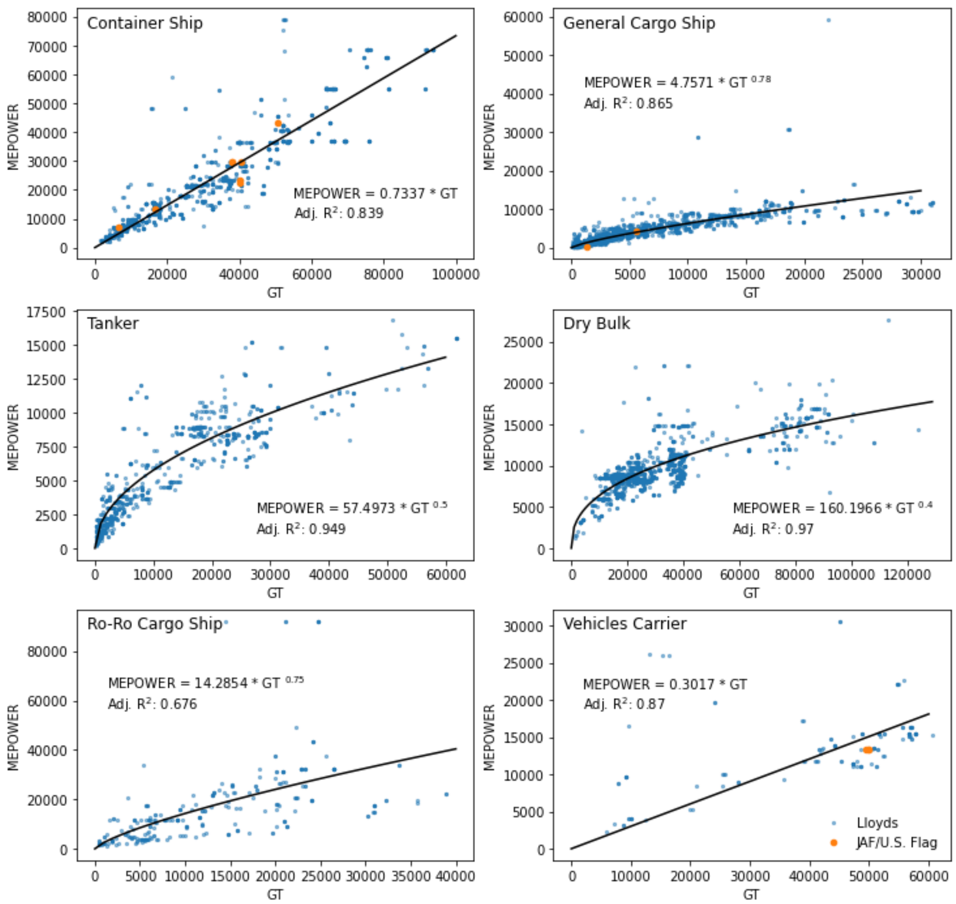
Positional vessel power, in kWh, is then estimated based on the following equation,

[87] https://www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance

$$\text{kWh} = \text{Installed Power} * \text{Engine Load} * \text{Activity Hours} + \text{AEB}$$

Where AEB is the auxiliary engine and boiler load, by vessel type and operational mode, using default loads from GHG4. Installed power was gap-filled, where classification society data were not available, using estimates based on the curves shown in Figure 10. The statistical relationships between vessel gross tonnage, which is known, and main engine power are well-defined. These relationships show strong goodness of fit using simple linear and log-linear ordinary least squares regression models for each of the vessel types in the JAF and U.S.-flagged fleet.

Figure 10: Relationship between vessel gross tonnage and main engine power by vessel type. Orange dots show Jones Act and U.S. flagged vessels.

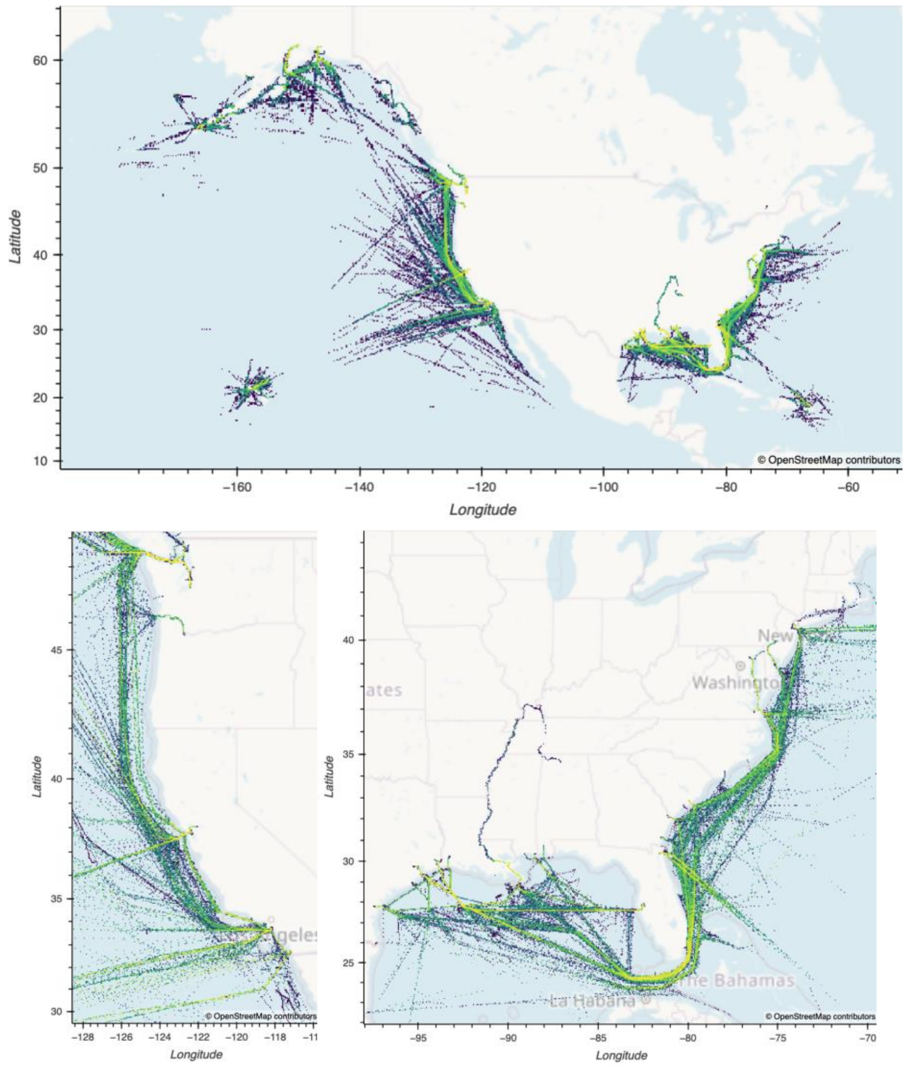


1.13 Jones Act and U.S. Flagged Fleet

Analysis of oceangoing vessels focuses on vessels larger than 1,000 gross tons that are privately owned, included in the MARAD United States-Flag Privately-Owned Merchant Fleet Report, and carry oceangoing cargo from port to port.[88] These data contain 180 total ships, and do not include fishing, tug, or offshore supply vessels. The processed AIS data contained 659,427 unique positional records across 153 unique vessels from 1 January 2019 through 31 December 2019. AIS data shows Jones Act and U.S. flag fleet positions along the east coast, west coast, in the Gulf, along the Alaskan panhandle and southern coast and around Hawaii and Puerto Rico (Figure 11). Note that available AIS coverage does not always extend to distant waters, and so gaps may exist between transits from the west coast to Hawaii and Alaska, for example. These gaps do not affect estimates of port entrances, but may affect estimates of energy use, as the voyages are partially unobserved. As such, estimates of energy consumption are likely conservative, undercounting due to unobserved movements.

Figure 11: AIS positions for U.S. flagged vessels for the entire U.S. (top), west coast (bottom left) and east and gulf coasts (bottom right). Brighter colors show greater density of vessel positions.

[88] https://www.maritime.dot.gov/sites/marad.dot.gov/files/2022-05/DS_USFlag-Fleet_2022_1_16Bundle.pdf



The greatest density of ship traffic can be seen along coastwise shipping lanes between U.S. ports, particularly along the east and Gulf coasts, where limited trans-oceanic AIS tracks are found. Greater density of trans-oceanic voyages is shown on the west coast, including positions for vessels traveling to and from Hawaii and Alaska.

In total, Jones Act and U.S. flag fleet vessels saw 8,278 entrances at U.S. ports in 2019.[89] The top 10 U.S. port pairs, by number of connections in 2019 are shown in Table 7. These data do not include internal intra-port moves less than 12 hours, where the vessel left the dock, and hotel mode, en route to another berth in the same port.

Table 7: Top 10 port-pairs (directional) by number of connections by Jones Act and U.S. flag fleet vessels in 2019

[89] These estimates include some intra-port moves, where the vessel left the dock, and hotel mode, en route to another berth in the same port. Intra-port moves less than 12 hours were cleaned from the data.

Origin	Destination	Voyages
Jacksonville, FL 🔴 🔵	San Juan, PR 🔵	199
San Juan, PR 🔵	Jacksonville, FL 🔴 🔵	198
Tacoma, WA 🔴 🔵	Anchorage, AK 🔵	196
Anchorage, AK 🔵	Tacoma, WA 🔴 🔵	104
New Orleans, LA 🔵	South Louisiana, LA, Port of	103
Los Angeles, CA 🔴 🔵	Honolulu, HI 🔵	103
Long Beach, CA 🔴 🔵	Honolulu, HI 🔵	102
Oakland, CA 🔵	Los Angeles, CA 🔴 🔵	94
Honolulu, HI 🔵	Oakland, CA 🔵	94
Anchorage, AK 🔵	Kodiak, AK	91

🔴 Chemicals and chemical products
🔵 Fertilizer
◉ Ammonia
◉ Hydrogen

As shown in Table 7, three port-pairs account for seven of the top 10 port-pairs. Taken together, entrances at Jacksonville, FL - San Juan, PR; Tacoma, WA - Anchorage, AK; and Los Angeles/Long Beach - Honolulu, HI, account for 902 entrances, or 10.9% of the total. Color-coded circles show port commodity facilities listed in the USACE Master Docks file. As shown in Table 7, all ports listed, other than Kodiak, Alaska, have facilities for handling fertilizer, meaning ammonia bunkering may be possible at these ports. Ports listed as having facilities for chemicals and chemical products may also have facilities for handling methanol, which can also be stored using conventional bunkering infrastructure that has been modified.

Total estimated energy for the Jones Act and U.S. flag fleet is 4,000 GWh in 2019, equivalent to around 337,900 MT of fuel,[90] or around 1.5% of global domestic navigation, as estimated by GHG4.[91] In total, of the 153 large oceangoing cargo vessels studied, tankers accounted for the greatest energy use, consuming 43.1% of estimated energy, followed by containerships at 32.1% and Ro-Ro vessels at 22.8%.

The number of voyages between port pairs identifies the frequency with which vessels transit between the two ports but does not describe the energy used for those voyages. Depending on policy goals it may be preferable to capture as many vessels as possible, or to maximize program efficiency where funds are limited by focusing on the highest energy routes. Results discussed here allow for interpretation and analysis of vessel, call, and energy data across a range of policy scenarios.
We present results primarily in terms of energy consumption,[92] rather than fuel, as energy consumption is the primary input for the fuel required, depending on the energy content of the fuel and varying degrees of engine efficiency. The ten vessels with the greatest energy consumption in 2019 are shown in Table 8. Together, these 10 vessels account for 25.6% of total estimated energy

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90 Assuming MGO with an energy content of 42.8 MJ/kg. The Fourth IMO GHG Study (Table 19 of that report) assuming a base specific fuel consumption of 185 g/kWh, not accounting for the parabolic function of fuel consumption under varying engine loads.
91 See Fourth IMO GHG Study, Table 38
92 1 kWh = 3.6 MJ

consumption. The vessel with the greatest energy consumption was the Marjorie C,[93] a 1,400 TEU, 1,200 automobile Ro-Ro/Container vessel that serves the U.S. mainland and Hawaii. The Polar Enterprise and Polar Adventure,[94] the two next largest consumers of energy are Endeavour-class tankers owned and operated by Polar Tankers, Inc. a subsidiary of ConocoPhillips. These two vessels serve the Trans-Alaskan Pipeline System, lifting crude in Valdez, AK and discharging at five ports along the west coast. Together they account for 6.2% of total fleet energy consumption. The Midnight Sun and North Star,[95] which account for 4.1% of total energy consumption, are owned by TOTE Maritime Alaska, providing Ro-Ro service for larger vehicles, such as 53' tractor trailers between Tacoma, WA, and Anchorage, AK.

Table 8: Top 10 Jones Act and U.S. flag fleet vessels by total energy consumption in 2019

MMSI	Vessel Name	Ship Type	Total Energy	MGO Equivalent (MT)	% Total
367641230	*Marjorie C*	Ro-Ro	287.2	24,150	7.2
367067110	*Polar Enterprise*	Tanker	134.4	11,310	3.4
303031000	*Polar Adventure*	Tanker	110.1	9,260	2.8
369701000	*Midnight Sun*	Ro-Ro	84.4	7,100	2.1
369285000	*North Star*	Ro-Ro	81.3	6,840	2
367438000	*Maunawili*	Container	77.1	6,490	1.9
367003380	*Jean Anne*	Ro-Ro	76.0	6,390	1.9
369390000	*Safmarine Mafadi*	Container	72.0	6,050	1.8
303584000	*Pelican State*	Tanker	53.0	4,460	1.3
36656300	*Overseas Los Angeles*	Tanker	52.7	4,430	1.3

Based on vessel characteristics, speeds, and drafts, we also estimate the energy, in GWh, used by vessels transiting between port pairs, shown in Table 9. Vessels transiting between Los Angeles, CA, and Honolulu, HI, consumed the greatest energy overall on an origin-destination pair basis, accounting for 4.8% of total estimated energy across the fleet, followed by vessels transiting between Houston, TX, and Elizabeth River, VA, part of the Port of Virginia complex, which account for 4.7% of overall energy usage. Considering the San Pedro Bay ports of Los Angeles and Long Beach, vessels visiting Honolulu, HI, from those ports account for 7.6% of all estimated energy use by the Jones Act and U.S. flag fleet vessels in 2019.

Considering the Jones Act and U.S. flag fleet, just 35 of 153 vessels (22.8%) account for 50.2% of the total estimated annual energy. These vessels are shown in the Appendix, Table A4. Together, these 35 vessels, which we term high-flyers, account for 2,446 entrances, following a distribution of origin and destination ports similar to the fleet as a whole, as shown in Table 9.

[93] https://www.pashahawaii.com/services/vessels/mv-marjorie-c
[94] https://polartankers.conocophillips.com/who-we-are/about-us/
[95] http://www.toteservices.com/fleet/vessels-managed/midnight-sun/ and http://www.toteservices.com/fleet/vessels-managed/north-star/

Table 9. Top 10 port-pairs (directional) by total estimated energy by Jones Act and U.S. flag fleet vessels in 2019

Origin	Destination	Total Energy (GWh)
Los Angeles, CA	Honolulu, HI	190.7
Houston, TX	Elizabeth River, VA	187.9
Long Beach, CA	Honolulu, HI	111.7
Tacoma, WA	Anchorage, AK	105.6
Oakland, CA	Los Angeles, CA	104.7
Honolulu, HI	Long Beach, CA	91.6
Kahului, Maui, HI	San Diego, CA	89.8
Anchorage, AK	Tacoma, WA	86.9
San Juan, PR	Jacksonville, FL	76.1
Honolulu, HI	San Diego, CA	71.4

- Chemicals and chemical products
- Fertilizer
- Ammonia
- Hydrogen

These data show frequent voyages between Jacksonville, FL, and San Juan, PR, as well as Anchorage, AK, and Tacoma, WA. Connections from the mainland to Honolulu, HI, are also frequent among the high-flier voyages, with connections between Honolulu and Oakland, CA, and Los Angeles/Long Beach, CA, among the most frequent.

All ports shown in the top ten directional port pairs (Table 9) are listed as having fertilizer handling facilities in the USACE master docks dataset, and thus have the potential for ammonia storage, handling, and bunkering. Table 9 shows that chemical and chemical product facilities, which may help to facilitate methanol bunkering, are available only at mainland ports for connections between California and Hawaii and Florida and Puerto Rico, and continental U.S. ports for connections between the Pacific Northwest and Alaska. None of the top ten port pairs by estimated energy list hydrogen facilities in the USACE Master Docks dataset, but all mainland ports are within a day's drive of hydrogen production facilities, potentially allowing for hydrogen refueling at mainland ports. Hawaii has legislated efforts to develop renewable hydrogen on the islands.[96] Though plans are initially small-scale and focused on land-based transit and fueling, there is potential for development of renewable hydrogen utilizing the state's significant geothermal resources.[97] Hydrogen infrastructure is also in its infancy in Alaska, though the potential to use hydrogen as a transportation fuel has been recognized by the air transportation industry in Alaska,[98] which may lead to additional hydrogen infrastructure development.

Table 10. Top 10 port-pairs (directional) by number of connections for the 35 high-flier Jones Act and U.S. flag fleet vessels that account for up to 50% of estimated energy in 2019

96 https://www.capitol.hawaii.gov/hrscurrent/vol03_ch0121-0200d/hrs0196/HRS_0196-0010.htm
97 https://www.energy.gov/sites/default/files/2014/03/f12/hawaii_renewable_hydrogen_program.pdf
98 https://www.zeroavia.com/alaskaair

Origin	Destination	Voyages
Jacksonville, FL	San Juan, PR	150
San Juan, PR	Jacksonville, FL	149
Anchorage, AK	Tacoma, WA	99
Tacoma, WA	Anchorage, AK	98
Honolulu, HI	Oakland, CA	90
Long Beach, CA	Honolulu, HI	76
Los Angeles, CA	Honolulu, HI	70
Oakland, CA	Honolulu, HI	64
Honolulu, HI	Long Beach, CA	48
Oakland, CA	Los Angeles, CA	45

Chemicals and chemical products Ammonia
Fertilizer Hydrogen

Table 11. Top 10 port-pairs (directional) by estimated energy for the 35 high-flier Jones Act and U.S. flag fleet vessels that account for 50% of estimated energy in 2019

Origin	Destination	Voyages
Los Angeles, CA	Honolulu, HI	186.3
Long Beach, CA	Honolulu, HI	90.8
Kahului, Maui, HI	San Diego, CA	89.8
Anchorage, AK	Tacoma, WA	85.1
Tacoma, WA	Anchorage, AK	79.1
Houston, TX	Elizabeth River, VA	76.6
Honolulu, HI	Long Beach, CA	70.4
Honolulu, HI	San Diego, CA	67.7
San Juan, PR	Jacksonville, FL	61.0
Oakland, CA	Honolulu, HI	58.6

Chemicals and chemical products Ammonia
Fertilizer Hydrogen

The estimated total energy consumption for the Jones Act and U.S. flag fleets was 4,000 GWh. As shown in Figure 12 (bottom left), energy consumption is skewed right, with median energy consumption across all voyages of 0.31 GWh and a mean of 0.48 GWh. Looking at the mean voyage energy by O-D pair, the data are similarly distributed, with a median of 0.35 GWh and a mean of 0.49 GWh. Analysis of the mean duration between O-D pairs shows the data are skewed right, with a median of 4.8 days, and a mean of 10.5 days. 90% of voyages between O-D pairs have a duration less than 22.7 days. Analysis of mean distance between O-D pairs shows a median of 770 nautical miles, and a mean of 1,100 nautical miles.

These data show that, taking the 153 cargo-carrying oceangoing vessels in the Jones Act and U.S. Flag fleet studied, 50% of voyages are less than 770 nautical miles, take less than 4.8 days, and consume less than 0.31 GWh. Similarly, 50% of O-D pairs show mean voyage energy consumption of less than 0.35 GWh. As discussed in the previous section 35 vessels account for 50% of energy consumption, with the greatest energy consumption by this group along routes between Southern

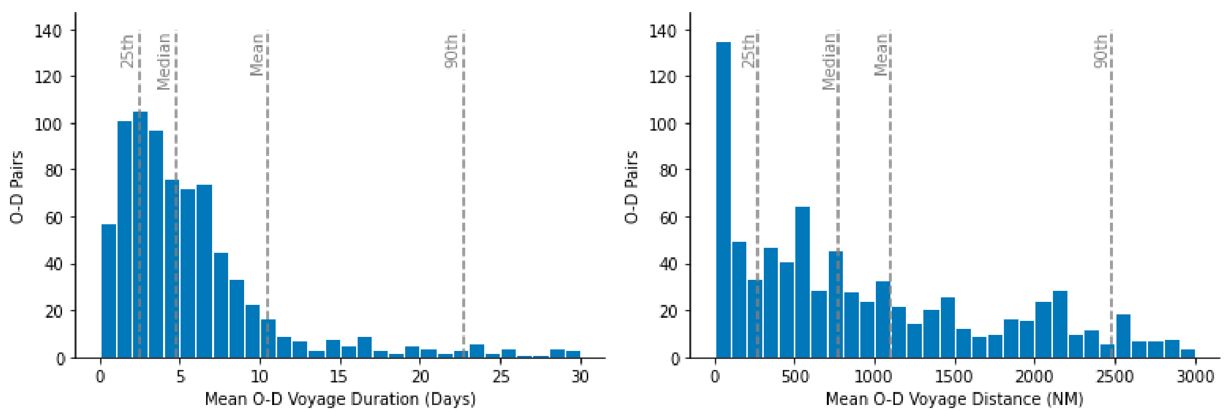
California (Los Angeles, Long Beach, and San Diego) and Hawaii; Tacoma, WA, and Anchorage, AK; Houston, TX, and Elizabeth River, VA; and Jacksonville, FL, and San Juan, PR.

In addition to studying routes and energy use, age of vessel is a likely factor in retrofit and new build/replacement scenarios. Newer vessels may be less likely to be retrofit, as the owners/operators may still be paying off initial capital expenditures for up to 20 years. Figure 13 shows total estimated annual energy consumption as a function of vessel age. With the exception of a few notable outliers, there is generally not a trend toward higher per-vessel energy consumption by newer vessels across the fleet, but fuel consumption by decade of build is higher by dint of there being more vessels built since the year 2000 than before.

By decade, vessels built prior to the year 2000, i.e., older than 22 years, account for 17.9% of total estimated energy demand, and vessels 12 years or older (built prior to 2010) account for 64.7% of estimated energy demand. These older vessels may offer an opportunity for retrofit for low and zero carbon fuels as part of an engine rebuild, or for replacement upon retirement. The top 50% of annual energy consumption is accounted for by just 35 high-flier vessels, shown in the appendix.

In summary, analysis of these data show that there is significant energy consumption along routes from central and southern California ports to Hawaii, accounting for six of the top 10 O-D pairs by total energy consumption, followed by connections from the Puget Sound to Alaska, and Houston, TX, and Elizabeth River, VA. Just 35 vessels account for the top 50% of energy consumption, following a similar pattern to the fleet as a whole, with connections between California and Hawaii accounting for five of the top 10 connections by energy consumption.

Figure 12: Voyage duration (top left), distance traveled (top right), energy consumption (bottom left) and mean O-D pair voyage energy consumption (bottom right)



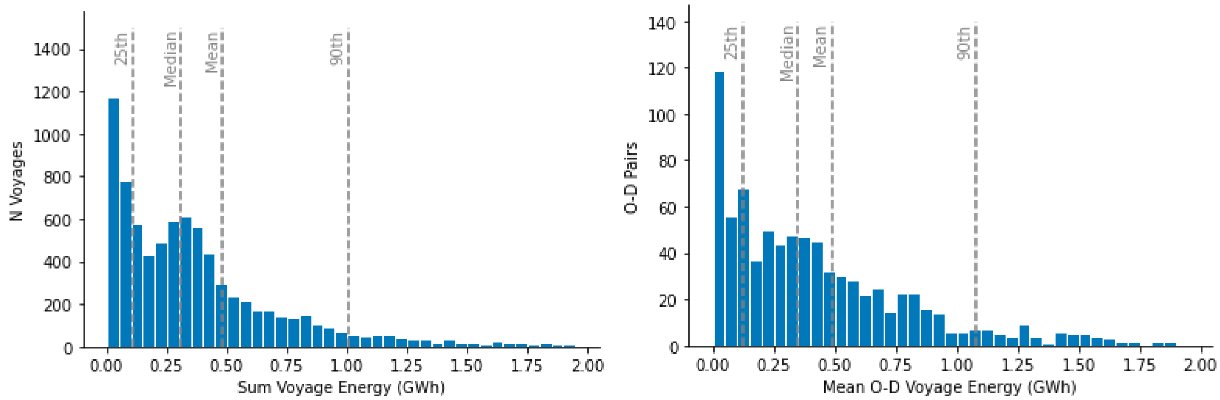
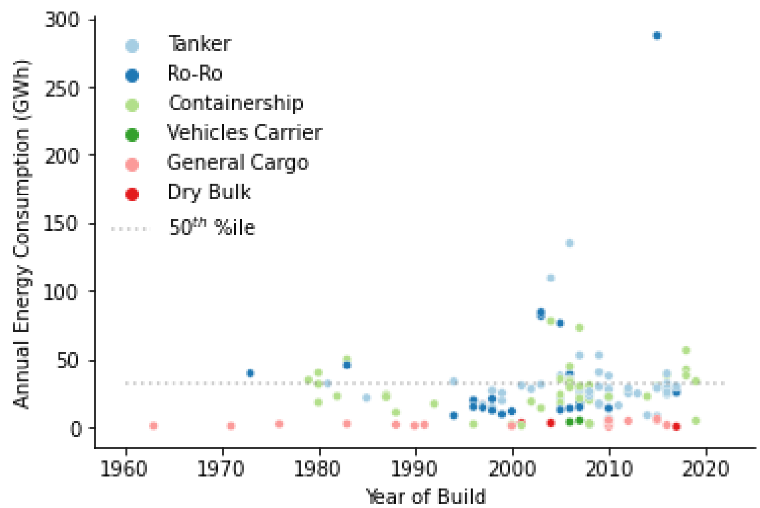


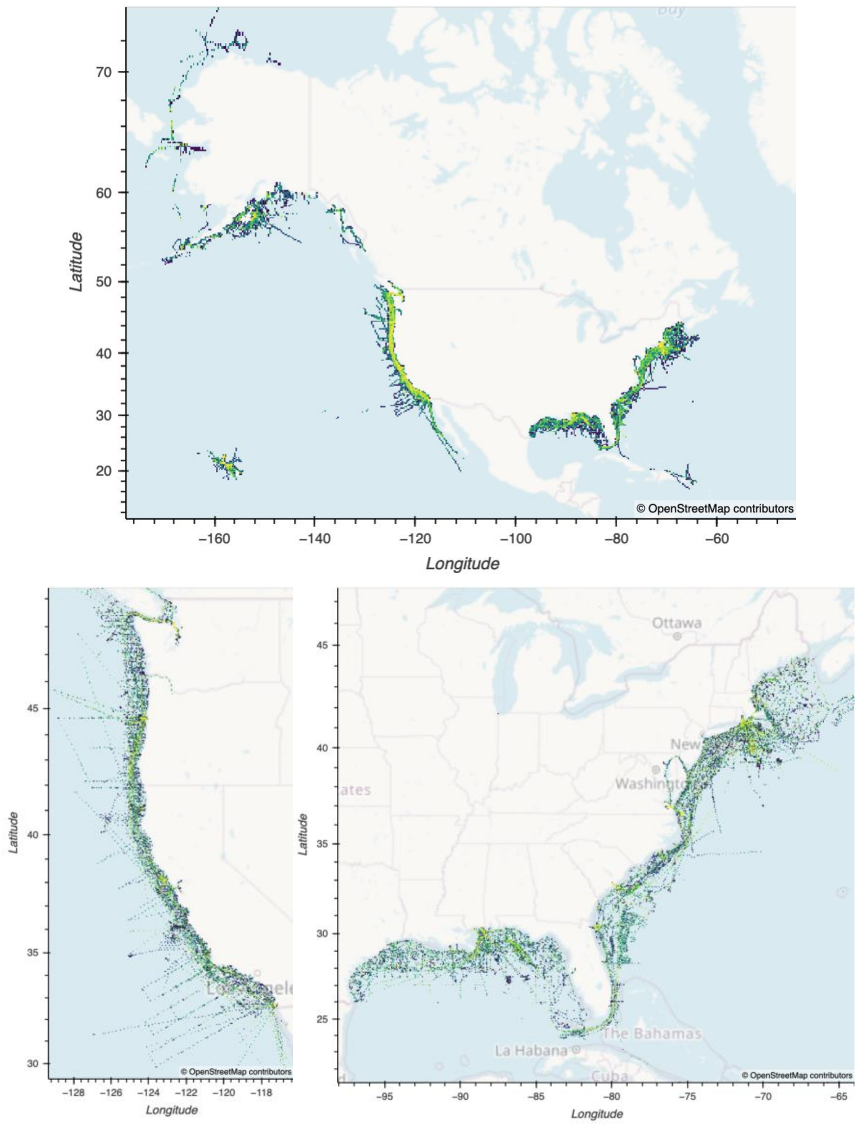
Figure 13: Estimated annual energy consumption (GWh) and year of vessel build



1.14 Federal Fleet

This distribution of vessels in the Federal Fleet is more local than as seen for the Jones Act and U.S. flag fleet vessels, as expected given the purpose, range, and research-oriented mission of the vessels in the Federal Fleet. As shown in Figure 14, Federal Fleet vessels generally do not make coastwise trips. While their research missions may extend far offshore, typically Federal Fleet vessels return to their home port after each voyage. Vessel tracks in the AIS data show Federal Fleet vessels following defined sampling tracks, in many cases running along transects perpendicular to the shore, particularly along the west coast, or running out to specific sampling locations where dense clusters of positions are recorded.

Figure 14: AIS positions for federal fleet vessels for the entire U.S. (top), west coast (bottom left) and east and gulf coasts (bottom right). Brighter colors show greater density of vessel positions.



As shown in Table 12, most vessels return to their port of origin upon completion of the voyage, with vessels departing Pearl Harbor, HI, Pascagoula, MS, and Narragansett Bay, RI, showing the most voyages. There is some voyage connectivity between Seattle, WA, and Kodiak, AK, by Federal Fleet vessels, ranking 11th by total voyages. With the exception of those five voyages between Seattle, WA, and Kodiak, AK, there are no port pairs with more than four voyage connections in 2019.

Total energy consumption by Federal Fleet vessels is estimated at 279.6 GWh in 2019, or around 8.2% of the energy use of the Jones Act and U.S. flagged vessels. The top 10 vessels, by total annual energy use are shown in Table 13.

Table 12: Top 10 ports by origin and destination for Federal Fleet vessels by number of voyages in 2019.

Origin	Destination	Voyages
Pearl Harbor, Oahu, HI	Pearl Harbor, Oahu, HI	36
Pascagoula, MS	Pascagoula, MS	26
Narragansett Bay, RI	Narragansett Bay, RI	22
Charleston, SC	Charleston, SC	21
Honolulu, HI	Honolulu, HI	19
Gulfport, MS	Gulfport, MS	16
Seattle, WA	Seattle, WA	12
San Diego, CA	San Diego, CA	12
Lower Delaware Bay DE	Lower Delaware Bay DE	10
Elizabeth River, VA	Elizabeth River, VA	8

Chemicals and chemical products
Fertilizer
Ammonia
Hydrogen

Table 13: Top 10 Federal Fleet vessels by total energy consumption in 2019

MMSI	Vessel Name	Total Energy (GWh)	% Total
369970573	*Reuben Lasker*	21.9	7.9
369991000	*Henry B Bigelow*	19.4	6.9
369970147	*Bell M Shimada*	17.2	6.2
367241000	*Atlantis*	16.8	6
303913000	*Gordon Gunter*	14	5
369888000	*Okeanos Explorer*	13.6	4.9
369960000	*Fairweather*	12.3	4.4
367977000	*Oceanus*	12.2	4.4
303902000	*Cg Healy*	12.1	4.3
303999000	*Oscar Elton Sette*	11.2	4

The top three vessels by total energy consumption are all Oscar Dyson-class NOAA fisheries survey vessels. Together, they account for 21% of estimated energy consumption. The vessel with the greatest overall estimated energy use in 2019, the *Reuben Lasker*, accounted for around 7.9% of total energy consumption by the Federal Fleet. The *Reuben Lasker* is homeported in San Diego with the primary objective to support fish, marine mammal, seabird, and turtle surveys on the west coast and eastern Pacific Ocean. The *Henry B. Bigelow*, which accounts for 6.9% of total energy consumption, is also an Oscar Dyson-class fisheries survey vessel, homeported in Newport, RI, with a primary objective of surveying marine and bird life along the east coast. The *Bell M. Shimada* accounts for 6.2% of total energy consumption and is homeported in Newport, OR.

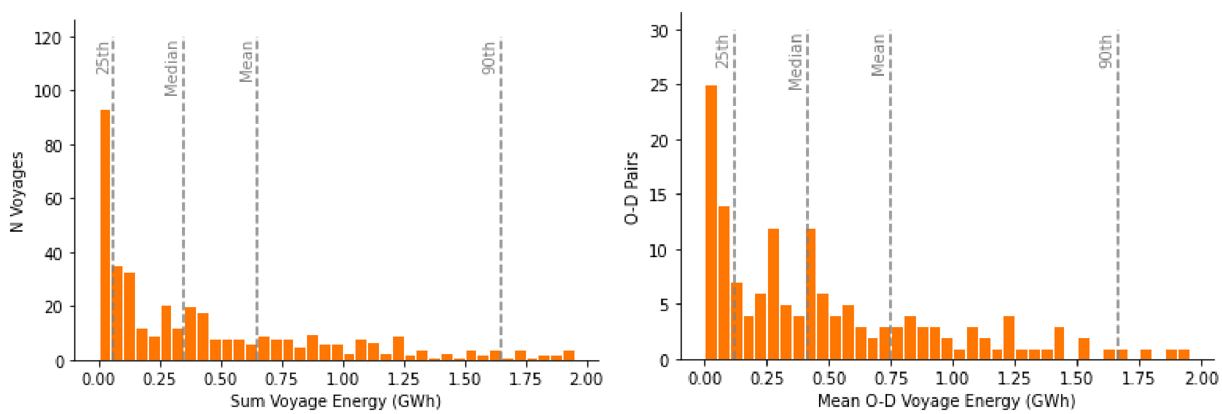
The *Atlantis*, owned by the U.S. Navy and operated by Woods Hole Oceanographic Institution, is specifically designed, and outfitted to support operations of the manned submersible, *Alvin*. Given the global mission of the *Atlantis*, to support the exploration of the world's deepest oceans by the submersible *Alvin*, the *Atlantis* is rarely seen at her homeport of Woods Hole, Massachusetts.

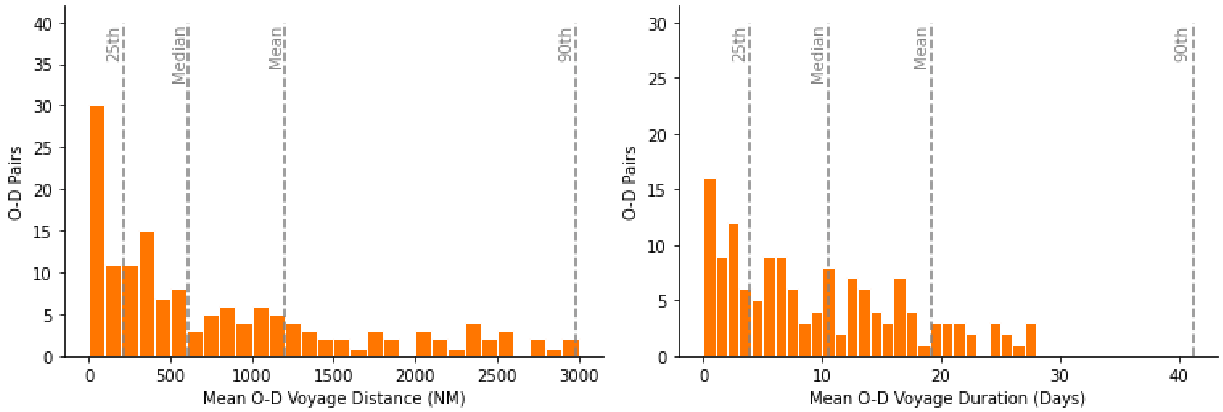
The estimated total energy consumption for the Federal Fleet was 279.6 GWh in 2019. As shown in Figure 15 (bottom left), energy consumption is skewed right, with median energy consumption across all voyages of 0.35 GWh and a mean of 0.65 GWh. Looking at the mean voyage energy by O-D pair, the data are similarly distributed, with a median of 0.42 GWh and a mean of 0.75 GWh. Analysis of the mean duration between O-D pairs shows the data are skewed right, with a median of 10.5 days, and a mean of 19.2 days. 90% of voyages between O-D pairs have a duration less than 41 days. Analysis of mean distance between O-D pairs shows a median of 606 nautical miles, and a mean of 1,201 nautical miles.

These data show that, taking the Federal Fleet as a whole, 50% of voyages are less than 600 nautical miles, take less than 10.5 days, and consume less than 0.35 GWh. Similarly, 50% of O-D pairs show mean voyage energy consumption of less than 0.42 GWh. As discussed above, 3 vessels account for nearly 22% of energy consumption, and vessels generally return to their home port, rather than calling at alternate ports. Vessels departing from Narragansett Bay, RI, account for 8.3% of Federal Fleet energy consumption, followed by San Diego, CA, (5.3%) and Pascagoula, MS (3.7%).

Existing alternative fuel infrastructure may be more limited at Federal Fleet ports. All but three of the top ten ports list fertilizer facilities at their ports, two list chemical and chemical product facilities, and only Pascagoula, MS, lists ammonia facilities. As with JAF and U.S. flag vessels, all of the top ten ports are within 500 miles of hydrogen production facilities, and so bunkering of hydrogen using tanker trucks is possible at all ports.

Figure 15: Voyage duration (top left), distance traveled (top right), energy consumption (bottom left) and mean O-D pair voyage energy consumption (bottom right) for Federal Fleet vessels.





Technology Assessment

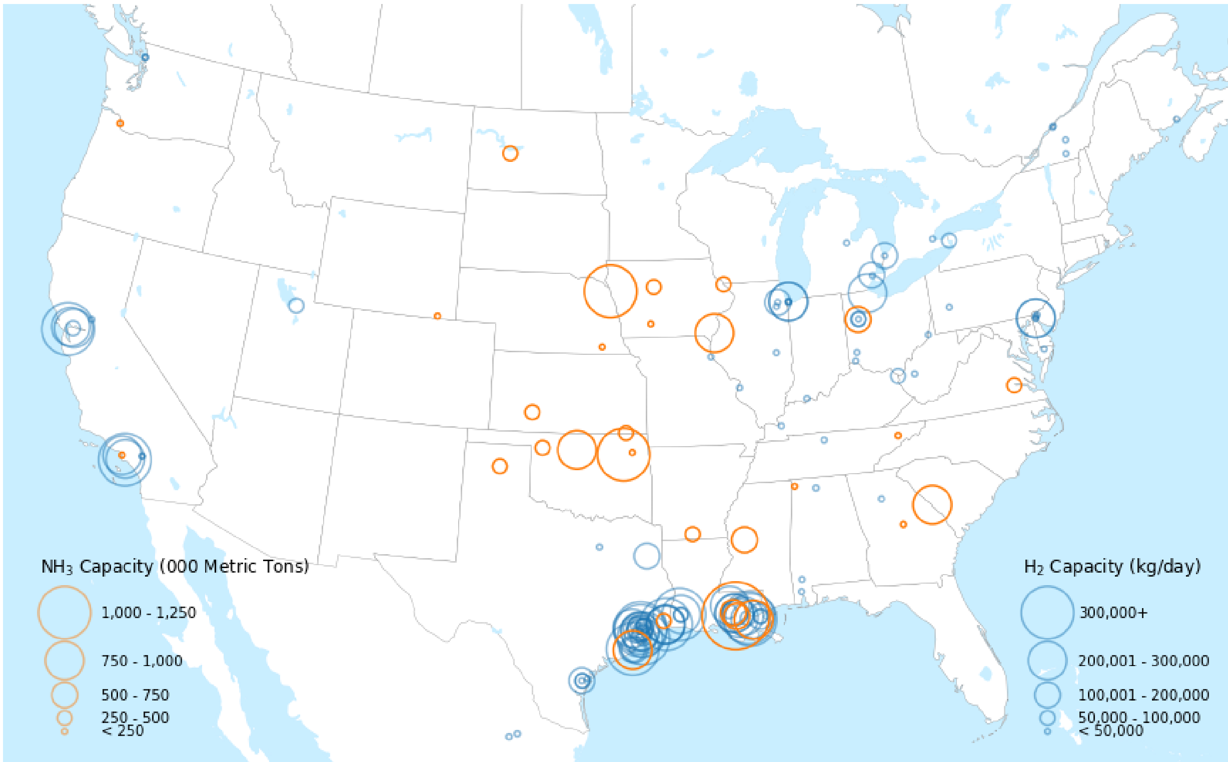
1.15 Ammonia

Ammonia may be used in two-stroke engines that are functionally similar to marine diesel engines. Wartsila expects to have a marine engine that runs solely on ammonia by 2023,[99] and MAN aims to have a commercially available engine by 2024, with a retrofit package by 2025.[100] Both firms note the imperative for safe handling of toxic ammonia as a critical challenge.

Ammonia engines are relatively new technologies, and engine and storage costs are not readily available. A 2020 analysis for Smartport[101] estimates additional costs of around $13 million for an ammonia vessel with a 30 MW engine ($433/kW), including fuel storage tanks, engine, and fuel system. The additional engine cost is estimated at around $5.3 million. The authors note that these costs are estimates and will likely vary on a case-by-case basis.

99 https://www.argusmedia.com/en/news/2234110-wartsila-targets-ammoniaready-engine-in-2023
100 https://www.man-es.com/discover/two-stroke-ammonia-engine
101 https://smartport.nl/wp-content/uploads/2020/09/Cost-Analysis-Power-2-Fuel_def_2020.pdf

Figure 16: Location of ammonia and hydrogen production facilities. Larger circles denote larger capacity facilities.



Ammonia production in the U.S. is concentrated in the Midwest and the Gulf, shown by the orange circles in Figure 16. Two pipelines connect ammonia production facilities in the hinterland with the Gulf region at the mouth of the Mississippi. The Kaneb pipeline runs roughly parallel to the Mississippi and Ohio Rivers, and the MAPCO pipeline connects northern Texas and Oklahoma facilities with those in Arkansas and Nebraska with the Kaneb pipeline in Iowa.

Ammonia may be transported by pipeline, tank truck, and specialized waterborne tankers. Ammonia transport and storage requires low temperatures pressurized systems and/or low temperatures at -34°C (1 bar) or -20°C (10 bar).

Analysis of the potential for fleetwide CO_2 abatement, based on WtW emissions estimates from the literature, shows that by using ammonia fuels, were all vessels in the fleet to switch to ammonia, only blue and green ammonia offer CO_2 abatement potential. Blue NH_3 could reduce CO_2 emissions by between 18.0% - 76.1%, based on assessment of WtW emissions outlined in Table 2, and green NH_3 by 74.4% - 87.5%. Brown ammonia has the potential to increase CO_2 emissions by 4.9% - 19.5%. Due to the lower energy density of ammonia, the payload of fuel required is 130% larger than the equivalent MGO fuel payload, and fuel volume requirements are around 3.2x MGO fuel volumes, meaning that for an equivalent sized fuel tank, the range of an ammonia vessel would be around 31.2% of an MGO vessel.

Table 14: WtW CO_2e emissions, fuel consumption, and fuel costs for MGO and ammonia for the U.S. and Jones Act Fleet based on 2019 activity

	CO_2e Emissions (MT)			Fuel Cost ($million)	
	Lower	Upper	Fuel (MT)	Lower	Upper
MGO	1,365,900	1,365,900	337,900	300.73	334.52
NH_3 Brown	1,632,500	2,798,600	777,400	427.57	466.44
NH_3 Blue	326,400	1,119,600	777,400	466.44	621.92
NH_3 Green	170,800	349,600	777,400	1,243.84	1,438.19

Ammonia is commonly transported using truck tankers for agricultural purposes, and pipelines connect the Midwest to the Gulf. Fertilizer products, of which ammonia is among the most common, are handled at ports throughout the country (

Figure 9) indicating that there is sufficient infrastructure to handle ammonia transport and storage.

In addition to higher engine and fuel system costs, ammonia costs are significantly higher than MGO costs. Brown ammonia, the lowest cost option, is 1.39-1.42x more expensive than MGO for an equivalent energy content and does not offer CO_2 abatement. Blue NH_3 is 1.55-1.86x more expensive, and green ammonia is 4.14 - 4.30x more expensive than MGO.

Considering the median JAF voyage, which consumes around 0.31 GWh of energy, this translates to approximately 97 m^3 of NH_3 fuel storage volume on an energy basis, compared to around 30.5 m^3 for MGO. Taking the fuel system into account, pressurized ammonia systems require approximately 6-7x the space take up by MGO systems. On large vessels that transit shorter voyages, space is not likely to be a determining factor, but the vessel will likely need to bunker more frequently.

Considering the median Federal Fleet voyage, which consumes around 0.35 GWh of energy, this translates to 110 m^3 of fuel storage volume on an energy basis, compared to around 34.4 m^3 for MGO. Not accounting for the fuel system, based on existing tank parameters, the range of a larger

research vessel like the *R/V Roger Revelle*[102] would be cut from 15,000 NM to just over 4,700 NM, or from 52 days to just over 16 days. Pressurized ammonia systems require approximately 6-7x the space taken up by MGO systems, further limiting the operating range of the vessel.
Though widely available and offering significant reductions in GHGs if produced using blue or green methods, high fuel and vessel costs mean ammonia will require significant subsidies to be economically viable for merchant vessels in the short term. Furthermore, there is potential for methane slip from engines when ammonia blends are used. For research vessels, in addition to high fuel costs and environmental spill issues, the fuel space requirements on board space-constrained research vessels, limits the viability of ammonia for the federal fleet.

Table 15 provides a summary of the energy, technology, fuel, safety, and cost parameters of ammonia in the context of decarbonizing maritime transportation. This study estimates that the annual energy demands of the JAF and U.S.-flagged vessels are equivalent to around 5.6% of total U.S. production of ammonia and are roughly equivalent to the total U.S. production of low carbon blue and green ammonia. In 2021 approximately 88% of ammonia production in the U.S. was for fertilizer use, with other uses including plastics, synthetic fibers and resins, explosives, and numerous other chemical compounds.[103] The U.S. imports another 2.2 million metric tons for a total consumption of around 16 million metric tons per year (260,000 MT exported annually). Accordingly, widespread adoption of low-carbon ammonia as an alternative fuel by the JAF and U.S.-flagged fleets will require roughly doubling current production via blue and green pathways.

Based on review of the literature, outlined in Table 2, blue ammonia may reduce CO_2 by 18.0% - 76.1%, compared to MGO, whereas green ammonia reduces CO_2 emissions by 74.4% - 87.5%. Given the wide range in GHG reductions associated with blue ammonia, and the limit in total reductions, blue ammonia may be deployed in the interim, but green ammonia is preferable in the long term for use on board ships. As is the case with many, if not all, low carbon fuels, the source of electricity used to produce the fuel is critical to the carbon intensity of the fuel. These results show that in the case of ammonia, even with the best CCS available, the maximum GHG abatement is roughly on par with the low end of reductions associated with ammonia produced with electricity generated from renewable sources.

102 https://scripps.ucsd.edu/ships/revelle/rv-roger-revelle-specifications
103 https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nitrogen.pdf

Table 15: Summary of ammonia parameters in the context of decarbonizing maritime transport

	Brown	Blue	Green
Volumetric Energy Density (MJ/L)	11.5 MJ/L		
Technology Maturity	Commercially available marine engines by 2025 (new build and retrofit).		
WtW CO_2e (kg per MJ fuel)	0.113 - 0.194	0.023 - 0.077	0.012 - 0.024
Vessel Capital Costs ($/kW)	$433/kW		
Fuel Cost ($/MT)	550 - 600	600 - 800	1,600 - 1,850
Fuel Cost ($/MJ)	0.030-0.032	0.032-0.043	0.086-0.099
MGO Fuel Cost ($/MT) ($/MJ)	890-990 $/MT 0.021-0.023 $/MJ		
Safety	Storage and transport infrastructure is mature. Ammonia leaks may be hazardous to the crew but can easily be detected by smell without equipment.		
U.S. Production (MT)	13.3 million	~0.7 million*	

* 95% of ammonia production in the U.S. is produced via SMR from natural gas feedstocks. The remaining ammonia production is via blue and green pathways

1.16 Biofuels

Biofuels offer a possible drop-in solution for CO_2 reductions. Biofuels may be used in existing engines, fuel systems, and storage tanks with little or no modification. Biofuels may be transported, stored, and bunkered using existing infrastructure. The WtW CO_2 abatement potential for biofuels is dependent on the type of biofuel and, importantly, the feedstocks. In instances where biofuels are derived from vegetation, it is imperative to consider the potential for land use and land cover changes, which have potentially deleterious effects on the environment.

Table 16: WtW CO_2e emissions, fuel consumption, and fuel costs for MGO and biofuels for the U.S. and Jones Act Fleet based on 2019 activity

	CO_2e Emissions (MT)	Fuel (MT)	Fuel Cost ($million)	
			Lower	Upper
MGO	1,365,900	337,900	300.73	334.52
FAME	470,400	500,400	430.34	715.57
HVO	340,100	500,400	540.43	885.71
FT Diesel	59,700	500,400	545.44	1,516.21
DME	29,800	500,400	200.16	300.24

Analysis of the potential for fleetwide CO_2 abatement through using biofuels (Table 16) indicates that, were all vessels in the fleet to switch to biofuels, all biofuels studied offer CO_2 abatement potential. FAME fuels have the potential for abatement of 65.6% of CO_2 emissions, and DME offers up to 97.8% CO_2 abatement. Due to the lower energy density of biofuels, compared to MGO, the payload of fuel required is 48% larger than the equivalent MGO fuel payload, and fuel volume requirements are around 1.9x MGO fuel volumes, meaning that for an equivalent sized fuel tank, the range of a biofuel powered vessel would be around 52% of an MGO vessel, or require a tank that is nearly twice as large.

Biofuel costs are significantly higher than MGO costs, with the exception of DME. DME, the lowest cost biofuel studied, which also has the greatest CO_2 abatement potential, is 0.66x - 0.90x the cost of MGO. FAME is 1.43x - 2.14x more expensive, and FT diesel is 1.81x - 4.53x more expensive than MGO.

Considering the median JAF voyage, which consumes around 0.31 GWh of energy, this translates to approximately 58 m^3 of fuel storage volume on an energy basis, compared to around 30.5 m^3 for MGO. Biofuels may be used in existing MGO engines, with slight modifications to the fuel system and lubrication systems. Fuel volume for biofuels is not likely to be a determining factor.

Considering the median Federal Fleet voyage, which consumes around 0.35 GWh of energy, this translates to 65.6 m^3 of fuel storage volume on an energy basis, compared to around 34.4 m^3 for MGO. Based on existing tank parameters, the range of a larger research vessel like the *R/V Kilo Moana*[104] may be reduced from 10,000 NM to just over 5,250 NM, based on the volumetric energy content of the fuel, though reports from operations on board the *R/V Sproul* at Scripps indicate that the use of biofuels may not lead to increased fueling needs.

Biofuels offer significant reductions in GHGs, particularly DME and FT Diesel, and can be used as drop-in fuels in existing systems. However, the range in fuel costs is broad and, with the exception of DME, not economically viable. Furthermore, biofuels have been shown to not alleviate emissions of

[104] https://www.soest.hawaii.edu/UMC/cms/KiloMoana.php

particulates and black carbon, and if feedstocks are not sustainably harvested or gathered have the potential to lead to land use and land cover change, deleterious to the environment.

Table 17 provides a summary of the energy, technology, fuel, safety, and cost parameters of biofuels in the context of decarbonizing maritime transportation. In 2020, the U.S. produced around 6.9 million metric tons of biodiesel,[105] primarily from corn and grain sorghum. Total production capacity of renewable diesel and other biofuels stands at 2.95 million metric tons, across six plants.[106] Nearly all of the domestically produced and imported renewable diesel is consumed in California.[107]

This study estimates that the annual energy demands of the JAF and U.S.-flagged vessels are equivalent to around 17% of total U.S. renewable diesel and biofuels production capacity. The U.S. imports another 1.25 million metric tons, almost exclusively from Singapore. Accordingly, widespread adoption of low-carbon biofuels as an alternative fuel by the JAF and U.S.-flagged fleets will require increasing domestic production by 17% or increasing imports by around 40%.

Biofuels have the potential to reduce CO_2 emissions by around 66% to 98%, depending on the production pathway. Cost ranges are wide, and are generally not competitive with MGO fuel prices, with the exception of DME biofuels, which are cost-competitive but not commercially available in the U.S.[108]

Due to their lower energy density Biofuels require approximately 50% larger tanks to store the same amount of energy as conventional marine fuels. Accordingly, biofuels may be more appropriate for use on shorter routes for existing vessels. Furthermore, while biofuels have the potential to significantly reduce GHG emissions, and contain no sulfur, they have been indicated to produce NOx and PM criteria emissions during combustion.

Table 17: Summary of biofuel parameters in the context of decarbonizing maritime transport

	FAME	HVO	FT-Diesel	DME
Volumetric Energy Density (MJ/L)	19.2 MJ/L			
Technology Maturity	Can be blended with existing fuels or used in existing marine engines as a drop-in fuel with minor engine modifications.			
WtW CO_2e (kg per MJ fuel)	0.025	0.016	0.003	0.002
Vessel Capital Costs ($/kW)	Minor			
Fuel Cost ($/MT)	860 - 1,430	1,080 - 1,770	1,090 - 3,030	400 - 600

[105] 2020 biodiesel production was 1,857 million gallons. 1 bbl. = 44 gallons. 7.46 bbl. per metric ton https://www.eia.gov/biofuels/biodiesel/production/table1.pdf
[106] 791 MMgal/year as of 1 January 2021 https://www.eia.gov/biofuels/renewable/capacity/
[107] https://afdc.energy.gov/fuels/emerging_hydrocarbon.html
[108] https://afdc.energy.gov/fuels/emerging_dme.html

Fuel Cost ($/MJ)	0.030-0.049	0.037-0.061	0.038-0.105	0.014-0.021
MGO Fuel Cost ($/MT) ($/MJ)	890-990 $/MT 0.021-0.023 $/MJ			
Safety	Existing bunker and transport infrastructure may be used. Safety issues are similar to those of conventional bunkers.			
U.S. Production Capacity (MT)	2.95 million MT			

1.17 Hydrogen

Hydrogen may be used on board in a variety of forms, including dual fuel engines, turbines, and fuel cells. This analysis focuses on fuel cells, which are among the more widely studied applications to date, based on our review of the literature.

The U.S. Department of Energy, through research at Argonne National Laboratory, has undertaken a study of the total cost of ownership and feasibility of powering vessels using hydrogen fuel cells fed by liquid hydrogen storage tanks.[109] Using the *Isla Bella*, a 26 MW 3,100 TEU container ship operated on the Jacksonville - San Juan route by Tote Maritime Puerto Rico,[110] the DOE report presents a set of CAPEX and OPEX estimates, shown in Table 18.

Table 18: Estimated costs of hydrogen fuel cell and conventional marine fuel engines (Source: U.S. DOE)[111]

	Category	Sub-Category	MGO	LH_2 - FC
CAPEX	Propulsion System	Propulsion ($/kW)	280	60
		Aux genset ($/kW)	380	-
		NOx Emission Control ($/kW)	50	-
		Gearbox/Motor ($/kW)	70	120
		Power Conditioning ($/kW)	60	60
		Propulsion Subtotal	**840**	**240**
	Fuel Storage	Fuel Storage ($/m³)	50	2,960
	Vessel Upgrades	Vessel Upgrades ($000)	-	3,000

109 https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-viii5-ahluwalia.pdf
110 http://www.toteservices.com/fleet/vessels-managed/
111 See footnote 109

OPEX	Fuel ($/ton) ($/MJ)	700 (0.016)	4,000 (0.033)
	Maintenance ($000/yr.)	290	607
	Consumables	170	-
	Lifetime overhaul ($000)	-	200

As shown in Table 18, the propulsion systems costs of a liquid hydrogen fuel cell (LH_2 - FC) are considerably lower (0.21x) than the engine costs for a conventionally fueled vessel operating using MGO. NOx controls are not necessary for Tier III performance when using liquid hydrogen, but fuel storage system costs are around 60x the costs of MGO storage. Additionally, the DOE report assumes a hydrogen cost of $4 per kg, compared to $0.7 per kg for MGO. The total CAPEX expenditures estimated by DOE for the *MV Isla Bella*, a 26 MW 3,100 TEU container ship, are $12.76 million for a MGO powered vessel, and $19.39 million for a hydrogen-propelled vessel.

The DOE study assumes that the vessel would be refueled once per round trip from Jacksonville, FL, to San Juan, PR, with four 820m^3 tanks providing storage. The size of these tanks is equivalent to around 99 TEU,[112] and these larger tanks would require additional space compared to conventional MGO storage tanks, therefore reducing payload.

U.S. hydrogen production is on the order of 10 million metric tons per year. According to the most recently released data on production in North America from the U.S. DOE,[113] much of the hydrogen production in the U.S. is in Texas (41.9%), Louisiana (26.4%), and California (15.4%), which together account for 83.7% of total U.S. hydrogen production.

Table 19: WtW CO_2e emissions, fuel consumption, and fuel costs for MGO and hydrogen for the U.S. and Jones Act Fleet based on 2019 activity

	CO_{2e} Emissions (MT)			Fuel Cost ($million)	
	Lower	Upper	Fuel (MT)	Lower	Upper
MGO	1,365,900	1,365,900	337,900	300.73	334.52
H_2 grey	903,800	1,205,000	120,500	120.50	331.38
H_2 blue	144,300	470,000	120,500	180.75	494.05
H_2 green	35,900	120,100	120,500	301.25	723.00

Analysis of the potential for fleetwide CO_2 abatement through using hydrogen (Table 19) indicates that, were all vessels in the fleet to switch to hydrogen, all hydrogen types studied offer CO_2 abatement potential compared to MGO. Grey hydrogen fuels have the potential for abatement of

[112] 1 TEU ≅ 6.1m x 2.44m x 2.59m ≅ 33.2m^3
[113] https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america

33.8% of CO_2 emissions, and blue H_2 offers up to 89.4% CO_2 abatement. Green hydrogen offers the greatest abatement potential at 97.3% abatement compared to MGO.

Due to the higher energy density by mass of hydrogen, compared to MGO, the payload of fuel required is just 64% of the energy equivalent MGO fuel payload. However, even when stored cryogenically, hydrogen's volumetric energy density is around 23% of MGO. Accordingly, fuel volume requirements are around 4.3x MGO fuel volumes, meaning that for an equivalent sized fuel tank, the range of a hydrogen powered vessel would be around one quarter that of an MGO vessel. Furthermore, due to the cryogenic requirements of liquid hydrogen, additional space is required for the fuel system, including cooling apparatus, with total space requirements around 7.7x that of MGO on a per-unit energy basis.[114]

Considering the median JAF voyage, which consumes around 0.31 GWh of energy, this translates to approximately 131.3 m^3 of fuel storage volume on an energy basis (not including additional fuel system space requirements), compared to around 30.5 m^3 for MGO. Hydrogen fuels require significant engine modifications, or the use of fuel cells, all of which are considerably more expensive than conventional fuel systems.

Considering the median Federal Fleet voyage, which consumes around 0.35 GWh of energy, this translates to 148.2 m^3 of fuel storage volume on an energy basis, compared to around 34.4 m^3 for MGO. Reports from planning at Scripps indicate that the use of hydrogen is appealing for a smaller regional vessel, if used in a diesel-hybrid system, as fuel cell-powered motors are quiet, and the risk of environmental damage from spills is low.

Depending on the hydrogen production pathway fuel costs may be lower than for MGO. Grey hydrogen costs may be as low as 40% of MGO costs, or roughly on par. Blue hydrogen is also potentially lower cost per unit fuel, ranging from 60% of MGO, up to 1.48x the cost of MGO. For green hydrogen, which has the greatest CO_2 abatement potential, costs range from on par with MGO up to 2.16x the cost of MGO.

Hydrogen offers significant reductions in GHGs, if produced through blue or green methods, but requires an entirely different fuel and propulsion system, with cryogenic tanks that take up considerably more space on board than conventional fuel tanks. The range in fuel costs is broad, and lower than MGO in some cases for grey and blue hydrogen, but propulsion and fuel system costs are high.

Table 20 provides a summary of the energy, technology, fuel, safety, and cost parameters of hydrogen in the context of decarbonizing maritime transportation. In 2020, the U.S. produced around 10 million metric tons of hydrogen, primarily through SMR.

This study estimates that the annual energy demands of the JAF and U.S.-flagged vessels are equivalent to around 1.2% of total U.S. hydrogen production, though much of the currently produced hydrogen is used as a feedstock for fertilizer and in refining. Accordingly, widespread adoption of low-

[114] https://smartport.nl/wp-content/uploads/2020/09/Cost-Analysis-Power-2-Fuel_def_2020.pdf

carbon blue and green hydrogen as an alternative fuel by the JAF and U.S. flagged fleets will require significant investment in blue and green hydrogen production facilities, as blue and green H_2 production accounts for less than 5% of global H_2 production.

Hydrogen has the potential to reduce CO_2 emissions by around 33% to 91%, depending on the production pathway. Cost ranges are wide and are generally not competitive with MGO fuel prices, particularly for blue and green hydrogen, which are as much as 1.7x-6.1x the price of MGO.

Hydrogen has lower volumetric energy density than MGO and requires cryogenic systems to maintain the liquid state of the fuel. Accordingly, hydrogen fuel systems require up to around 7x more space than conventional fuel systems, making retrofits on board large oceangoing vessels challenging, and unfeasible on smaller research vessels. Given these constraints, hydrogen fuels may be more likely to be adopted on board new-build vessels, which can be designed to optimize space for cargo vessels and on-board research vessels. Designs for the *Zero-V* hydrogen powered research vessel[115] show the hydrogen tanks mounted above deck aft of the pilot house.

Hydrogen storage infrastructure at U.S. ports is very limited. Analysis of hydrogen production facility locations shows that all port regions on the U.S. East, West, and Gulf coasts are within 500 miles, approximately one day's driving distance for a LH_2 delivery truck, of a production facility. This proximity means that bunkering from LH_2 delivery trucks is both feasible, and the most likely near-term bunkering option for ocean going cargo and research vessels.

Table 20: Summary of hydrogen parameters in the context of decarbonizing maritime transport

	Grey	Blue	Green
Volumetric Energy Density (MJ/L)	8.5 MJ/L		
Technology Maturity	Vessels may need to be equipped with hydrogen fuel cells to convert hydrogen into electricity for propulsion energy. Hydrogen fuel cells have not been commercially applied to powering large oceangoing vessels.		
WtW CO_2e (kg per MJ fuel)	0.063 - 0.083	0.01 - 0.033	0.003 - 0.008
Vessel Capital Costs ($/kW)	Propulsion system: $240/kW Fuel storage: $2,960/$m^3$ Vessel upgrades: ~$3 million		
Fuel Cost ($/MT)	1,000 - 2,750	1,500 - 4,100	2,500 - 6,000
Fuel Cost ($/MJ)	0.008-0.023	0.013-0.034	0.021-0.050
MGO Fuel Cost ($/MT) ($/MJ)	890-990 $/MT 0.021-0.023 $/MJ		

115 http://glosten.com/wp-content/uploads/2018/07/SAND2018-4664_Zero-V_Feasibility_Report_8.5x11_Spreads_FINALDRAFT_compress.pdf

Safety	Flammable in all states, should be handled using proper safety considerations. Cryogenic conditions mean that liquid hydrogen can cause cold injuries. Biologically inert, but if released in high volumes may displace oxygen.
U.S. Production Capacity (MT)	10 million MT

1.18 Methanol

Methanol is a liquid under ambient conditions, is stable, easy to handle, and can be stored for extended periods without degradation. Methanol is close to a drop-in fuel using existing fueling distribution, storage, and bunkering infrastructure. Methanol cannot be used directly in existing two- and four-stroke engines, but with retrofit modifications to the injection, storage, and fuel handling systems, MAN reports that existing four-stroke engines and fuel systems can run on methanol.[116] New build dual fuel engines, that can natively run on methanol have been ordered to supply power for eight 16,000 TEU container ships being built by Hyundai Heavy Industries for A.P. Møller-Maersk.[117]

IMO estimates the capital costs for retrofit and new build for a 24 MW Ro-Ro vessel to operate on methanol with a tank capacity for three days sailing. These estimates are shown in Table 21.

Table 21: Estimated costs of methanol new build and retrofit engines

	Category	MeOH (new build)	MeOH (retrofit)
CAPEX	Engine and Equipment ($/kW)	229.2	145.8
	Other equipment ($/kW)		145.8
	Shipyard Costs ($/kW)		145.8
	Fuel Storage ($/m^3)	0.1	

IMO presents total costs for a new build with a methanol engine and fuel system are on the order of $5.6 million for a 24 MW Ro-Ro vessel, and retrofit costs are estimated at $10.5 million, 1.875x new build costs, for a total cost of $437.4/kw. A 2015 report by FCBI for the Methanol Institute[118] reports estimated retrofit costs from diesel to dual fuel at between $323/kw and $451/kw (2022$) all in, which is aligned at the upper end with the IMO estimate.

116 https://www.man-es.com/marine/strategic-expertise/future-fuels/methanol
117 https://www.man-es.com/company/press-releases/press-details/2021/08/25/milestone-order-for-world-s-largest-methanol-dual-fuel-engine
118 https://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf

As of 2020, the U.S. produces around 9.4 million metric tons of methanol per year,[119] with production concentrated in the Gulf Coast, specifically in Texas and Louisiana, with additional capacity in West Virginia (Figure 4). Methanol may be distributed, stored, and bunkered using existing infrastructure, with minor modifications to account for the lower viscosity and different fuel properties of methanol.

IMO identifies all aspects of methanol bunkering, storage, and handling as mature[120], with the exception of fire detection, which requires infrared detection systems as methanol fire is not visible to the naked eye. IMO finds that methanol fuel systems are mainly built from well-known components and mature maritime technology. The greatest challenges identified by industry are primarily related to the low viscosity of methanol, requiring safeguards against leakages in the fuel system and fire safety systems.

Table 22: WtW CO_2e emissions, fuel consumption, and fuel costs for MGO and methanol for the U.S. and Jones Act Fleet based on 2019 activity

	CO_2e Emissions (MT)			Fuel Cost ($million)	
	Lower	Upper	Fuel (MT)	Lower	Upper
MGO	1,365,900	1,365,900	337,900	300.73	334.52
MeOH Brown	1,533,200	2,354,300	726,600	72.66	181.65
MeOH Grey	813,900	908,300	726,600	72.66	181.65
MeOH Bio	28,900	312,400	726,600	232.51	559.48
E-MeOH	200	297,800	726,600	581.28	1,162.56

Analysis of the potential for fleetwide CO_2 abatement through using methanol (Table 22) indicates that, were all vessels in the fleet to switch to methanol, all methanol types studied, other than brown methanol, offer CO_2 abatement potential compared to MGO. Grey methanol fuels have the potential for abatement of 40.4% of CO_2 emissions, and bio-methanol offers up to 97.9% CO_2 abatement. E-methanol offers the greatest abatement potential at 99.9%+ CO_2 abatement compared to MGO.

Due to the lower energy density by mass of methanol compared to MGO, the payload of fuel required is 115% (2.15x) of the energy equivalent MGO fuel payload. Accordingly, fuel volume requirements are around 2.15x MGO fuel volumes.

Depending on the methanol production pathway, fuel costs may be significantly lower than for MGO. Brown and grey methanol costs may be as low as 0.24x-0.54x of MGO costs. Bio-methanol is also potentially lower cost per unit fuel, ranging from 0.76x-1.7x the cost of MGO. For E-methanol, which has the greatest CO_2 abatement potential—offering near-zero WtW CO_2 emissions—costs range from 1.90x up to 3.48x the cost of MGO.

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[119] https://www.eia.gov/todayinenergy/detail.php?id=38412
[120] https://greenvoyage2050.imo.org/wp-content/uploads/2021/01/METHANOL-AS-MARINE-FUEL-ENVIRONMENTAL-BENEFITS-TECHNOLOGY-READINESS-AND-ECONOMIC-FEASIBLITY.pdf

Methanol offers potentially significant reductions in GHGs, with a fuel volume trade off, but can be used as a drop in fuel with minor modifications to the existing system. The range in fuel costs is broad, with bio- and E-methanol, which offer the greatest CO_2 reductions, also significantly more expensive than MGO.

Table 23 provides a summary of the energy, technology, fuel, safety, and cost parameters of methanol in the context of decarbonizing maritime transportation. This study estimates that the annual energy demands of the JAF and U.S.-flagged vessels are equivalent to around 7.8% of total U.S. production of methanol, most of which is located in the Gulf Coast region. Pipelines connect natural gas fields in west Tests and New Mexico to production facilities in the Gulf. At present, most methanol produced in the U.S. is derived from natural gas feedstocks. Accordingly, widespread adoption of low-carbon methanol as an alternative fuel by the JAF and U.S. flagged fleets will require significant shifts in current production toward blue and green pathways, which can produce significant GHG benefits.

Grey methanol reduces CO_2 by around 40% compared to MGO, whereas bio- and E-methanol reduce CO_2 emissions by upwards of 98%. Given the limit in total GHG reductions associated with grey methanol, it may be useful in the interim as a transition fuel, but bio- and E-methanol are preferable in the long term for use on board ships from a carbon abatement perspective.

Table 23: Summary of methanol parameters in the context of decarbonizing maritime transport

	Grey	Brown	Bio-methanol	E-methanol
Volumetric Energy Density (MJ/L)	15.8 MJ/L			
Technology Maturity	May be used directly as a fuel in diesel engines, either with a small amount of diesel pilot fuel or through engine modifications to improve ignition conditions.			
WtW CO_2e (kg per MJ fuel)	0.056 - 0.063	0.106 - 0.163	0.002 - 0.022	0 - 0.021
Vessel Capital Costs ($/kW)	Minor additional costs for slight engine modifications			
Fuel Cost ($/MT)	100-250	100-250	320-770	800 - 1,600
Fuel Cost ($/MJ)	0.005-0.013	0.005-0.013	0.016-0.039	0.040 - 0.080
MGO Fuel Cost ($/MT) ($/MJ)	890-990 $/MT 0.021-0.023 $/MJ			
Safety	May be distributed, stored, and bunkered using existing oil and gas infrastructure, with low-cost modifications. All aspects of methanol bunkering, storage, and handling are mature, with the exception of fire detection.			

U.S. Production Capacity (MT)	9.4 million

1.19 Factors Affecting Investment Decisions

Vessel operators face a set of decisions in determining the fuel choice set for their vessel. For existing vessels and their fuel systems, the choice set is limited by the capability of the vessel to receive and store fuel, move fuel through the fuel system, and release the energy of the fuel in the engine. Furthermore, waste, exhaust, and fuel return must be managed. Accordingly, so-called drop-in fuels may appeal more to existing vessels, as their fuel qualities allow them to be used in existing systems with minor modifications to the fuel system. Table 24, excerpted from Table 9 in Uria-Martinez et al. (2021), summarizes the fuel choice elements and enabling/determining factors. In weighing these factors vessel owners and operators may determine the optimal strategy for investment (or no investment) in their vessel, considering fuel parameters, space constraint on board vessels, availability, safety, environmental impact, and economic costs.

Table 24: Enabling and determining factors affecting fuel choice

Fuel Choice	Enabling Factors	Determining Factors
Fuel	Bunkering Storage Handling	Fuel price Availability
Technology	Engine-Fuel match Pre-/post-treatment	Installation/retrofit cost Maintenance costs
Operations	Fuel training and certification Voyage range and fuel energy	Revenue Payload

1.20 Decarbonizing the Electricity Grid

As is the case with many, if not all, low carbon fuels, the source of electricity used to produce the fuel is critical to the carbon intensity of the fuel. All of the alternative fuels discussed in this report use electricity at some stage in the production process. At present in the U.S., electricity generation averages around 0.39 kg CO_2 per kWh of electricity generated.[121] Coal powered generation accounts for 19.1% of total generation, and natural gas another 39.9%.[122] Zero-carbon sources, of which 49% are nuclear, account for another 40.6% of total generation.

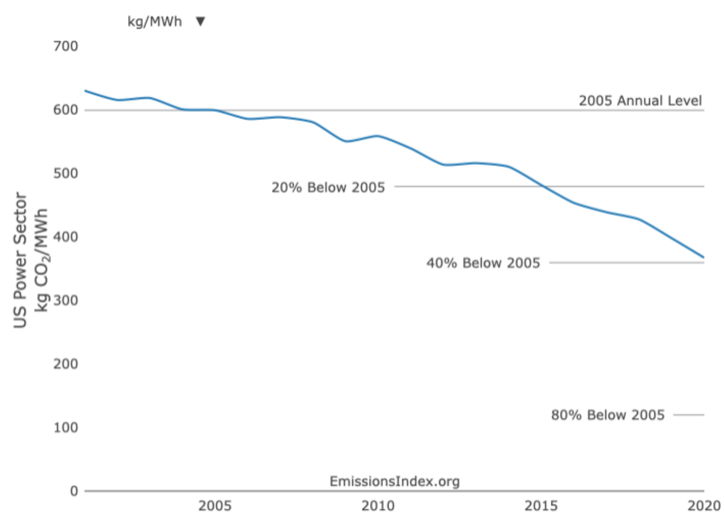
CO_2 emissions from electricity generation are generally trending downwards, with emissions intensity (kg CO_2/kWh) in 2020 nearly 40% below the emissions intensity in 2005 Figure 17.[123]

[121] https://www.eia.gov/tools/faqs/faq.php?id=74&t=11
[122] https://www.eia.gov/environment/emissions/carbon/
[123] https://emissionsindex.org/#chart-1-view-3

Regions and states with electricity grids with lower carbon intensity may be preferable to high carbon intensity states and grids, as the WtT upstream CO_2 emissions from fuel production will be lower. EPA's eGRID[124] provides national, state, and regional estimates of emissions from energy generation, as well as providing detailed plant-level data.

Regional energy grids differ in their overall emissions of carbon dioxide, due to differences in the energy resource mix. At the state/regional level Alaska, Hawaii, and Puerto Rico have higher emissions rates due to higher proportions of coal, oil, and natural gas in their energy grids, while U.S. West Coast states are among the lowest due to higher proportions of renewable resources, primarily wind, solar, and hydropower.[125]

Figure 17: Carbon emissions intensity in the U.S. electricity generation sector. (Credit: EmissionsIndex.com)



Policies and programs that promote low-carbon fuels should consider the fuel feedstock, as well as the source(s) of electricity used to synthesize the alternative fuel. Without the funding and incentives to drive land-side energy systems toward greener solutions, the life cycle emissions of alternative marine fuels will remain high.

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124 https://www.epa.gov/egrid
125 https://www.epa.gov/egrid/data-explorer

Policy Analysis

1.21 Overview

This section provides analysis of the policy landscape for decarbonizing oceangoing vessels and the research fleet. This analysis includes discussion of federal funding and financing mechanisms, as well as discussion of a case study around efforts at Scripps Institution of Oceanography to replace an older diesel-engine vessel with a zero-emission vessel.

There are significant efforts at the IMO and within the U.S. federal government to decarbonize oceangoing vessels. Despite these efforts, a diverse array of hurdles remains before widespread adoption and operation of low- and zero-carbon vessels in the U.S. fleet. Significant efforts are required to fund technical research and development to ensure availability of safe, efficient fuels and propulsion systems.

These efforts are necessary on the vessel and maritime operations side, but also on the land side. Clean and green electricity grids are essential to producing low carbon hydrogen, methanol, ammonia, and biofuels. Without the funding and incentives to drive land-side energy systems toward greener solutions, the life cycle emissions of alternative marine fuels will remain high. Furthermore, without lowering green electricity costs through widespread adoption and deployment of renewable energy, low carbon fuels will not be economically viable without significant subsidy.

Large oceangoing vessels that spend multiple days at sea present a different set of challenges to smaller regional vessels, including harbor craft. With greater daily access to bunkering for harbor craft, smaller vessels may be better placed to adopt alternative fuels and they can refuel more frequently. Alternative fuels may be more difficult to deploy on larger vessels on longer routes, where fuel volumes necessary for safe and efficient operations may impact the payloads and available space on board those vessels.

Barriers to widespread adoption of low carbon fuels include concerns over stranded assets, regulatory certainty, and funding. The federal government offers a suite of incentive programs, but there are limited funding streams specific to the maritime industry for research and development, including demonstration and pilot projects. Federal incentive programs cannot prescribe exactly what vessels and ports can do but remain critical to adoption of novel technologies.

The maritime industry has historically been slow to adopt new technologies. In the case of low and zero carbon fuels, where there are a range of options with no clear frontrunner at this time, firms are unwilling to risk spending large sums of money and ending up with stranded assets—or the need to retrofit vessels ahead of schedule—due to the lack of fuel availability, bunkering infrastructure, or poor fuel performance. In the short term, drop-in fuels like methanol and biofuels may be preferred as bridge fuels in the fleet until research and development can advance hydrogen and ammonia technologies to the point where engines are cost competitive, fuels are available, and WtW emissions are low.

As noted in the case of Scripps' planned low-carbon vessel, regulatory uncertainty is also a barrier to adoption. The U.S. Coast Guard certifies merchant vessels before going to sea, and in the advent of novel technologies and fuel the certification process can take many years, in addition to planning, design, and building the vessel. This lengthy certification process is not without merit, as it helps to ensure the safety of vessels and seafarers across a range of scenarios.

Low carbon fuels and propulsion systems come at a cost premium. In many instances the fuels are more expensive and existing engines and fuel systems require retrofit. In the case of drop-in fuels, retrofits may be relatively minor, but hydrogen and ammonia systems require engine technologies, fuel systems, and storage tanks that differ from conventional bunker fuel systems. Incentives are being used to help promote investment in these areas and remain an important mechanism to spur research and development and ultimately drive down costs while improving efficiency.

1.22 Funding and Financing Programs to Support JAF Decarbonization Efforts

1.22.1 National Sealift Defense Fund

The National Sealift Defense Fund (10 U.S. Code § 2218) was established by Congress and is administered by the Department of Defense to fund construction and efforts to maintain and operate fleets used in sealift, provided that ships and systems are built and/or assembled in the United States.

In P.L. 113-76 (2014), Title V, Congress appropriated $597.2 million for the National Sealift Defense fund to allocate toward necessary expenses to maintain and preserve the National Defense Reserve Fleet and U.S.-flag merchant fleet. It was stipulated that the funds were not to be used to award new contracts to purchase certain equipment—"auxiliary equipment, including pumps, for all shipboard services; propulsion system components (engines, reduction gears, and propellers); shipboard cranes; and spreaders for shipboard cranes"— unless these components were manufactured in the United States. This restriction could present a barrier to certain retrofits, which may be required and/or helpful in moving toward decarbonization of Jones Act Fleet vessels, if key components are not manufactured—or available—in the U.S.

However, the language also specified that: "the Secretary of the military department responsible for such procurement may waive the restrictions in the first proviso on a case-by-case basis by certifying in writing [to House and Senate Committees] that adequate domestic supplies are not available to meet Department of Defense requirements on a timely basis and that such an acquisition must be made in order to acquire capability for national security purposes."

It may be possible then, depending on the situation and interpretation of these requirements, that exceptions may be made, and funding may be available for certain decarbonization retrofits on a case-by-case basis, if and when they meet these conditions. As of FY2022, the National Sealift Defense Fund had $106 million in unobligated resources (USASpending.gov 2022).

1.22.2 Maritime Guaranteed Loan Program—Title XI Loans

MARAD, through the Maritime Guaranteed Loan Program (also referred to as "Title XI"), guarantees favorable-rate loans for ships constructed in U.S. shipyards, as the cost of U.S.-built ships tend to be comparatively high, up to several times the cost of foreign-built vessels (Frittelli 2019; Bonello et al. 2022; Goldman 2021). The program, established by the Marine Merchant Act of 1936, issues and guarantees loans to both shipyards and buyers of U.S.-built vessels. As of 1993, Title XI was expanded to support funding to modernize U.S. shipyards, as well (Goldman 2021). The program not only covers ship construction but also reconstruction or reconditioning projects, which "include designing, inspecting, outfitting, and equipping" (MARAD 2020a; 46 U.S. Code § 537 2019)—indicating that rebuilding and retrofitting projects for decarbonization of JAF vessels may also be eligible.

For much of the history of the program, Title XI loans were federally backed and guaranteed, but issued by commercial lenders. In return, MARAD would charge the borrower a fee of between 0.5% and 1% of the loan; which could be financed in tandem with the loan (Goldman 2021). New rules specify that the Federal Financing Bank replace commercial banks as the purchaser of debt for Title XI loans; a $331 million loan in April 2020 was the first loan issued under these rules. In response to the reform, MARAD no longer charges the upfront one-time fee (Goldman 2021; Romero 2020). The annual interest rate on the first loan issued was 1.22%, with an effective rate (for accounting purposes) of 1.6% (Romero 2020). Loan guarantees cover no more than 87.5% of the project's cost, with a maximum repayment period of 25 years from vessel delivery (Frittelli 2020).

MARAD is currently unable to offer loan guarantees at levels seen historically. After a period of defaults on Title XI loans in the 1980s, the program was reorganized to comply with Federal Credit Reform Act of 1990 requirements. In 1998 MARAD guaranteed an all-time high of $1.4 billion in loans. In 2001, one company—which alone had received $1.2 billion in guaranteed loans to build two cruise ships—defaulted; and many other loans defaulted following September 11, 2001. Since that time, Title XI financing through MARAD is at much lower levels overall; over a ten-year period MARAD guaranteed only seven loans which totaled $1.9 billion, and which supported the construction of 19 vessels (Goldman, 2021). As of April 2021, MARAD had approximately $34.5 million available in Title XI subsidies, which could support about $487 million in loan guarantees; and as of that same time, Title XI had not been allocated funding by Congress since 2018 (MARAD 2021a).

The Trump Administration proposed to eliminate the Title XI program in the FY2021 budget request—and to transfer the loan portfolio to DOT's National Surface Transportation and Innovative Finance Bureau, but Congress did not support these actions in the 2021 Consolidated Appropriations Act (Goldman 2021).

Title XI financing may support JAF vessels in efforts toward decarbonization by reducing upfront overall costs of purchasing new vessels which have systems, designs, or technologies, etc. that support decarbonization goals, and by potentially reducing upfront costs of investments in retrofits supporting decarbonization efforts.

1.22.3 Capital Construction Fund (CCF) Program

The Capital Construction Fund (CCF—46 U.S.C. §53501), also established by the Merchant Marine Act of 1936, is a program administered by MARAD and the National Oceanographic and Atmospheric Administration, in which vessel owners are permitted to deposit a share of their income—taxed at 0%—into CCF accounts (Goldman 2021). Funds may be withdrawn from these accounts to pay for "construction, reconstruction, or acquisition of vessels built or rebuilt in a U.S. shipyard" (Frittelli 2020). As of 2021, approximately 180 companies had CCF accounts (Goldman 2021).

1.22.4 Grants for Small Shipyards

As of FY2006, MARAD is authorized to provide matching grants to small shipyards—those with fewer than 1,200 employees—for capital and other improvements, as well as training programs; Congress authorized $30 million/year from 2006-2017, and in FY2018 increased this to $35 million. The program funding level is not guaranteed, however, as it has no dedicated funding source, and must rely on annual appropriations; though Congress had authorized a total of $435 million for the program over its history, only $228 million had been appropriated (as of 2021, in nominal dollars)—$10 to $20 million less annually than authorized (Goldman 2021).

These grants may indirectly support JAF vessels in efforts toward decarbonization by reducing overall costs of ship construction, repair, and retrofits in these small shipyards, and by improving the capabilities of shipyards and employees, potentially increasing the availability of certain retrofits, systems, designs, or technologies, etc. that support decarbonization goals.

Case Study: Scripps Institution of Oceanography Zero-Emission Vessel

Scripps Institution of Oceanography[126] is in the process of replacing the 41-year-old *R/V Robert Gordon Sproul*, a regional vessel that serves research and education missions offshore California and along the U.S. West Coast.[127] She is 125 feet long and weighs 85 registered tons. The *Sproul* is able to spend up to 14 days at sea, limited by her 25,000-gallon fuel capacity.

Scripps is in the advanced stages of replacing the *R/V Robert Gordon Sproul* with a zero-emission vessel, with a primary focus on deploying a liquid hydrogen hybrid fuel system. The reported benefits of hydrogen include limited environmental impacts from fuel spills, and very quiet electric drive motors, which are beneficial for the scientific experiments, including acoustic monitoring, on board the vessel.

Scripps received $35m in funding[128] to build the proposed zero emission hydrogen vessel, with a 5-year timeline for delivery. Two feasibility studies were performed at Sandia National Labs, in partnership with naval architects at Glosten, among others.[129] With a view toward developing a vessel capable of spending up to 15 days at sea, with a range of 2,400 NM, the planning and design team are aiming for a diesel-hydrogen hybrid vessel, citing liquid hydrogen storage space limitations as a barrier to a fully hydrogen powered vessel. It is estimated that 75% of the missions of the new vessel will be able to run 100% on hydrogen. The diesel component of hybrid operations will run on biofuels.

From a bunkering perspective, the planned vessel will receive liquid hydrogen from a 4,000 kg LH_2 trailer. The research team determined that delivery in this manner was feasible and provided sufficient flexibility and delivery reliability for operations. The planned vessel will be homeported in San Diego, where there are a range of companies producing hydrogen within one day's drive of the facility but would be able to bunker hydrogen from any facility with sufficient space at the dock to bring a hydrogen tank truck alongside to fuel.

In the process of planning the alternatively fueled vessel, the *R/V Robert Gordon Sproul* was run using biofuels for around a year and a half. Biofuels were able to serve as a drop in alternative to diesel fuel, with supplemental lubrication additives added to aid the engine performance. No negative impacts on fuel systems were reported, but the team determined that running the new vessel solely on biofuels was undesirable due to the criteria pollutant emissions, including elevated hydroxyl, PM, and black carbon emissions relative to ULSD (Betha et al. 2017; Kuang et al. 2017; Price et al. 2017).

In addition to the $35m in funding for the planned vessel already received, Scripps is in the process of raising an additional $15m to fully finance the vessel build. From a policy perspective, while financial support for first movers was highlighted, regulatory barriers were cited as the single biggest risk factor for the success of the vessel. DNV-GL provided a conditional approval in principle (CAIP) for the zero-emission vessel design, and there were no "show-stopping" design concerns, but both DNV-GL and the USCG cited the need for additional development and design, including detailed risk assessment of the gas systems, before final regulatory approval.[130] It is possible that if Scripps' zero-emission vessel receives class approval, the vessel design may pave the way for other similar designs. However, the use case of the Scripps vessel may not be appropriate in all cases, and the design is specific to hydrogen storage and propulsion. Vessels designed to use other alternative fuels would likely have to undergo the entire approval process.

1.22.5 RAISE/TIGER/BUILD Grants

Initially originating in the American Recovery and Reinvestment Act of 2009 (ARRA; P.L. 111-5), these grants are not specific to JAF vessels or maritime shipping or shipyards, but funding opportunities may be available through this program to invest in infrastructure to support decarbonization efforts. Projects are evaluated on a number of criteria, including climate change. The U.S. Department of Transportation announced $1.5 billion in funding for RAISE (Rebuilding American Infrastructure with Sustainability and Equity) grants was available in 2022 (Frittelli 2020; U.S. DOT 2022).

1.22.6 Duty on Foreign Ship Repairs and Maintenance

To discourage U.S. flag vessel operators from having repairs and maintenance done in foreign shipyards (as opposed to domestic), U.S. vessel operators are required to pay a 50% duty on any maintenance and repairs on vessels conducted at foreign shipyards, under the Smoot-Hawley Act of 1930 (19 U.S.C. §1466) (Frittelli 2020).

1.22.7 1915 Statutory Requirement

A 1915 law requires that crew on vessels are available for all three shifts (round-the-clock), and prohibits crew from working in both the deck and engine departments, which some have argued discourages adoption of new technology (Frittelli 2020; Bonello et al. 2022; National Research Council 1990).

1.22.8 Operational Subsidies Offered for Other Sealift (MSP) Vessel

The U.S. Maritime Administration offers operational subsidies to vessels participating in the Maritime Security Program (MSP) but does not provide subsidies for vessels covered by the Jones Act, under the rationale that the industry is protected from foreign competition (Goldman 2021). This rationale, however, has perhaps been weakened in recent decades, as the increased cost associated with the U.S.-build and U.S.-crew requirements leads to much higher operating costs for JAF vessels. According to one estimate, annual operation of U.S. flag vessels can cost ~$5 to $6 million more than that of foreign-flag vessels.

The increased comparative cost of operating JAF vessels has potentially led to:

1. Modal shifts in domestic transportation (i.e., from ship to rail or truck, modes which are generally higher in energy and GHG/CO_2 intensity compared to ships).
2. Importation of goods that are produced domestically, but for which the increased transportation cost using JAF vessels makes these goods more expensive than importing them from distant nations using foreign-flag ships.

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[126] Special thanks to Bruce Appelgate, Associate Director at Scripps Institution of Oceanography
[127] https://scripps.ucsd.edu/ships/sproul
[128] https://scripps.ucsd.edu/news/uc-san-diego-receives-35-million-state-funding-new-california-coastal-research-vessel
[129] http://glosten.com/wp-content/uploads/2018/07/SAND2018-4664_Zero-V_Feasibility_Report_8.5x11_Spreads_FINALDRAFT_compress.pdf
[130] Ibid.

3. Reducing the number of vessels in the JAF, in response to loss of demand to foreign-flag vessels and domestic truck and rail, and the comparative loss of interest by shippers to operate JAF vessels due to the increased costs and constraints, and difficulty in remaining competitive.

1.22.9 Bipartisan Infrastructure Law

The Bipartisan Infrastructure Law (BIL) (GPO 2021), signed into law in November 2021 by President Biden, invests more than $17 billion in maritime projects, including port infrastructure and waterways, port congestion and throughput projects, and emission abatement technology and infrastructure.

The BIL designates $2.25 billion over five years for the Port Infrastructure Development Program (PIDP), with $680 million in funding available in 2022. In addition to funding projects designed to improve port capacity and throughput, the PIDP funds also apply to projects targeting resilience and climate change, and environmental and emissions mitigation measures including greenhouse gas abatement.[131]

The BIL provides support for port electrification projects, as well as $250 million toward electric and low-emitting ferries. Hydrogen pipeline infrastructure is also supported in the BIL (Section 40313), and the law provides support for activities that advance and support convenient and economic refueling of maritime vessels (among other vehicle types) and advanced vehicle engine, energy storage, and propulsion systems, including fuel cells. Marine Highway Grant funds of $25 million can be used for upgrades to material handling and equipment, and for the procurement of zero or near-zero emission vessel modifications.

1.22.10 Policies in Progress/Potential Policies/In Development

In the Consolidated Appropriations Act (2014), Congress instructed the DoT and DoD to collaborate in producing a national sealift strategy that would ensure the long-term viability of the merchant marine; and Section 603 of the Cable Coast Guard and Maritime Transportation act of 2014 directed the DOT, in collaboration with the USCG to produce and submit to Congress a national maritime strategy (U.S. DOT 2020; Frittelli 2019)(P.L. 113-76).

After a several-year delay, the first part of the plan, "Goals and Objectives for a Stronger Maritime Nation," (U.S. DOT 2020) was released in 2020, and includes 4 goals and 39 objectives to improve the U.S. maritime system, including:

Under Goal 1 - Strengthen U.S. Maritime Capabilities Essential to National Security and Economic Prosperity:

- Recapitalizing the Ready Reserve Force (RRF) with modern vessels (1.7);
- Improving the capability of U.S. flag international trading vessels to better align with DOD and DOT sealift requirements through a combination of MSP funding, MSC chartering,

[131] https://www.maritime.dot.gov/about-us/bipartisan-infrastructure-law-maritime-administration

enforcement of preference cargo requirements, regulatory reform and policy, and incentives to reduce vessel operating costs (1.8);
- Examining new ways to support shipbuilding and repair facilities, and increase U.S. coastwise trade for eligible U.S. flag vessels (1.9);
- Enhancing the U.S. shipyard base by fostering support for shipyard modernization and innovation and promoting use of the Capital Construction Fund (CCF) and Construction Reserve Fund (CRF) programs (1.10).

Under Goal 3 - Support Enhancement of U.S. Port Infrastructure and Performance:
- Working with stakeholders to improve and expand wind energy shore side support (3.11);
- Working with stakeholders to leverage emerging future technologies to improve port efficiency (3.12);

And, under Goal 4: Drive Maritime Innovation in Information, Automation, Safety, Environmental Impact, and Other Areas:
- Work with government and industry stakeholders to facilitate innovations that improve the safety, security, and resilience of the [Marine Transportation System] (4.1);
- Promote research to reduce environmental impacts of maritime activities, including assistance to ports and vessel operators to comply with Federal regulations regarding invasive species, vessel emissions (including by using alternative fuels), and other marine impacts (4.4).

These stated objectives indicate that the DOT and DOD will be making efforts and initiatives and developing and implementing policies which could provide support for decarbonization efforts related to the JAF fleet, in the near future. The report, however, does not cover topics required to be covered by the Congressional order—and several key issues of potential relevance to decarbonization of the JAF. These include prioritizing objectives for near-, medium- and long-term; developing an implementation plan and timeline; reviewing and reporting on policies that impact the competitiveness of the U.S. flag fleet; and including recommendations on making U.S.flag vessels more competitive and enhancing U.S. shipbuilding capability (U.S. DOT 2020).

The February 2020 report states that these issues will be addressed in a report to be released within one year, but as of February 2022 it had yet to be formally issued/addressed. This report (and related directives) indicate there may be potential opportunity for substantial change supporting the decarbonization of JAF (and other) vessels, if/when official policy and strategy are developed and released by DOT and DOD.

Conclusion

This research identifies opportunities for decarbonizing the oceangoing Jones Act and U.S. flagged fleet, and the Federal Fleet. Jones Act Fleet vessels are potentially “low-hanging fruit” in decarbonization efforts, typically being older, less fuel-efficient, and more energy- and GHG-intensive than comparable vessels participating in international trade. Jones Act Fleet vessel routes involve U.S. point-to-U.S. point voyages on shorter routes, leading to the potential to develop U.S. infrastructure supporting zero-carbon fueling and electrification infrastructure, and to act as a test bed to demonstrate and mature technologies.

In total, Jones Act and U.S. flagged fleet vessels saw nearly 8,300 entrances at U.S. ports in 2019, with the most frequent port pairs being Jacksonville, FL-San Juan, PR; Tacoma, WA-Anchorage, AK; and the San Pedro Bay Ports (Los Angeles and Long Beach)-Honolulu, HI. Total estimated energy for the Jones Act and U.S. flagged fleet is 4,000 GWh in 2019, equivalent to around 337,900 MT of MGO fuel, or around 1.5% of global domestic navigation. Total WtW life cycle GHG emissions are estimated at around 1.37 million metric tons CO_2e. In total, of the 153 large oceangoing cargo vessels studied, tankers accounted for the greatest energy use, consuming 43.1% of estimated energy, followed by containerships at 32.1% and Ro-Ro vessels at 22.8%. The top ten vessels account for just over 25% of total estimated energy consumption and just 35 vessels account for over half of total estimated energy.

Federal Fleet vessels typically depart from and return to the same port. Total energy consumption by Federal Fleet vessels is estimated at around 280 GWh in 2019, or around 8.2% of the energy consumption of the Jones Act and U.S. flag fleets. On the whole, 50% of voyages are less than 600 nautical miles, take less than 10.5 days, and consume less than 0.35 GWh with vessels generally returning to their home port, rather than calling at alternate ports.

From a decarbonization perspective, vessel operators and ports have a range of alternative low- and zero-carbon fuels identified as potential opportunities for decarbonization.

Ammonia is an efficient energy carrier and may be used in engines that are similar to current marine diesel engines. Ammonia may be transported by pipeline, and existing transportation infrastructure for ammonia is mature due to its widespread use as an agricultural fertilizer. Ammonia is currently typically produced via carbon intensive pathways (brown/grey ammonia), and under current conditions does not offer the potential for WtW GHG abatement. WtW GHG abatement with blue ammonia ranges from 18-76%, and green ammonia offers up to around 74% - 88% GHG abatement. Fuel costs for brown and blue ammonia are 1.39-1.86x the cost of MGO for the equivalent energy content, and green ammonia is up to 4.3x the cost of MGO. Ammonia requires cooling and pressurization, requiring larger fuel system and storage tanks, and engine costs are potentially up to $5.3 million higher than the cost of equivalent marine diesel engines.

Biofuels have the potential to be used as drop-in (or near-drop-in) fuels, providing GHG abatement of up to around 66-98% but require larger storage tanks due to lower energy density. Biofuel costs vary broadly. DME biofuels, which offer the greatest abatement potential, are 0.66-0.90x the cost of MGO, FAME ranges from 1.43-2.14x the cost of MGO, and FT diesel is 1.81-4.53x the cost. FT diesel and DME biofuels offer the greatest GHG abatement potential, at 95.6% and 97.8%, respectively. Biofuels contain no sulfur, but are indicated to produce NOx, particulate matter, and black carbon emissions. Considering the life cycle of the fuel, if feedstocks are not sustainably harvested or gathered, then land use and land cover changes associated with biofuel production pathways may be deleterious to the environment.

Hydrogen fuel cells are among the most widely studied applications for marine propulsion. Grey hydrogen, derived from natural gas, offers WtW GHG abatement of around 34%, while blue and green hydrogen offer much higher abatement potential at around 89% and 97% respectively. Hydrogen must be stored cryogenically, and the fuel tanks and system together require nearly 8x as much space as MGO fuel. Grey and blue hydrogen are potentially lower cost, on a per unit energy basis, than MGO, ranging from around 0.4x-1x and 0.6x-1.5x, respectively. Green hydrogen costs range from on par with MGO to as much as 2.16x. Hydrogen is a promising marine fuel for new-build vessels, but fuel volume constraints, limited availability in the U.S., and high capital cost barriers need to be overcome before widespread adoption may occur.

Methanol may be used in existing two- and four-stroke engines with minor modifications to the injection, storage, and fuel handling systems. Methanol may also be used in existing fuel storage, transportation, and bunkering infrastructure, and the IMO has identified all aspects of methanol storage, bunkering, and handling as mature. Grey methanol, derived from natural gas, offers up to around 40% GHG abatement, bio-methanol offers nearly 98% GHG abatement, and E-methanol offers near total GHG abatement. Though lower in cost per unit energy, brown methanol is not a feasible fuel for decarbonizing shipping. Grey methanol fuel costs range from around 0.24x-0.54x MGO, and bio-methanol costs range from round 0.8x to 1.7x MGO costs.

Existing alternative fuel infrastructure may be more limited at Federal Fleet ports. All but three of the top ten ports list fertilizer facilities at their ports, two list chemical and chemical product facilities, and only Pascagoula, MS, lists ammonia facilities. As with JAF and U.S.-flagged vessels, all of the top ten ports are within 500 miles of hydrogen production facilities, and so bunkering of liquid hydrogen using tanker trucks is possible.

While there are significant national and international efforts to decarbonize oceangoing vessels, many hurdles remain before widespread adoption and operation of low- and zero-carbon vessels in the U.S. fleet. Significant efforts are required to fund technical research and development to ensure availability of safe, efficient, and cost-effective fuels and propulsion systems. Clean and green electricity grids are critical to producing low-carbon hydrogen, methanol, ammonia, and biofuels. Without greener solutions for land-side energy systems, the life cycle emissions of alternative marine fuels will remain high. Furthermore, without lowering green electricity costs through widespread adoption and deployment of renewable energy, low carbon fuels will not be economically viable without significant subsidy.

The maritime industry has historically been slow to adopt new technologies, which come at a cost premium. In the case of low- and zero-carbon fuels, there are a range of options with no clear frontrunner at this time. Jones Act and U.S.-flagged vessels may use engine and propulsion components manufactured overseas, enabling access to the global market of low-carbon systems.

However, firms are unwilling to risk spending large sums of money and ending up with stranded assets or the need to retrofit vessels ahead of schedule due to the lack of fuel availability, bunkering infrastructure, or poor fuel performance. In the short term, drop-in fuels like methanol and biofuels may be preferred as bridge fuels in the fleet until research and development can advance hydrogen and ammonia technologies to the point where engines are cost-competitive, fuels are widely available and economically viable, and renewable electricity grids mean well-to-wake emissions are low.

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Appendix

Table A 1: Fuel property conversions. Source (IRENA 2021, unless noted)

Fuel	LHV (MJ/kg)	Volumetric Energy Density (MJ/L)	Storage Pressure (bar)	Storage Temperature (°C)
MGO	42.8	36.6	1	20
Gasoline	44	32	1	20
NH_3 (l)	18.6	11.5	1-10	-34 (1 bar) to -20 (10 bar)
H_2 (l)	120	8.5	1	-253
DME	28.9	19.2	5	20
MeOH	19.9	15.8	1	20
Battery		0.54	1	15-30

Table A 2: Other Useful Conversions

1 MJ	0.2778 kWh
1 bbl.	44 U.S. gallons
1 MT	7.46 bbl. diesel
1 MT	6.35 bbl. MGO

Table A 3: Facility color coding

◉ (red)	Chemicals and chemical products
◉ (light blue)	Fertilizer
◉ (brown)	Ammonia
◉ (blue-grey)	Hydrogen

Table A 4: Top 35 Jones Act and U.S. flag fleet vessels by fuel consumption

MMSI	Vessel Name	Ship Type	Year of Build	CO_2 MGO (MT)	MGO Fuel (MT)
367641230	*Marjorie C*	Ro-Ro	2015	97650	24150
367067110	*Polar Enterprise*	Tanker	2006	45710	11310
303031000	*Polar Adventure*	Tanker	2004	37450	9260
369701000	*Midnight Sun*	Ro-Ro	2003	28690	7100
369285000	*North Star*	Ro-Ro	2003	27650	6840
367438000	*Maunawili*	Containership	2004	26230	6490
367003380	*Jean Anne*	Ro-Ro	2005	25830	6390
369390000	*Safmarine Mafadi*	Containership	2007	24480	6050
367353110	*Pelican State*	Tanker	2009	18040	4460
367134000	*Overseas Los Angeles*	Tanker	2007	17910	4430
366563000	*Mahimahi*	Containership	1983	17150	4240
367196000	*Mokihana*	Ro-Ro	1983	15390	3810
303584000	*Maunalei*	Containership	2006	14850	3670
367781630	*El Coqui*	Containership	2018	14410	3570
366758000	*Horizon Enterprise*	Containership	1980	13690	3390
368445000	*Overseas Nikiski*	Tanker	2009	13640	3370
338221000	*Overseas Boston*	Tanker	2009	13470	3330
366365000	*Matsonia*	Ro-Ro	1973	13370	3310
369040000	*American Endurance*	Tanker	2016	13240	3270
338789000	*Perla Del Caribe*	Containership	2016	12940	3200
367688000	*Alaskan Navigator*	Tanker	2005	12830	3170
367353070	*Evergreen State*	Tanker	2010	12720	3150
303210000	*Patriot*	Ro-Ro	2006	12680	3140
303656000	*Alaskan Legend*	Tanker	2006	11800	2920
366799000	*Horizon Pacific*	Containership	1979	11660	2890
368305000	*Manulani*	Containership	2005	11640	2880
367606000	*Maersk Iowa*	Containership	2006	11380	2810
303520000	*Sulphur Enterprise*	Tanker	1994	11320	2800
303104000	*Seabulk Challenge*	Tanker	1981	11070	2740
367759000	*Maersk Montana*	Containership	2006	11060	2740
338188000	*Independence*	Tanker	2016	10750	2660
366791000	*Horizon Reliance*	Containership	1980	10710	2650

Figure A 1: Dock facilities listing bunkering/fueling infrastructure

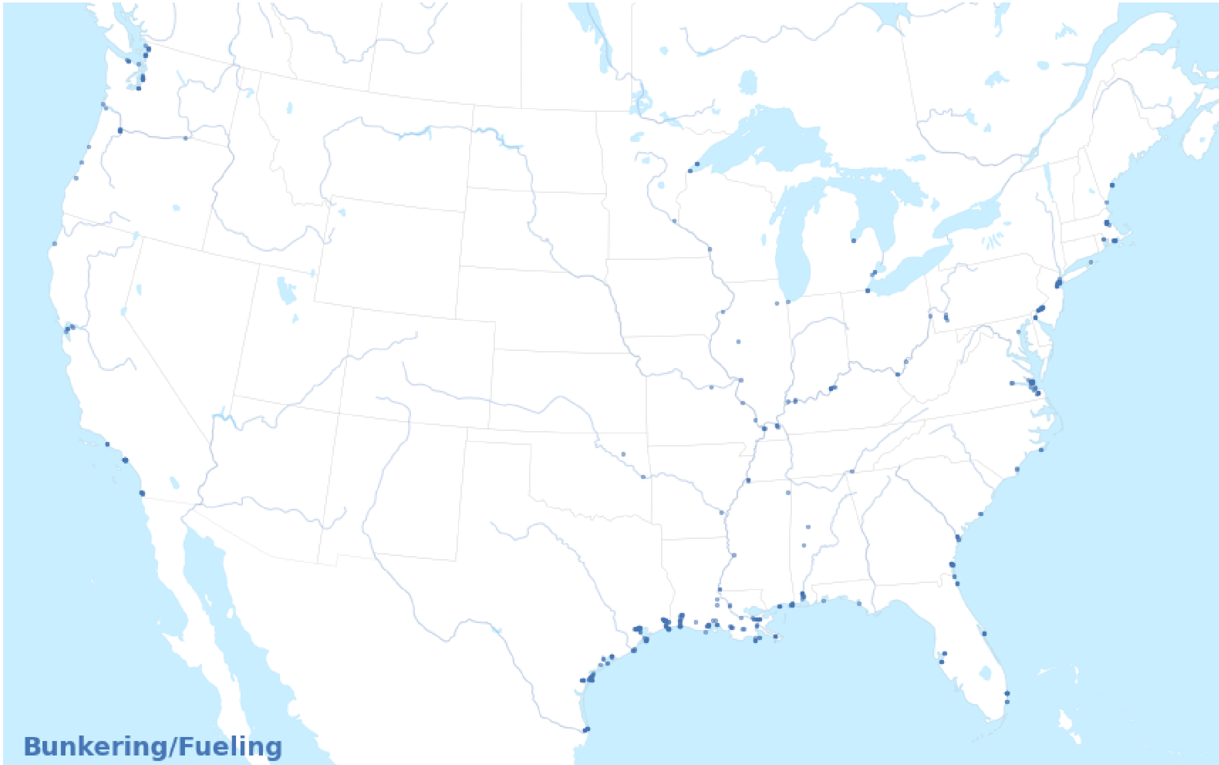

Figure A 2: Docks listing petroleum and petroleum product commodity facilities

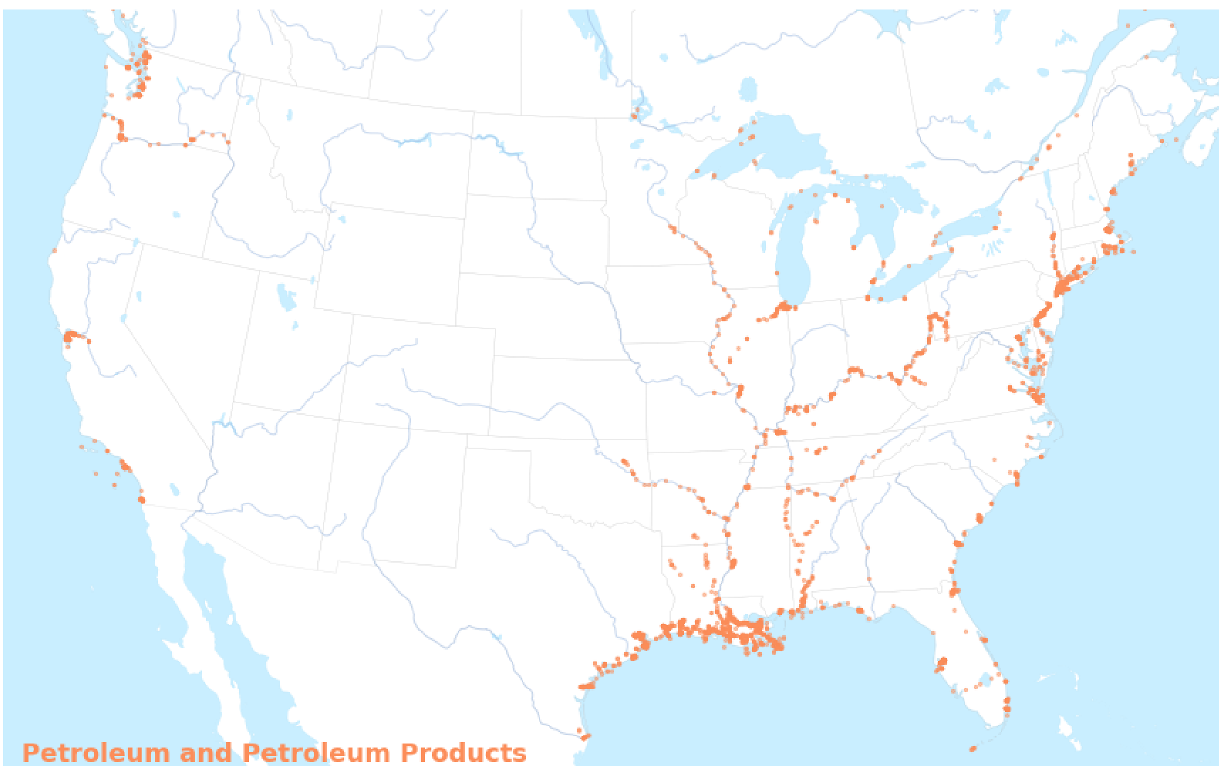

Figure A 3: Docks listing chemicals and chemical product commodity facilities

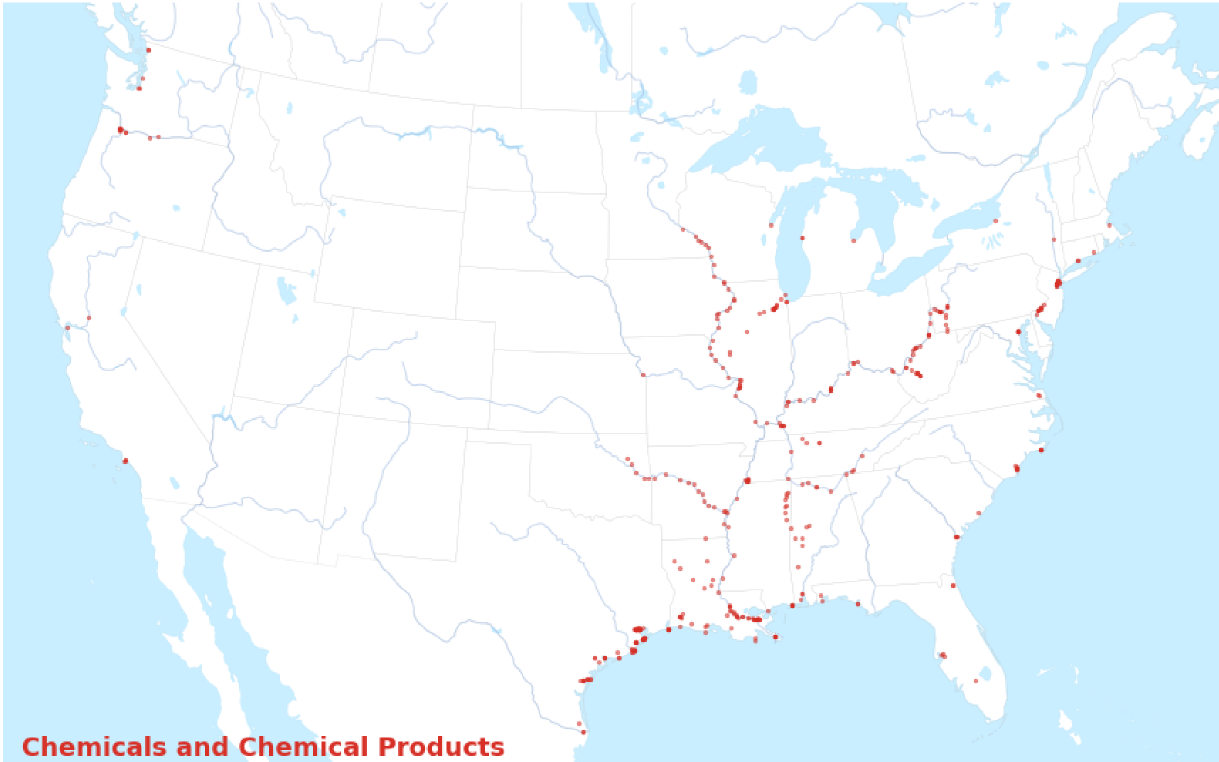

Figure A 4: Docks listing fertilizer product commodity facilities

Figure A 5: Docks listing ammonia and hydrogen product commodity facilities