Ocean-Going Vessel Decarbonization Technology Assessment

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EE
RA
Energy & Environmental
Research Associates

Prepared For:
Jamie Yates, Climate & Renewable Energy Analyst
Teresa Bui, Climate Policy Director
Pacific Environment
E: jyates@pacificenvironment.org

Prepared By:
Edward W. Carr, Ph.D.
James J. Winebrake, Ph.D.
Samantha J. McCabe
Maxwell Elling
Erin H. Green
Energy and Environmental Research Associates
E: ecarr@energyandenvironmental.com

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Acronyms and Abbreviations

°C	Degrees celsius
AAPA	American Association of Port Authorities
AFC	Alkaline fuel cell
AMP	Alternative maritime power
B20 (30, 50, 100, ##)	Biodiesel blend %. (e.g. B20 = 20% biofuel blend)
BOG	Boil-off gas
BSS	Battery-swapping stations
BtL	Biomass-to-liquid
CA	California
CAECS	CARB approved emissions control strategies
CAPEX	Capital expenditure
CARB	California Air Resources Board
CCUS	Carbon Capture, Usage, and Storage
CH_3OH	Methanol
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent units
DAFC	Direct ammonia fuel cells
DME	Dimethyl ether
DNV	Det Norske Veritas
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DSR	Direct steam reforming
DWT	Deadweight tonnage
ECA	Emissions control area
EERA	Energy and Environmental Research Associates
EGR	Exhaust gas recirculation
EJ	Exajoule
EMSA	European Maritime Safety Agency
FAME	Fatty Acid Methyl Ester
FOG	Fats, oils, and greases
FP	Fast pyrolysis
FT	Fischer-Tropsch process
GGE	Gasoline equivalent
GHG	Greenhouse gas
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GT	Gross tonnage
GWP	Global Warming Potential
H_2	Hydrogen
H_2O	Water
HDO	Hydro-deoxygenation
HFO	Heavy fuel oil

HTL	Hydrothermal liquefaction
HVO	Hydrotreated vegetable oil
HVSC	High-voltage shore connection
ICE	Internal combustion engine
IMO	International Maritime Organization
J	Joule
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour
L	Liter
LCA	Life cycle analysis
LEO	Lignin ethanol oil
LH_2	Liquid hydrogen
LNG	Liquefied natural gas
LOHC	Liquid organic hydrogen carrier
LPG	Liquefied petroleum gas
LSMGO	Low-sulfur marine gas oil
LVSC	Low-voltage shore connections
m	Meter
m^3	Cubic meter
MCFC	Molten carbonate fuel cell
MDO	Marine diesel oil
MeOH	Methanol
MGO	Marine gas oil
MJ	Megajoule
mL	Milliliter
Mt	Megatonnes or million metric tonnes
MT	Metric tonne
Mtoe	Million tons of oil equivalent
MW	Megawatt
MWh	Megawatt-hour
N_2	Nitrogen
NaOH	Sodium hydroxide
NASA	The National Aeronautics and Space Administration
NG	Natural gas
NH_3	Ammonia
NM	Nautical mile
NO	Nitric oxide
NO_2	Nitrous oxide
NOx	Nitrogen oxides; collective term for NO and NO_2
OGV	Ocean-going vessel
OPEX	Operating expenditures
PAFC	Phosphoric acid fuel cell
PEM	Polymer electrolyte membrane
PJ	Petajoule
PM	Particulate matter

PV	[Solar] photovoltaic cell
R&D	Research and development
RO-LO	Roll-on/lift-off cargo vessel
RO-RO	Roll-on/roll-off cargo vessel
RoPax	Roll-on/roll-off passenger vessel
SCR	Selective catalytic reduction
SMR	Steam methane reforming
SOFC	Solid oxide fuel cell
SOx	Sulfur oxides; collective term for SO_2 and SO_3
SVO	Straight vegetable oil
TEU	Twenty-foot equivalent units
TIE	Terminal incident event
TRL	Technology readiness level
TtW	Tank-to-wake
U.S.	United States
UCO	Used cooking oil
UHC	Unburned hydrocarbons
ULSD	Ultra-low sulfur diesel
USCG	U.S. Coast Guard
USD	U.S. dollars
VIE	Vessel incident event
VLSFO	Very-low sulfur fuel oil
WGSR	Water-gas shift reaction
WtT	Well-to-tank
WtW	Well-to-wake

Units and Conversions

1 Euro (EUR, €)	1.08 U.S. Dollar (USD, $) (2023)
1 Exajoule (EJ)	1×10^{18} J
1 Horsepower (HP)	745.7 W
1 Kilogram (kg)	2.20462 lb
1 Kilometer (km)	1,000 m
1 Kilowatt (kW)	1,000 W
1 Kilowatt-hour (kWh)	3.6 MJ
1 Knot	1 nautical mile per hour
1 Megajoule (MJ)	1×10^{6} J
1 Megatonne (Mt)	1×10^{6} metric tonnes
1 Megawatt (MW)	1,000 kW
1 Megawatt-hour (MWh)	1,000 kWh
1 Metric tonne (MT)	1,000 kg
1 Million ton oil equivalent (Mtoe)	0.041868 EJ
1 Nautical Mile (NM)	1.852 km
1 Petajoule (PJ)	1×10^{15} J
1 Tonne fuel oil equivalent (TFOE)	41,868 MJ
1 US ton	2,000 lb

Ocean-Going Vessel Decarbonization Technology Assessment - Executive Summary

California (CA) has historically set precedents in addressing air pollution and greenhouse gas (GHG) emissions, often exceeding stringency in standards set by the federal government. California ports play a pivotal role in global trade, handling over one-third of shipping container traffic in the United States (U.S.). As the maritime fleet faces tightening GHG emissions regulations, both domestically and abroad, fleets will find it necessary to adopt cleaner fuel and technology solutions. Availability, applicability, and economic viability of these fuels and technologies will determine their potential.

This report provides an assessment of the current fleet of ocean-going vessels (OGVs), and evaluates low- and zero-GHG fuels and technologies for adoption by port and vessel operators. Through examining factors such as life cycle emissions, production volumes, infrastructure requirements, and capital and operating costs, this study offers practical insights into the feasibility and readiness of alternative propulsion options for maritime transport. In alignment with the International Maritime Organization (IMO) and other regulatory agencies, this report discusses the comprehensive tank-to-wake (TtW) and well-to-wake (WtW) impacts of these technologies, in order to support informed decisions that will effectively decarbonize OGVs. This report is co-released with a report by Goldman School of Public Policy, University of California, Berkeley, which discusses policy options to decarbonize OGVs.[1]

Current Fleet and Orderbook

The global fleet and orderbook show significant uptake of methanol-powered and methanol-ready vessels and ammonia-ready vessels. Time-series trends show little uptake of these vessels until the early 2020s, followed by rapid growth in new-build and orderbook vessels. These insights show a commitment by some in the industry to develop capacity for low-GHG fuels in their fleets that has not previously been observed.

Orderbook data for 2023-Q4 show that the number of methanol-fueled and methanol-ready vessels is set to increase by 6.8 times, reaching around 285 vessels within the next 5 years. Ammonia-ready vessels are set to increase by 4.5 times, totaling around 200 vessels over the same time period. Other low-GHG vessel technologies like hydrogen fuel cells, battery power and assist, and solar and wind propulsion are also growing rapidly, indicating a shift towards early uptake of these technologies in the fleet.

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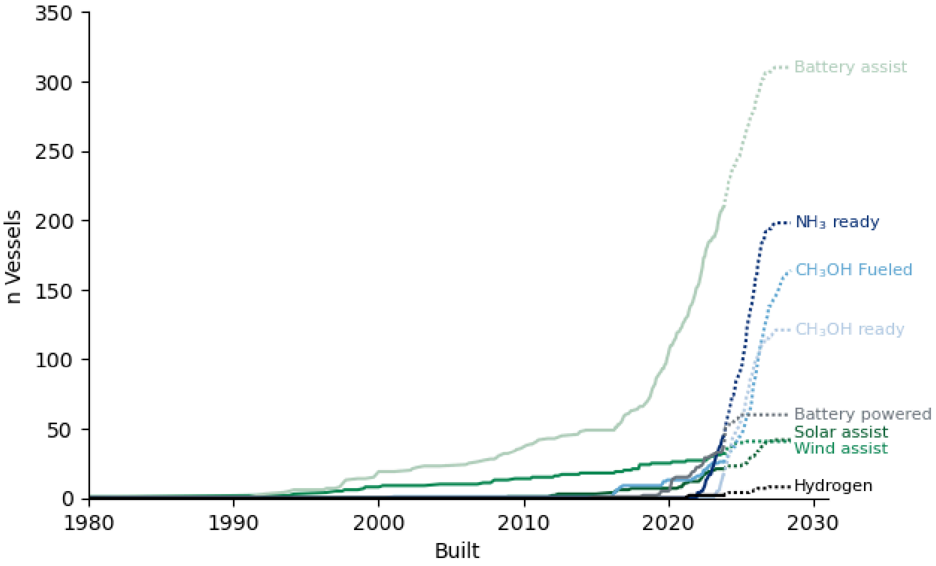
[1] Wooley et al. *Policy Options to Decarbonize Ocean-Going Vessels*, May 13, 2024, https://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/ocean-going-vessel-decarbonization

Figure ES-1

Trends in Alternative Fuels and Supplemental Power Systems on Oceangoing Vessels



Low and Zero-GHG Fuels and Technologies

Low and zero-GHG fuels and propulsion technologies are in varying degrees of technological readiness, both in terms of fuel production and distribution and on-board technology. Hydrogen is a primary feedstock for liquid hydrogen, methanol, and ammonia production, but the vast majority of hydrogen produced currently is derived from fossil sources, including coal and natural gas, which have high upstream emissions. Low-GHG hydrogen production and development is important for decarbonizing methanol and ammonia production, which have higher degrees of technology readiness.

As a marine fuel, hydrogen fuel cells are in the demonstration stage, and are typically developed on board smaller vessels that aren’t engaged in transoceanic trade. Liquid hydrogen, which is the most energy-dense state, requires cryogenic conditions which take up significant on-board space, and bunkering options are limited. These challenges make hydrogen impractical for application on large OGVs at its current stage of development. However, hydrogen holds significant potential as a feedstock for other alternative fuels like methanol and ammonia, which offer higher energy densities, easier storage, and better established and understood infrastructure. Additionally, these molecules can serve as carriers for hydrogen, overcoming the logistical challenges of liquid hydrogen storage and transport, but allowing its use in a fuel cell for emission-free power generation. Thus, while hydrogen may be impractical for direct use on large OGVs, its utilization as a feedstock and/or within carriers, alongside other innovations, presents a potential pathway towards decarbonizing maritime transport.

All production pathways of hydrogen result in a fuel with minimal-to-no TtW emissions. However, the majority of hydrogen production today stems from fossil sources (i.e. coal and natural gas) referred to as brown or gray hydrogen, which are associated with substantial upstream emissions. Using fossil feedstocks with reliance on Carbon Capture, Usage, and Storage (CCUS) technologies to mitigate emissions (blue hydrogen), have limited proven viability and cost-effectiveness. The carbon-intensity of fossil feedstock hydrogen exceeds the U.S. Department of Energy's "clean hydrogen standard" and are incompatible with Paris Agreement climate targets, at their current technological readiness.

E- or green hydrogen production offers the lowest life cycle emissions, but remains a small fraction of global output. Derived from electrolysis, e-hydrogen aims to utilize renewable energies from the grid for its production, requiring additional investments in renewable grid infrastructure to ensure sufficient capacity and efficiency. However, global grid infrastructure is predominantly reliant on fossil fuels. California benefits from its progressive energy transition targets and currently offers a grid with over half of its energy mix supported by zero-GHG and renewable energies. Thus, CA has a solid foundation to support the deployment of renewable hydrogen production and technologies compared to other regions. U.S. initiatives including the Regional Clean Hydrogen Hubs and Hydrogen Earth Shot underscore the demand for low-GHG and renewable hydrogen, crucial for its direct use and as a feedstock for other alternative fuels.

Methanol currently offers the highest degree of technological readiness among the hydrogen-carrying fuels, with around 42 methanol-fueled and -ready vessels built, and over 240 more on order. Low-GHG bio- and e-methanol currently comprise less than 1% of global methanol (the vast majority is sourced from fossil feedstocks), though efforts are underway to scale production. While it is less volumetrically energy dense than conventional marine fuels, methanol is widely handled and distributed as a chemical product and feedstock, classification societies have developed guidance on its use as a marine fuel, and there are vessels built and operational using methanol. Retrofitting vessels for methanol involves minor modifications and doesn't necessitate cryogenic tanks or pressurization; on-board safety is a concern with methanol bunkering and use, due to toxicity and flammability.

Methanol sourced from fossil feedstocks does not contribute to decarbonization efforts and may, in fact, result in increased emissions compared to conventional fuels. Methanol, even when derived from renewable sources, is not carbon-free when combusted. However, bio- and e-methanol can align with climate targets when produced using renewable sources, provided that the carbon is from sustainable biomass, direct air capture, and/or supported by a grid powered by renewable energies rather than fossil fuels. Moreover, it has long-term potential in global energy transitions. Methanol can be used directly as a fuel today, with the potential to transition to applications as a hydrogen carrier for use in fuel cells to bypass its exhaust emissions, when the technology becomes commercially scalable.

Ammonia does not require cryogenic storage, but requires cooling to -33°C in specialized tanks to prevent corrosion and leakage. Historically, ammonia was stored in pressurized tanks, common for holding liquefied gasses such as propane. However, a shift has occurred towards storing ammonia under standard atmospheric pressure and cooling, requiring less capital per unit volume and enhanced safety.[2]

On board safety concerns persist as ammonia is toxic to humans and the environment, though it has been handled as an agricultural commodity and chemical for many decades. From a technology-readiness perspective, the commercial availability of low-GHG ammonia is linked to low-GHG hydrogen production. Hydrogen is a precursor to ammonia production, thereby directly influencing the decarbonization potential of ammonia fuel. As a consequence, the limited production capacity of renewable hydrogen means there is currently low availability of low-GHG ammonia.

While there are nearly 200 vessels built and on order that are ammonia-ready, there are none that are currently switched over to run on ammonia as a combustion fuel. Despite operational ammonia-ready vessels in the present fleet, they continue to rely on conventional fuels. Ammonia requires specialized combustion technologies, and ammonia-fueled vessels are expected to enter the operational fleet by 2026-2027.

Biofuels are generally able to be used as drop-in fuels, as little-to-no modifications to engines or fuel systems are required, and in their current applications are typically blended with conventional marine fuels. While fuel additives may be needed to maintain fuel stability, biofuel blends up to 30% are treated the same as conventional marine fuels by IMO. Biofuels are a diverse category and, though there are a range of biofuel production pathways, sustainable biofuel production relies on second-generation feedstocks (i.e. non-food biomass). Access to sufficient quantities of appropriately sustainable second-generation feedstocks currently presents the largest barrier to economically efficient production, availability, scalability, and widespread uptake of low-GHG biofuels.

Supplemental power systems, including solar and wind power, and electrification are in varying degrees of technological readiness. Wind power is among the oldest technologies for marine propulsion but has not been widely deployed to ocean-going cargo ships, with just over 30 ships operating with wind-assist technologies. There have been some successful demonstrations of wind-assist technologies aboard relatively large ships, such as cargo ships. Current and foreseeable advancements deem solar technologies

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[2] https://ammoniaknowhow.com/ammonia-storage-tanks/

unfeasible for primary propulsion systems, particularly for OGVs. However, solar can supplement power needs in combination with electric power generation.

Electrification in maritime transport encompasses two distinct applications, shore power infrastructure at berth and onboard propulsion systems. Shore power is well-established in California under CARB's At Berth Regulation. There are approximately 1,600 commercial vessels (>5,000 gross tonnage) globally equipped with connections for shore power. These technologies are technologically mature and commercially scalable for the global fleet. However, grid upgrades and renewable energy generation are necessary to support the increased power demand and widespread adoption. Battery assist, which involves integrating battery technologies to supplement traditional propulsion systems, may also contribute to this transition. Battery-electric propulsion of the ocean-going fleet is still in early research stages and is primarily targeting applications on small and/or inland vessels.

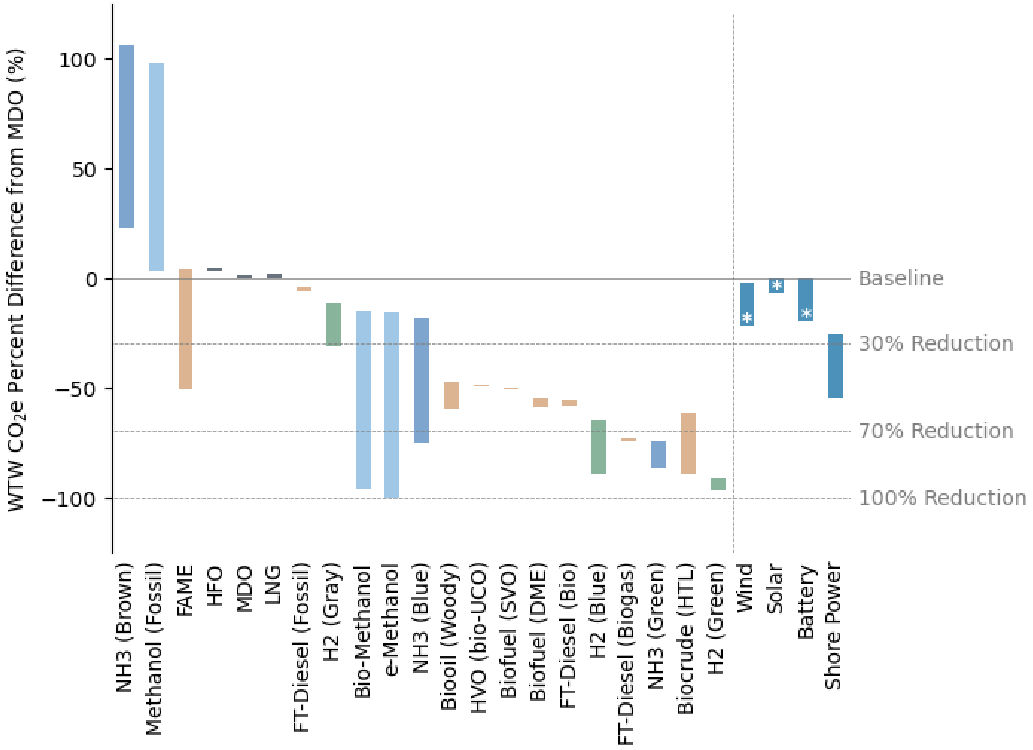
Decarbonization Potential

The decarbonization potential of alternative marine fuels is highly dependent on fuel feedstocks and production pathways. All decarbonization potential should be considered on a well-to-wake basis, accounting for the full life cycle of the fuel including production, distribution, and consumption. Fuels produced from fossil feedstocks including coal (brown) and natural gas (gray) have limited potential for GHG emissions reduction, and may in fact increase life cycle emissions. Fuels derived using fossil feedstocks and CCUS technologies (so-called blue fuels) offer significant potential GHG abatement, but rely on the efficacy of carbon capture technologies, which are not widely commercially proven. Biological and electrolysis-sourced feedstocks (so-called bio/E- or green fuels) offer the deepest decarbonization potential, but are highly dependent on the availability and sustainability of second-generation feedstocks and the capacity of the fuels to be blended effectively for use in marine engines, in the case of biofuels. As for e-fuels, significant abatement necessitates a decarbonized electrical grid and availability of direct air capture for carbon-containing fuels. Wind, solar, and battery technologies offer limited potential for deep decarbonization using current technologies, though they reduce total fuel consumption. Shore power can provide significant decarbonization benefits depending on the GHG intensity of the grid supplying energy to the shore power system.

Against the backdrop of evaluating the decarbonization potential of alternative fuels, it is important to acknowledge the lack of real-world operational emissions testing concerning emission profiles of alternative fuels, particularly large OGVs. Furthermore, life cycle modeling is inherently complex, resulting in total emissions estimates that can vary greatly depending on feedstocks and modeling assumptions. Presently, research heavily relies on model estimates and testing of fuels in non-marine applications. Thus, there is yet to be a complete picture of the emissions performance of these fuels in marine environments. As shown in Figure ES-2, even within similar fuel production pathways there is a wide range in potential emissions. There is a clear need for greater transparency in life cycle emission estimates and comprehensive emissions data from early pilots of alternative engine and vessel technologies to inform decision making and sustainable fuel solutions within the maritime sector.

Figure ES-2

Decarbonization Potential of Marine Fuels Compared to MDO



Section 1: Introduction to Low and Zero-GHG Fuels and Propulsion Technologies

Low- and zero-GHG marine fuels are necessary to meet IMO-international, regional, national and subnational GHG targets. Low- and zero-GHG marine fuels can also reduce emissions of criteria pollutants[3] (e.g., sulfur oxides, nitrogen oxides, particulate matter), offering additional health benefits. CA aims to reduce criteria pollutants and cut GHG emissions by 85% by 2045;[4] IMO targets also emphasize decarbonization and reducing GHG emissions, especially carbon dioxide (CO_2). IMO's 2023 Revised GHG Strategy includes measures to address not only CO_2, but also other GHGs such as methane (CH_4) and nitrous oxide (N_2O), with updated targets utilizing a well-to-wake approach to GHG emissions that considers the full life cycle of the fuels, from production to combustion.[5,6] For regulatory background and strategies for achieving these targets, please refer to the accompanying *Policy Options to Decarbonize Ocean-Going Vessels* by the Goldman School of Public Policy.[7]

The North American Emission Control Area[8] (ECA) extends 200 nautical miles (NM) from the CA shoreline, for which the U.S. Coast Guard (USCG) has primary authority for enforcement, while the California Air Resources Board's (CARB) OGV Fuel Regulation extends 24 nautical miles under enforcement by CARB.[9]

CARB's 2020 OGV emission inventory[10] estimates statewide total GHG emissions of 9,564 metric tonnes (MT) CO_2 equivalent (CO_2e) per day,[11] or around 3.5 million tonnes per year–roughly equivalent to the annual GHG emissions produced by 760,000 typical passenger vehicles.[12] CARB assumes vessels are consuming fuels that comply with the North American ECA in California waters out to 100 NM, corresponding to around 1.07 million tonnes (Mt)[13] of fuel consumed per year by vessels serving California ports.[14,15]

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[3] https://ww2.arb.ca.gov/resources/common-air-pollutants

[4] https://www.gov.ca.gov/2022/09/16/governor-newsom-signs-sweeping-climate-measures-ushering-in-new-era-of-world-leading-climate-action/

[5] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

[6] https://cms.globalmaritimeforum.org/wp-content/uploads/2023/11/Insight-brief_The-implications-of-the-IMO-Revised-GHG-Strategy-for-shipping.pdf

[7] Wooley et al. Policy Options to Decarbonize Ocean-Going Vessels, May 13, 2024, pageeshttps://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/ocean-going-vessel-decarbonization

[8] An IMO established geographical zone of stricter emission limits for ships, aiming to improve air quality in sensitive and/or coastal marine areas through limits of sulfur, nitrogen, and/or particulate matter

[9] https://ww2.arb.ca.gov/sites/default/files/2020-01/Marine%20Notice%202020-1_final_rev_ADA.pdf

[10] https://ww2.arb.ca.gov/sites/default/files/2022-03/CARB_2021_OGV_Documentation.pdf

[11] 9,435.03 MT CO2/day, GWP100 = 1
0.139 MT CH4/day, GWP100 = 27.9
0.458 MT N2O/day, GWP100 = 273
GWP100 from IPCC AR6

[12] https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

[13] 1 Mt = 1 Megaton or 1 million metric tonnes

[14] 3.206 gCO2 per g fuel for MDO per the Fourth IMO Greenhouse Gas Study.

[15] See Table 14 / https://ww2.arb.ca.gov/sites/default/files/2022-03/CARB_2021_OGV_Documentation.pdf

Efforts are underway to decarbonize maritime transport, and the density of ship traffic and California's position within the global economy provide strong economic leverage. With the goal to inform stakeholders and policymakers on the potential to reduce GHGs and criteria pollutants from the maritime sector, this report lays out a suite of decarbonization technologies, including fuel properties, engine and fuel system parameters, costs, life cycle emissions, and infrastructure.

Low and zero-GHG marine fuels, including hydrogen, ammonia, methanol, and biofuels, provide a potential pathway to reduce CO_2 and life cycle GHG emissions, but produce varying emissions of CH_4–a powerful GHG–and criteria pollutants[16] across their life cycles, including sulfur oxides (SO_x), nitrogen oxides (NO_x: NO_2 and NO), and particulate matter (PM).[17] Supplemental power technologies, such as solar, wind, and battery power can also provide clean energy sources to supplement vessel prime movers[18] and reduce carbon intensity of sea transport. For some vessels and duty cycles, battery power can serve as primary propulsion, and with 100% renewable energy supplied, can eliminate air pollutants and GHG emissions.

This work provides a technology review of low and zero-GHG marine fuels and supplemental power systems including decarbonization potential, costs, technology parameters, and infrastructure. Carbon-intensive, fossil-fuel-reliant fuel pathways are more comprehensively understood and, due to their dominance across global energy-grids, more prolific. Research and development (R&D) is being actively conducted in efforts to support renewable-sourced fuels in reaching sustainable commercial scale, especially for the power requirements of a large OGV.

IMO and other regulators consider both tank-to-wake (TtW) and life cycle or well-to-wake (WtW) emissions when assessing maritime fuels. TtW emissions are released from the stack during fuel consumption and combustion. TtW emission estimates do not account for upstream processes, including production, transportation, and storage. WtW emissions include TtW emissions, and encompass the entire life cycle of the fuel, from production to consumption. Low- and zero-GHG fuels are produced via a range of pathways, and consideration of WtW emissions is critical for accurately comparing fuels. Therefore, this report will predominantly focus on life cycle, WtW emissions.

Low- and zero-GHG fuels are categorized by production pathways based on the feedstock of the source, typically described as brown, gray, blue, and green for hydrogen (from highest to lowest carbon intensity). Hydrogen production is a precursor for

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[16] A term to describe six common air pollutants with adverse effects on human health and the environment – particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, ozone, and lead

[17] IMO MARPOL Annex VI limits air pollutants contained in ships' exhaust gas, including SOx, PM, and NOx, and prohibits deliberate emissions of ozone-depleting substances / https://www.imo.org/en/OurWork/Environment/Pages/Clean%20air%20in%20shipping.aspx

[18] The engine, turbine, water wheel, fuel cell, or other primary energy source (i.e. fuel) conversion machinery

ammonia and methanol[19] production pathways. These pathways are named after the hydrogen production method. Brown hydrogen refers to hydrogen sourced from coal feedstocks; Gray hydrogen is sourced from natural gas feedstocks (NG); Blue hydrogen is sourced from a fossil feedstock, with Carbon Capture, Usage, and Storage (CCUS) technologies used to reduce emissions from the exhaust gasses by capturing CO_2 and reusing or storing it to prevent it from entering the atmosphere; Green hydrogen is sourced using renewable energy to power electrolysis, and has the lowest carbon intensity. Other terms are used for methanol and biofuels that describe the production pathway and to describe the feedstocks (e.g. bio- or e- methanol).

Collectively, U.S. investments aimed at emissions reduction and decarbonization of maritime port operations are estimated to support and sustain an average of 32,000 jobs annually over the next ten years (largely allocated to the construction industry).[20,21] Many port infrastructure projects for decarbonization are focused on port electrification (e.g. shore power, electrified equipment and vehicles, etc.) to reduce GHG emissions and mitigate the localized impacts of port activities on air quality for communities adjacent to ports, due to the continuous exposure to pollutants.[22] Estimates of employment benefits from port electrification do not include employment opportunities in the low-GHG fuels sector and related supply chains.

Maritime Trade and Regulation in California

California has the largest economy in the United States, and the fifth largest in the world. In 2022, renewable energies accounted for half of in-state electricity generation, but reliance on out-of-state electricity accounted for 20-33% of California's grid.[23] In line with California's emission goals, enacted legislation requires grid utilities to procure 60% clean energy by 2030 and 100% by 2045.[24] This renewable infrastructure will be key not only for reducing overall emissions, but also for production of green fuels.

CA has historically taken early initiative in air pollution and GHG control measures, and has modeled actions for other states, national and subnational governments around the world. In 1988, CARB set limits on sulfur and other contents of diesel fuel to reduce criteria pollutants from motor vehicles.[25] By 2008, CARB adopted a regulation to mandate the use of low sulfur marine distillate fuels, applicable to all vessels within 24 nautical

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[19] Renewable methanol may be produced by synthesizing hydrogen and carbon from electric and/or biomass feedstocks

[20] The analysis does not account for "business-as-usual" activity, assuming all investments and demand to reduce emissions at ports are additional

[21] https://oceanconservancy.org/wp-content/uploads/2021/11/Maritime-Port-Clean-Energy-Infrastructure-Jobs-Study-Final-Draft-11.1.21.pdf

[22] https://www.epa.gov/community-port-collaboration/environmental-justice-primer-ports-impacts-port-operations-and-goods

[23] https://www.eia.gov/state/analysis.php?sid=CA

[24] https://www.energy.ca.gov/about/core-responsibility-fact-sheets/developing-renewable-energy

[25] https://ww2.arb.ca.gov/resources/fact-sheets/california-low-sulfur-diesel-fuel-fact-sheet

miles of the CA coast, regardless of flag.[26] In 2020, under Executive Order N-79-20, CARB aims for 100% reduction in emissions from "off-road" vehicles and equipment by 2035, for which marine vessels are included in their scope. Its regulatory authority extends to vessels operating within CA waters, regardless of flag state. Efforts include accelerating the deployment of fueling and charging options, and a "Just Transition Roadmap" to expedite the repurposing of conventional energy (i.e. oil) infrastructure.[27] Furthermore, the original *Ocean-Going Vessel At Berth* regulation, applicable to container and cruise vessels from 2014, was expanded in 2023 to mandate the use of shore power, or other CARB approved emissions control strategies[28] (CAECS), at CA ports for a more comprehensive list of vessel types.[29]

The Port of Los Angeles is the busiest seaport in the Western Hemisphere and the busiest container port in the United States, with the nearby Port of Long Beach as the second busiest container port (together referred to as the San Pedro Bay ports).[30] These and other CA ports handle about 40% of containers imported into the U.S. and 30% of all U.S. Exports.[31] Due to the concentrated emissions and impact on air quality from vessels, vehicles, and equipment, CARB estimated that activities at the San Pedro Bay ports have resulted in an average of 67 premature deaths and over 2,000 cases of harm to lower respiratory systems per year.[32]

In November 2017, the San Pedro Bay ports approved the 2017 *Clean Air Action Plan Update*, setting a comprehensive strategy to meet targets for the ports to reduce GHGs 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050. This plan includes transitioning terminal equipment to zero emissions by 2030, mandating that by 2020, new equipment purchases produce zero or near-zero emissions, if feasible (or cleanest available if zero/near-zero emissions are not yet feasible).[33] Currently, ports are largely considering electric and/or hydrogen fuel cell technologies as the solution to phase out fossil-powered cargo handling equipment.

In June 2023, the Port of Los Angeles recognized that local grid infrastructure would require upgrades to handle the projected loads of a fully electric fleet of cargo handling equipment, prompting the consideration of hydrogen fuel cell technologies as a solution

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[26] Exemptions for continuous navigation, emergency generators, government-owned vessels, engines using alternative fuels, and situations endangering vessel safety / https://www.law.cornell.edu/regulations/california/13-CCR-2299.2

[27] https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf

[28] Alternative CAECS must reduce the vessel's at berth criteria pollutants (e.g. NO_x and PM) by at least 80% (as well as meet g/kW-hr thresholds) and emit no more carbon than if powered by the CA grid

[29] https://www.sustainable-ships.org/rules-regulations/ogvb

[30] https://www.portoflosangeles.org/references/2022-news-releases/news_110722_green_corridor

[31] https://lao.ca.gov/Publications/Report/4618

[32] https://ww2.arb.ca.gov/sites/default/files/classic/ch/communities/ra/westoakland/documents/reduction.pdf

[33] https://kentico.portoflosangeles.org/getmedia/9d371f7b-9812-4c75-bcfd-23e83a191435/CAAP_2017_Draft_Document-Final

to alleviate this strain.[34,35] In October 2023, San Pedro Bay ports received a shared grant from the U.S. Department of Energy (DOE), funded by the *Bipartisan Infrastructure Law*, to support the deployment of cargo-handling equipment, trucks, and stations fueled by hydrogen in the ports' terminals. There is strong support with complimentary strategies for accelerating green hydrogen at the San Pedro Bay ports, however bunkering is not technologically ready.[36] The wide range of electric and hydrogen infrastructure being piloted and/or deployed in the San Pedro Bay will lend expertise to future decarbonization efforts for vessels frequenting these ports.

In September 2023, the San Pedro Bay ports entered into a Green Shipping Corridor agreement with the Port of Shanghai. At COP28 a partnership structure and governance mechanism were established to outline processes for financial management, decision-making, and other responsibilities of the partners. The partnership seeks to enhance supply chain efficiency and the scale of green shipping technologies and fuels. Next steps include a study to analyze trade and traffic between ports to estimate the quantity of low- and zero-GHG fuels required, and ongoing analyses of supply and demand of fuels to garner insights into where to invest their resources.[37,38] Other recent zero carbon trade corridor agreements have involved Port of Oakland, Japanese Ports, and Port of Singapore.[39]

A suite of potential options are available for deep sea decarbonization, yet there is no current, clear consensus on the optimal maritime fuel for the future.[40] Zero-GHG fuels are not broadly commercially available, and industry stakeholders grapple with technological uncertainties, infrastructure limitations, and evolving regulatory landscapes. However, a 2023 CE Delft study provides evidence to policymakers that halving shipping emissions by 2030 and reaching zero emissions by 2040 could be feasible.[41] Clear policy standards, continued stakeholder collaboration, investment, research, and support are required to scale low- and zero-emission technologies and fuels for industry application. The following report characterizes and assesses low and zero-GHG fuels and propulsion technologies, discussing their properties, readiness, emissions, and economics.

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[34] Total energy consumption for six Los Angeles container terminals under 100% electrification is ~1,018,000 MWh, according to a busy schedule where most equipment is operated in each shift

[35] https://kentico.portoflosangeles.org/getmedia/6b15966c-e99f-4ec0-9eca-3b9974e8a976/EPRI-POLA-ZE-Planning-Grid-Assessment

[36] https://polb.com/port-info/news-and-press/hydrogen-era-dawns-at-san-pedro-bay-ports-complex-10-13-2023/

[37] https://www.c40.org/news/ports-singapore-la-long-beach-green-digital-shipping-corridor/

[38] https://www.portoflosangeles.org/references/2023-news-releases/news_092223_green_shipping_corridor

[39] Wooley et al. *Policy Options to Decarbonize Ocean-Going Vessels*, and accompanying, Policy Compilation Spreadsheet, May 13, 2024, https://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/ocean-going-vessel-decarbonization

[40] Methanol notably became a leading alternative fuel on the 2023 orderbook

[41] https://cedelft.eu/wp-content/uploads/sites/2/2023/06/CE_Delft_230208_Shipping_GHG_emissions_2030_Def.pdf

Comparison to CARB 2018 Oceangoing Vessel Technology Assessment

The *2018 Draft CARB OGV Technology Assessment* sought to provide information on the state of existing and projected development of technologies that are useful in reducing OGV greenhouse gas emissions. There has been rapid change in the global fleet since the report was released, almost six years ago (Figure 1), with developments in policy, industry, and technology landscapes. For example, since 2018, several emissions-relevant policies[42] have been implemented or expanded, including the reduction of IMO sulfur limits[43] and IMO's adoption of the *Energy Efficiency eXisting ship Index* (EEXI) requirements,[44] which went into effect in 2023. Furthermore, the IMO set GHG targets under their 2023 *Revised Greenhouse Gas Strategy*, "striving" for 30% uptake of near-zero fuels by 2030, and 80% uptake by 2040.[45] Additionally, political events such as the 2022 Russian invasion of Ukraine have exposed fragility in global fossil fuel supply chains and the dangers of reliance on singular fuel types.

As a result, the maritime sector is increasingly compelled to explore diverse and sustainable energy solutions to align with climate targets and address geopolitical challenges. The global fleet is poised for rapid transformation away from conventional fuels and technologies due to regulatory mandates, economic incentives, stakeholder pressure, and technological innovations and advancements in alternative propulsion systems. While initial investments in these technologies may be significant, long-term operational savings, efficiency improvements, economies of scale and supportive policies will lead to a sustained downward trend in the cost of cleaner energies, making them increasingly competitive with conventional choices.

This report delves into current and developing technologies, offering an examination of recent advancements in supplemental power systems and a detailed review of a broader suite of alternative fuels in evolving regulatory, political, and physical environments.

The scope of this report focuses on non-fossil based options for OGVs. For example, while CARB has increasingly addressed the prospect of alternative fuels, such as hydrogen, methanol, ammonia, and biofuels, its draft 2018 study primarily focused on liquefied natural gas (LNG) due to its then-perceived promise as a fuel for OGVs. In that report, CARB underscored the potential growth in popularity of LNG, supported by its ability to be used for LNG new builds and retrofits, along with its potential to reduce GHG emissions and NO_x, SO_x, and PM. CARB discussed the challenges associated with developing LNG fueling infrastructure and the impact of the evolving regulatory landscape on the growth of LNG usage. Since the 2018 draft CARB study, LNG infrastructure has

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[42] Wooley et al. *Policy Options to Decarbonize Ocean-Going Vessels*, and accompanying, Policy Compilation Spreadsheet, May 13, 2024, https://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/ocean-going-vessel-decarbonization
[43] https://www.imo.org/en/MediaCentre/PressBriefings/pages/34-IMO-2020-sulphur-limit-.aspx
[44] https://www.imo.org/en/MediaCentre/PressBriefings/pages/CII-and-EEXI-entry-into-force.aspx
[45] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

evolved, the understanding of LNG's life cycle emissions relative to conventional fuels has expanded, and political events have influenced demand for LNG.

This study provides a detailed review of a wide range of low-GHG alternative fuels for the marine sector, excluding LNG, and explores their potential for decarbonization. LNG is another alternative to conventional fuels being considered in the market; However, for the purposes of this analysis, LNG and other fossil fuels are excluded. While LNG boasts lower exhaust emissions compared to conventionals, its overall well-to-wake GHG emissions are higher. Potential pathways to low-GHG LNG, such as bio- and e-LNG are being developed.

For additional information on LNG as a marine fuel see, among many others, the Green Ray project,[46] a summary of issues regarding methane emissions from LNG fueled ships,[47] LNG as a marine fuel in the U.S.,[48] and marine LNG uptake in Arctic states, including Alaska.[49]

Demonstrations of emerging technologies in supplemental power have been showcased in recent years, and have offered insights into the feasibility of supplemental power systems aboard large commercial ships. The 2018 CARB study included limited demonstrations of wind, solar, and fuel cell technologies that were available at the time. Since then, there have been more trials of supplemental systems, accompanied by the release of several empirical and modeling estimates of fuel savings. Additionally, implementations of supplemental power systems, while still limited in availability, have been growing over the past five years.

This study includes a review of more recent trials of wind- and solar-assisted propulsion technologies, and battery-assisted propulsion. Many supplemental power studies have come available since CARB's 2018 draft assessment study, however, R&D on these systems still appears to be in early stages, and the fuel reduction estimates vary widely from study to study. The primary focus of this report is on low-GHG technologies for vessel propulsion. In practice, these technologies will likely sit alongside a suite of energy efficiency measures, including hull lubrication, bulbous bows, speed adjustments, propeller adjustments, and hull coatings, among other options. While these technologies improve vessel performance and efficiency, they are complements, not replacements, for low-GHG fuels.

Advancements highlighted in this report include the 2022 maiden voyage of the world's first fully autonomous electric vessel and the 2023 maiden voyage of the first cargo ship

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[46] https://greenray-project.eu

[47] https://theicct.org/wp-content/uploads/2023/10/Options-for-Reducing-Methane-Emissions-from-New-and-Existing-LNG-Fueled-Ships-FINAL-926.pdf

[48] https://oceanconservancy.org/wp-content/uploads/2024/04/Final-LNG-as-a-Marine-Fuel-in-the-United-States.pdf

[49] https://cleanarctic.org/wp-content/uploads/2024/04/LNG-and-Shipping-in-the-Arctic-Final.pdf

retrofitted with wing sails. Several competing technologies have also undergone testing in recent years, which has provided more information of potential fuel savings and feasibility of wide-scale applications of supplemental systems (e.g. batteries, wind sails etc.). While large commercial ships are still in early stages of testing and adopting supplemental power systems, the emergence of competitive products and successful pilot programs, along with orders for supplemental power systems, signal growing industry and regulatory interest in these technologies.

Detailed descriptions of alternative fuels and supplemental power systems, based on the best available information, are provided in the following sections.

Section 2: Alternative Fueled Vessels - Current Fleet and Orderbook

This section presents a novel analysis of the existing low-GHG fleet and the orderbook based on classification society data. These data show significant recent uptake of methanol-powered, methanol-ready, and ammonia-ready vessels. Time-series trends show little uptake of these vessels until the early 2020s, followed by rapid growth in new-build and orderbook vessels. These insights show a commitment by some in the industry to develop capacity for low-GHG fuels in their fleets that has not previously been observed.

Subsequent sections of this report explore the availability and projections of these alternative fuels, including infrastructure requirements and scalability, alongside detailed comparative analysis of the fuels' benefits and challenges. Each fuel type is individually examined, culminating in Section 8: Technology Readiness, which summarizes their current states and preparedness for decarbonizing the maritime sector; Underscoring the policy attention, safety standards, and research necessary for further advancement.

IHS Seaweb provides a comprehensive database of ship characteristics worldwide. Focusing on ocean-going cargo-carrying vessels in Seaweb[50] yields a range of primary and secondary fuels.[51,52] Querying Seaweb's "Supplementary Features," also yields information on vessel readiness to consume ammonia (NH_3) and methanol (CH_3OH), run on battery power, and supplemental power technologies including battery-, solar-, and wind- assist.

As of October 2023, there are 26 vessels fueled by methanol, with 138 vessels ordered for delivery, i.e. on the orderbook. An additional 16 vessels are methanol-ready, meaning they currently run on conventional bunker fuels in dual fuel engines but are designed to

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[50] https://maritime.ihs.com

[51] Fuels listed include, Coal, Distillate Fuel, Ethane, Gas Boil Off, Hydrogen, Lng [sic.], Lpg [sic.], Methanol, "Not Applicable," Nuclear, Residual Fuel, and "Yes, But Type Not Known."

[52] There are two nuclear-powered ocean going cargo-carrying vessels listed, the Sevmorput and Yamal, both Russian-government owned ice-breaking vessels.

be easily converted to run on methanol at a later date if the vessel operator chooses. There are 44 vessels that are currently ammonia-ready, with an additional 154 vessels on order, but no ammonia-fueled vessels currently listed in Seaweb. Hydrogen is currently listed as the primary fuel for two sister vessels, the *Hydra* and the *Nesvik*, which are both Ro-Pax Ferries operating in Norway; LNG is listed as the secondary fuel. There are currently six hydrogen powered vessels on order.

Table 1

Alternative Fuel Readiness and Supplemental Power Systems on Oceangoing Vessels

October 2023	Built	Orderbook	Total
Battery Assist	209	101	310
Battery Power	36	24	60
CH_3OH Fueled	26	138	164
CH_3OH Ready	16	105	121
Hydrogen	2	6	8
NH_3 Ready	44	154	198
Solar Assist	21	21	42
Wind Assist	32	9	41
Total	**141**	**433**	**574**

Table 1 shows the current breakdown of alternative fuel powered and alternative fuel-ready vessels that are operational and on order. Table 1 also shows data from Seaweb for supplemental power technologies including battery-, solar-, and wind- assist.

Time-series data (Figure 1) show rapid growth across technologies since 2020. Solar-assist showed the largest growth (2.6x) from 2020 and battery assist (1.7x) and methanol-fueled vessels (2.0x) approximately doubled during that time frame. Battery-powered vessels grew by 2.4x and ammonia (NH_3)-ready vessels grew from zero at the end of 2020 to 44 vessels at present. Although there has already been rapid growth across technologies, the current orderbook shows significant increases in methanol-ready (7.6x), methanol-fueled (6.3x), ammonia-ready (4.5x) and hydrogen-fueled (4.0x) vessels from present to mid-2028.

Analysis of the reported current and orderbook deadweight tonnage[53] (DWT) for the selected technologies (Table 2) shows that ammonia-ready vessels currently make up the largest proportion of alternatively fueled (or with the potential to be alternatively fueled) vessels, and orderbook volumes will more than triple (3.3x) the DWT of ammonia-ready vessels by mid-2028 to 23.5 million DWT, comprising 41.6% of the built + orderbook DWT. The orderbook shows that methanol-fueled DWT is projected to grow to 13.7x current

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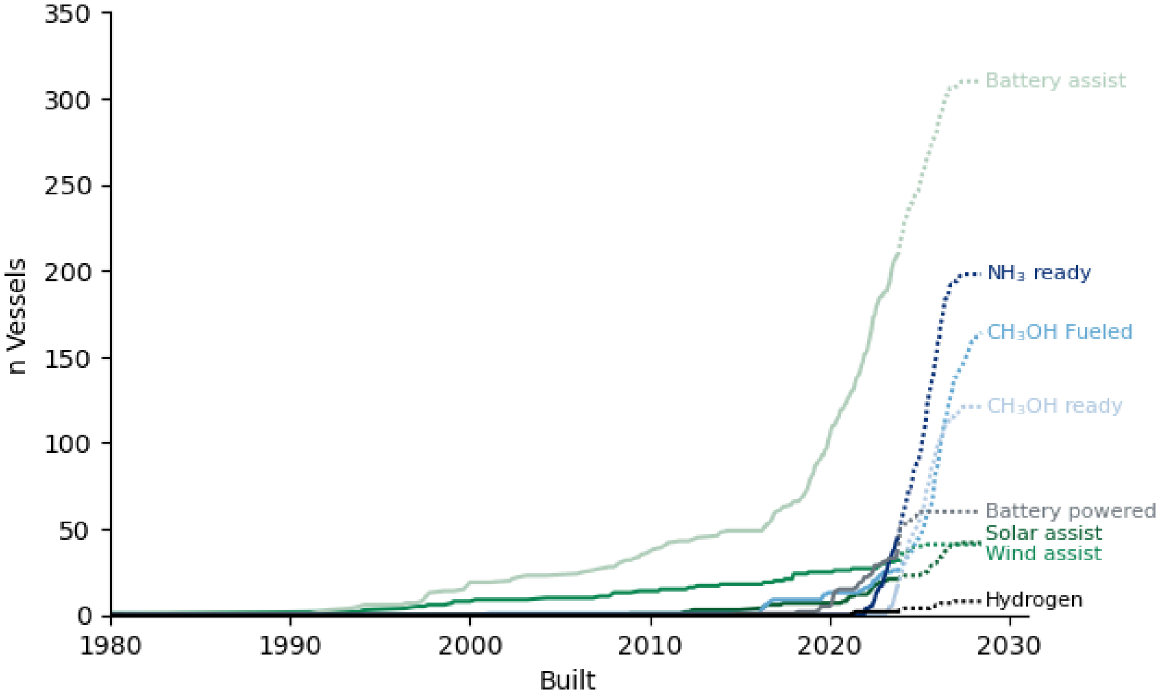
[53] Deadweight tonnage (DWT) refers to the measure of the maximum weight a ship can carry at full capacity, including cargo, fuel, ballast water, provisions, passengers and crew; DWT does not include the weight of the ship itself.

volumes by mid-2028 (30.2% of built + orderbook DWT) and methanol-ready DWT will grow by 5.4x, to comprise 17.8% of built + orderbook DWT.

Figure 1

Alternative Fuels and Supplemental Power Systems on Oceangoing Vessels



Time series graph showing cumulative count of alternative fuel and supplemental power systems on ocean-going cargo-carrying vessels since 1980. Dotted lines show vessels currently on order.

Table 2

Deadweight tonnage with alternative fuels and supplemental power systems

	Built DWT	Orderbook DWT	Total DWT
Battery Assist	2,048,288	1,010,003	3,058,291
Battery Power	10,683	19,816	30,499
CH_3OH Fueled	1,243,877	15,813,736	17,057,613
CH_3OH Ready	1,874,675	8,206,003	10,080,678
Hydrogen	-	52,300	52,300
NH_3 Ready	7,052,927	16,487,303	23,540,230
Solar Assist	341,439	379,700	721,139
Wind Assist	1,685,814	308,200	1,994,014
Total	12,198,732	41,247,242	53,445,974

Wind-assist supplemental power is projected to grow to 1.2x current volumes, but the total DWT (built + orderbook) remains small, comprising just 3.5% of total DWT by mid-2028. Other supplemental power technologies are projected to fare similarly. Solar-assist will make up just 1.3% of total DWT, and battery-assist 5.4%. Hydrogen and battery-powered vessels each make up less than 0.1% of the reported current and orderbook DWT.

It is also useful to consider total installed main engine power, as installed power (kilowatts, or kW) correlates directly with energy consumption (e.g. kilowatt-hours, or kWh). At present, considering built vessels plus those on order, methanol-powered vessels make up the largest proportion of installed power (29.0%), followed by ammonia-ready vessels (26.2%). Methanol-ready vessels comprise an additional 18.9% of the built + orderbook installed power for the identified technologies.

Table 3

Main engine total kW with alternative fuels and supplemental power systems

	Built kW	**Orderbook kW**	**Total kW**
Battery Assist	1,658,703	680,062	2,338,765
Battery Power	-	8,800	8,800
CH_3OH Fueled	229,214	3,556,042	3,785,256
CH_3OH Ready	567,462	1,904,242	2,471,704
Hydrogen	1,986	-	1,986
NH_3 Ready	694,023	2,730,096	3,424,119
Solar Assist	383,481	302,080	685,561
Wind Assist	291,663	38,897	330,560
Total	**2,167,829**	**8,531,357**	**10,699,186**

Supplemental power systems support propulsion on just over a quarter of the installed kW of the alternatively-fueled fleet (Table 3), with battery-assist technology accompanying 17.9% of the power in the identified technologies. Solar-assist (5.3%) and wind-assist (2.5%) comprise much smaller fractions of the total installed power, and fully battery or hydrogen powered each comprise less than 0.1%.

Figure 2 shows the distribution of main engine power and DWT by vessel for each of the identified technologies. Each point represents a single vessel. There are limited samples for battery and hydrogen powered vessels, where the Seaweb data are missing entries for either DWT or main engine power.[54] Additional summary statistics by technology and vessel type are shown in Table 4.

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[54] Missing data of this sort are not uncommon, and may reflect incomplete record-keeping, or as-yet undefined characteristics for the vessel.

The data show that solar assist is generally installed (or on order) on RO-ROs under 20,500 DWT and up to 26,000 kW. Battery assist is most commonly installed on smaller passenger and RO-RO vessels (means = 1,294 DWT and 16,829 DWT), though it is also found on larger vessels, up to 130,000 DWT. Three quarters of vessels with battery assist installed have main engine power less than 9,500 kW.[55] Battery-powered vessels are generally small (< 9,000 DWT) and the technology is predominately installed on passenger/ROPAX ferries under 600 DWT.

Wind assist is found on a broader range of vessel sizes, up to 324,200 DWT, though it is most frequently found on smaller vessels (overall median = 6,477 DWT) with lower installed power (median = 6,090 kW). Solar assist is most commonly found in RO-RO vessels, with 35 RO-RO vessels, built and on order, with solar assist technology

There is a wide distribution in size of methanol-fueled vessels, from 6,600 DWT to 225,000 DWT. The majority of methanol-fueled vessels, either built or on order, are container ships (115 of 164) or chemical tankers (41 of 164) and the overall mean methanol-fueled vessel power is 23,080 kW, though container ships are generally higher powered (mean = 29,431 kW). Methanol-ready vessels show a similar distribution, being mainly installed on container ships (71 of 121), RO-ROs (19 of 121) or chemical tankers (16 of 121) and the mean main engine power is 20,427 kW. This mean is heavily influenced by container ships which are higher powered (mean main engine power = 28,602 kW) than RO-ROs (mean = 13,584 kW) and chemical tankers, which are smaller and low powered (mean = 19,917 DWT, 5,235 kW).

The distribution of power and deadweight by vessel type is shown for each alternative fuel in Figure 2. The number of hydrogen-powered vessels, built and on order, is small (n=8) and the Seaweb data are incomplete (2 of 8 vessels list main engine power). Summary statistics may only reflect a few vessels where counts are low. The ammonia-ready fleet shows a bifurcation in the power trends for vessels larger than 50,000 DWT. The relationship between power and deadweight is linear, with ammonia-ready container ships following a trend towards higher main engine power per unit deadweight, with bulk carriers and tankers being lower powered (See Figure 2 on the following page).

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[55] Data on engine power, in kW, refer to the main engine installed power, not the battery power.

Figure 2

Deadweight tonnage and main engine power for alternatively fueled ocean-going vessels

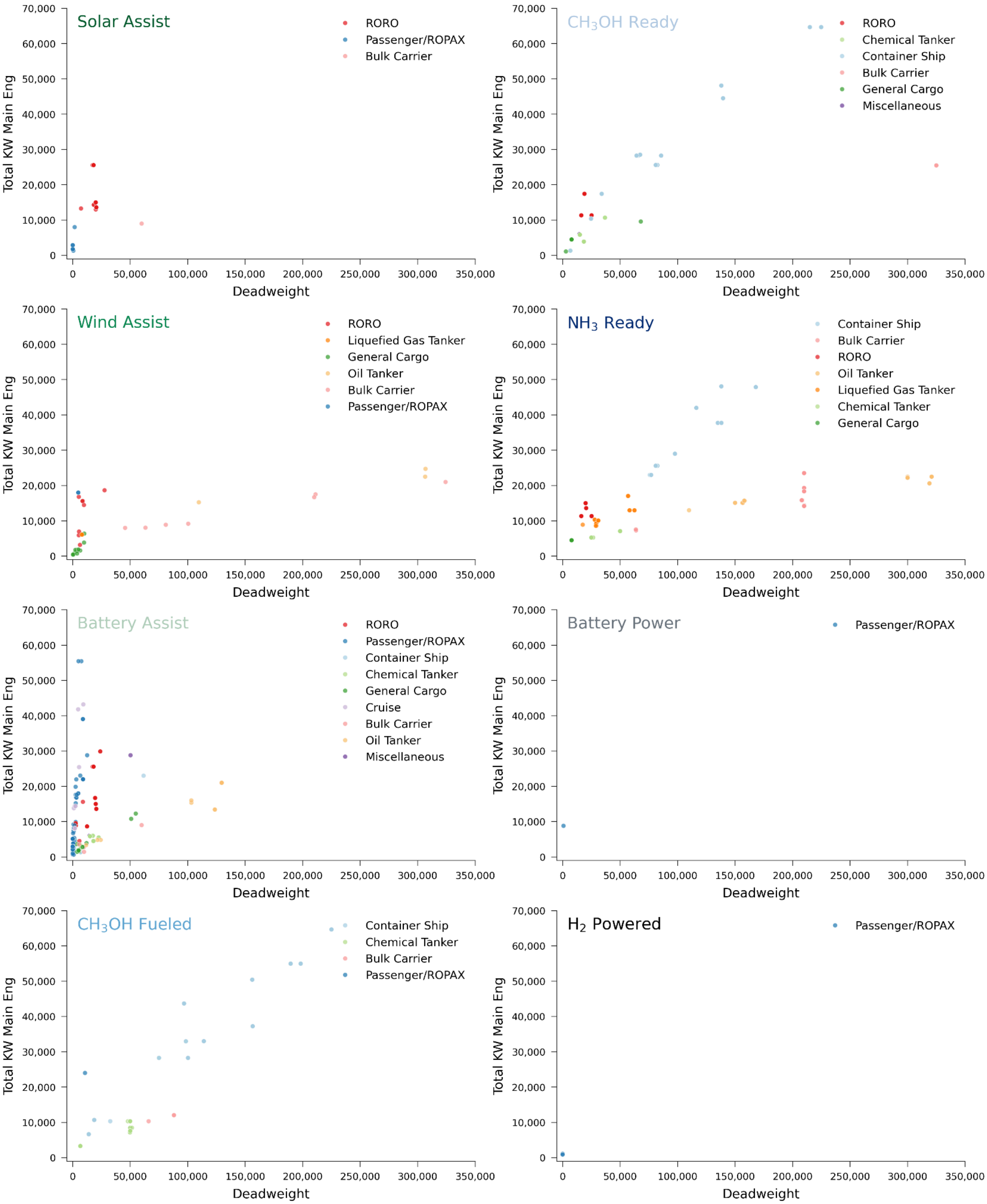


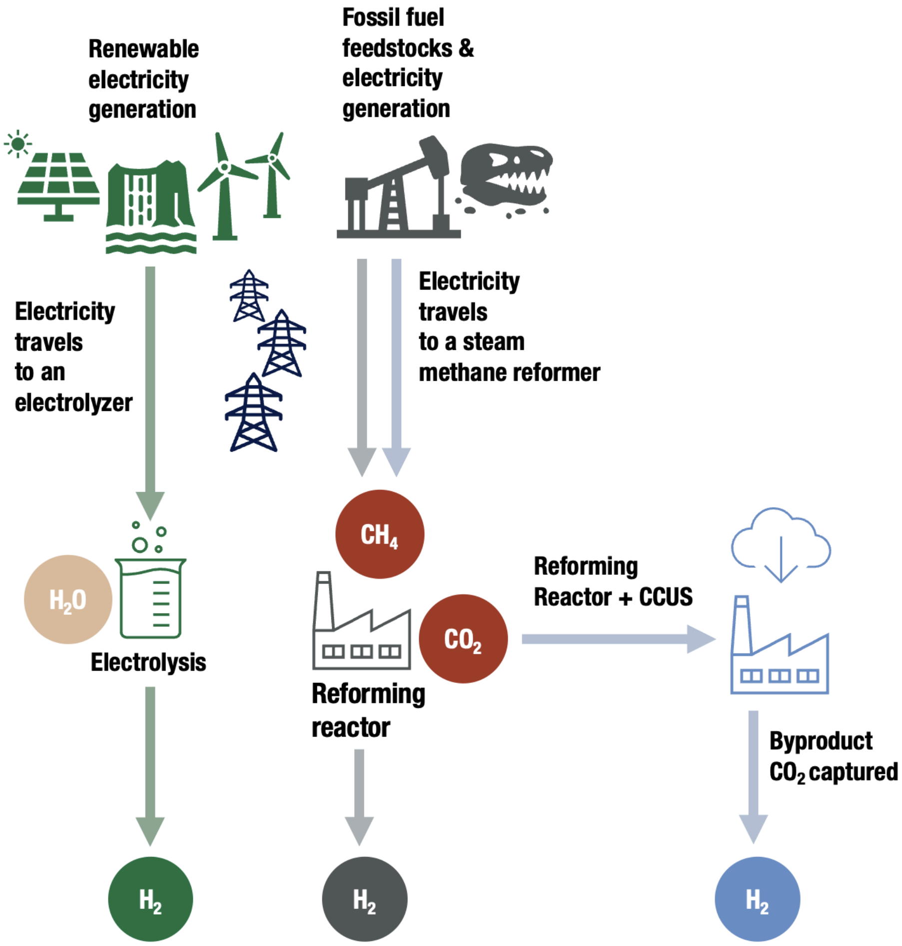
Table 4

Main engine total kW and deadweight summary statistics for existing and orderbook

Technology	Ship Type	Count	Mean DWT	Median DWT	Max DWT	Mean kW	Median kW	Max kW
Battery Assist	Bulk Carrier	5	18,806	9,435	59,914	3,888	2,720	9,000
	Chemical Tanker	28	14,750	17,500	22,554	4,555	4,500	6,000
	Container Ship	3	25,038	6,750	61,614	8,551	1,327	23,000
	Cruise	13	2,708	1,800	9,200	16,203	9,000	43,200
	General Cargo	33	8,574	5,350	54,810	2,357	1,920	12,268
	Miscellaneous	5	21,731	14,600	50,254	10,560	6,000	28,800
	Oil Tanker	11	93,580	123,602	129,734	14,101	15,360	21,000
	Passenger/ROPAX	164	1,294	660	12,540	5,228	2,147	55,440
	RO-RO	48	16,829	18,134	23,942	16,927	15,000	29,880
Battery Power	Container Ship	3	7,040	9,000	9,000	-	-	-
	Oil Tanker	1	1,083	1,083	1,083	-	-	-
	Passenger/ROPAX	54	120	41	600	163	-	8,800
	RO-RO	2	900	900	900	-	-	-
CH_3OH Fueled	Bulk Carrier	5	80,880	81,200	88,000	6,880	10,320	12,040
	Chemical Tanker	41	45,677	49,900	51,525	8,348	8,470	10,320
	Container Ship	115	128,268	114,000	225,000	29,431	33,000	64,650
	Passenger/ROPAX	1	10,670	10,670	10,670	24,000	24,000	24,000
	RO-RO	2	9,500	9,500	9,500	-	-	-
CH_3OH Ready	Bulk Carrier	2	325,000	325,000	325,000	25,479	25,479	25,479
	Chemical Tanker	16	19,917	18,500	36,836	5,235	3,900	10,680
	Container Ship	71	120,669	138,037	225,000	28,602	28,260	64,650
	General Cargo	9	13,589	7,000	68,004	2,687	1,100	9,582
	Miscellaneous	4	14,600	14,600	14,600	6,000	6,000	6,000
	RO-RO	19	19,147	19,000	25,200	13,584	11,340	17,430
H_2 Fueled	Container Ship	2	5,900	5,900	5,900	-	-	-
	Cruise	3	13,500	13,500	13,500	-	-	-
	Passenger/ROPAX	3	-	-	-	662	882	1,104
NH_3 Ready	Bulk Carrier	41	188,507	210,000	211,000	14,885	15,840	23,520
	Chemical Tanker	12	37,716	38,300	50,000	6,170	6,170	7,080
	Container Ship	64	123,479	138,037	168,000	26,093	25,600	48,090
	General Cargo	9	23,933	7,800	82,000	1,500	-	4,500
	Liquefied Gas Tanker	18	38,736	30,211	62,500	11,106	10,080	17,040
	Oil Tanker	25	238,769	299,847	320,917	19,008	20,616	22,500
	RO-RO	29	19,803	20,000	25,200	13,148	13,600	15,000
Solar Assist	Bulk Carrier	1	59,914	59,914	59,914	9,000	9,000	9,000
	Passenger/ROPAX	6	381	30	1,684	3,102	2,322	8,000
	RO-RO	35	18,827	20,000	20,500	18,799	15,000	25,560
Wind Assist	Bulk Carrier	8	137,304	90,692	324,230	11,163	9,030	21,000
	General Cargo	17	3,643	3,636	10,020	1,606	1,500	6,375
	Liquefied Gas Tanker	3	8,000	8,000	8,000	6,090	6,090	6,090
	Oil Tanker	3	240,959	306,474	306,752	20,827	22,500	24,720
	Passenger/ROPAX	2	4,825	4,825	4,835	18,000	18,000	18,000
	RO-RO	8	9,641	7,396	27,687	12,150	15,040	18,660

Figure 3

Hydrogen production pathways



Fuel description and properties

Hydrogen (H_2) is an energy carrier that does not typically exist in an isolated state in nature and must be extracted from other energy sources, including but not limited to biomass, solar energy, or water sources. It can also be cracked from other fuels,[56] like CH_4 and NH_3. Hydrogen can be derived from a variety and abundance of raw materials (Figure 3), however there are challenges to its production, transportation, and storage.

By accidental circumstance, a naturally occurring deposit of hydrogen gas was recently discovered, estimated between 6 to 250 Mt of "white hydrogen". Before this discovery,

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[56] Cracking refers to the breaking down or splitting of complex molecules into simpler molecules, under the influence of heat, catalysts or solvents

scientists believed meaningful quantities of hydrogen could only be synthesized in a laboratory or industrial setting. However, at this time, the concept is highly novel and it is unclear if commercially exploitable.[57,58]

Hydrogen combustion exhaust contains no carbon and minimal emissions compared to other marine bunker fuels. Moreover, its application in a fuel cell has no harmful exhaust, releasing only water and heat.[59] Thus, the sourced energies for its production and the thermal or electrolytic processes determine its life cycle, or WtW emissions. Presently, approximately 95% of all hydrogen is produced from steam reforming of natural gas.[60] While the marine stack emissions of hydrogen are favorable, its upstream emissions[61] remain controversial due to the low energy-density of the resulting fuel. Consequently, natural gas cannot be used in hydrogen production without fugitive methane emissions.

The volumetric energy density of liquid hydrogen (LH_2) is 9.5 Megajoules per liter (MJ/L). Compared to conventional bunker fuels such as marine gas oil (MGO) or marine diesel oil (MDO), the volumetric energy density of LH_2 is low (Table 5). Consequently, this can make its storage and transportation challenging, due to the relatively high volumes required for its commercial use.[62] Hydrogen is often converted to a liquid to increase its energy density, or carried within another molecule like ammonia or methanol for transportation and then cracked for use.[63] LH_2 requires special handling, with temperature and pressure management under cryogenic conditions (-253°C).

Cryogenic burns are possible with improper handling of LH_2, and rapid release into the environment can locally displace oxygen. In its natural state H_2 is odorless and colorless, making leakage difficult to detect without appropriate sensors and monitors. Though it is non-toxic and evaporates readily, hydrogen is extremely flammable and undetected leaks pose a significant safety risk. In addition to safety concerns, LH_2 also poses challenges in terms of on-board storage space and energy costs, especially for ships where cargo volume is a commodity.

Hydrogen demand is growing, although novel applications in long-distance transportation account for less than 0.1% of this demand. In the International Energy Agency's "Net Zero Emissions by 2050" Scenario, long-distance application should account for one-third of hydrogen demand by 2030. Green and blue hydrogen remained below 1% of global

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[57] https://www.euronews.com/green/2023/11/05/what-is-white-hydrogen-the-pros-and-cons-of-europes-latest-clean-energy-source?utm_source=yahoo&utm_campaign=feeds_articles2022&utm_medium=referral

[58] https://www.businessinsider.com/white-hydrogen-france-clean-energy-climate-change-2023-10

[59] https://afdc.energy.gov/fuels/hydrogen_benefits.html

[60] https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics

[61] Upstream emissions, or well-to-tank, are the emissions that occur during the extraction, production, transportation and storage before reaching the point of consumption

[62] https://doi.org/10.1016/B978-0-08-100167-7.00012-3

[63] https://demaco-cryogenics.com/blog/all-about-liquid-hydrogen/

hydrogen production in 2022, thus rapid scale-up is required to reach commercial scale in transportation.[64]

Table 5 presents a comprehensive overview of key properties pertaining to hydrogen as a fuel source, with details regarding its energy content, technological maturity, costs, emissions and more that are discussed throughout the hydrogen sections of this report.

Table 5

Hydrogen fuel parameters, costs, and emissions[65,66,67]

Hydrogen Properties:	Gray	Blue	Green
Volumetric Energy Density (MJ/L)	5.6 - gaseous state 9.5 - liquid state		
Storage Density (kg/m^3)	0.09 - gas 71 - liquid		
Technology Maturity	Immature. Space requirements are limiting for transoceanic voyages.		
WtW CO_2e (kg per MJ fuel)	0.063 - 0.083	0.01 - 0.033	0.003 - 0.008
WtW NO_x (kg per MJ fuel)	0.0006-0.0075		0.0004-0.0073
WtW SO_x (kg per MJ fuel)	NC-0.0003		NC-0.0004
WtW CH_4 (kg per MJ fuel)	0.0027-0.0031		0.0022-0.0030
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		

NC = negligible concentration

Engine and Fuel System Parameters

Over 95% of ships run on fossil fuels powered by internal combustion engines (ICEs).[68] Hydrogen fuel may be used within a modified ICE, however these technological adaptations have not yet been scaled commercially. Hydrogen ICEs have a high tolerance

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[64] https://www.iea.org/energy-system/low-emission-fuels/hydrogen

[65] https://oceanconservancy.org/wp-content/uploads/2023/03/Approaches-Decarbonizing-US-Fleet.pdf

[66] https://doi.org/10.3390/jmse11081611

[67] https://doi.org/10.1016/j.pecs.2018.07.001

[68] https://www.globalmaritimeforum.org/content/2023/04/the-shipping-industrys-fuel-choices-on-the-path-to-net-zero_final.pdf

to fuel impurities and suggest a more straightforward transition from current marine technologies. Direct-injection and dual fuel methods are still in the conceptual stage.[69]

Energy may also be extracted from hydrogen using fuel cells to produce electricity, which can then be used to drive electric motors connected to the propulsion system. Fuel cells are considered to be the most efficient technology for extracting energy from LH_2. As there are variations of ICEs, there are also variations of fuel cells classified by the type of membrane they use, with different levels of compatibility for maritime application (Table 6). OGVs require a large amount of electricity for propulsion, which means fuel cells can presently only be used on larger vessels as a supplemental system for auxiliary power. Moreover, hydrogen fuel cells have yet to be stress-tested at scale in a marine environment.[70]

Table 6

Comparison of hydrogen fuel cell technologies[71]

Fuel Cell	Operating Temperature	LHV Efficiency	Pros	Cons
Polymer electrolyte membrane (x)	<120°C	60%	Reduced corrosion Low temperature Quick start-up	Expensive catalysts Sensitive to fuel impurities Near-halved efficiency when stationary
Alkaline (AFC)	<100°C	60%	Lower cost Low temperature Quick start-up	Sensitive to CO_2 Challenges to electrolyte management and conductivity Degradation under standby and shutdown cycling
Phosphoric acid (PAFC)	150-200°C	40%	Increased tolerance to fuel impurities	Expensive catalysts Sensitive to sulfur Long start-up
Molten carbonate (MCFC)	600-700°C	50%	Fuel flexibility Hybrid-gas turbine cycle	High temp. corrosion and breakdown Low power density Long start-up
Solid oxide (SOFC)	500-1000°C	60%	Fuel flexibility Solid electrolyte Hybrid-gas turbine cycle	High temp. corrosion and breakdown Degradation under standby and shutdown cycling Long start-up

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[69] https://globalchange.mit.edu/sites/default/files/hong-tarahong-sm-sdm-2022-thesis.pdf

[70] https://www.globalmaritimeforum.org/content/2023/04/the-shipping-industrys-fuel-choices-on-the-path-to-net-zero_final.pdf

[71] https://www.energy.gov/eere/fuelcells/comparison-fuel-cell-technologies

Fuel cells occupy a comparable space to conventional marine ICEs, but the cryogenic fuel system and storage tanks of LH_2 require ~8x greater storage capacity than that of conventional systems.[72] Theoretically, if granted identical onboard fuel space capacities, a vessel could only transport ~13% of the energy carried by HFO. According to the European Maritime Safety Administration (EMSA), hydrogen tanks are less flexible in terms of space utilization, and given the existing storage options, would primarily suit ships sailing short-to-medium distance voyages.[73]

A European SmartPort study found hydrogen to be a suitable fuel choice for most transportation, but not applicable for large OGVs without building mid-sea refueling stations for transoceanic voyages. Using LH_2 as a primary propulsion would have a range of around 3 days, compared to around 25+ days with conventional diesel fuel.[74] The International Council on Clean Transportation (ICCT) identified potential ports for mid-voyage LH_2 refueling between China's Pearl River Delta and California's San Pedro Bay ports.[75] Norwegian Det Norske Veritas (DNV) reported that while hydrogen has potential in short-sea shipping, and in blended or auxiliary capacities, it does not believe pure hydrogen will be a strong candidate fuel for long-distance shipping.[76]

A key challenge for manufacturers to adapt engine and fuel systems for hydrogen, is that hydrogen is prone to material degradation, hastening the deterioration of many metals and plastics commonly employed in conventional infrastructure.[77] This material damage may lead to leakage, which can be susceptible to combustion and other serious harm. Thereby, it is imperative to address the safety considerations associated with handling LH_2 for its use as an alternative fuel; including selecting appropriate materials, designing safety features into hydrogen systems, and properly training on its handling.

Hydrogen is non-toxic and does not contain any carcinogens.[78,79] Hydrogen is colorless, odorless, and tasteless, however, which makes leaks difficult to detect without proper monitoring equipment, and increases the risk of suffocation due to the displacement of oxygen. LH_2 is also cryogenic (-253°C), posing risks of severe frostbite upon contact. The most dangerous aspect of LH_2 is its highly flammable nature and risk of spontaneous combustion during a high-pressure leak.[80] Hydrogen can burn with a nearly invisible flame, further complicating detection and mitigation without proper systems. However, while hydrogen is highly flammable, it also requires higher oxygen for explosive combustion than many conventional fuels.[81] Thus, continued R&D for hydrogen systems

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

[73] https://www.emsa.europa.eu/publications/reports/item/5062-potential-of-hydrogen-as-fuel-for-shipping.html

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

[75] https://theicct.org/wp-content/uploads/2021/06/ZEV-port-infra-hydrogren-oct2020-v2.pdf

[76] https://www.dnv.com/maritime/publications/maritime-forecast-2023/index.html

[77] https://h2tools.org/bestpractices/material-compatibility

[78] https://www.nrdc.org/bio/christian-tae/hydrogen-safety-lets-clear-air

[79] https://www.energy.gov/eere/fuelcells/safe-use-hydrogen

[80] https://doi.org/10.1016/j.egyr.2022.04.067

[81] https://www.nrdc.org/bio/christian-tae/hydrogen-safety-lets-clear-air

and proper handling can enable hydrogen to be comparably safe to the conventional fuels transported in mass quantities today.

Limitations to hydrogen's application are being challenged with continued R&D, as its low emissions are highly favorable for net-zero timelines. University of California San Diego's Scripps Institution of Oceanography worked with a naval architect to design a research vessel capable of running 75% of an expedition's vessel operations using green hydrogen. Expected to launch 2028, the vessel will be powered using a hybrid system of hydrogen fuel cells alongside a biofuel-powered diesel-electric propulsion system. The ship is less than 50m in length, with some designs showing two liquid hydrogen cryogenic tanks of 28,000 gallons on deck.[82] The design specifications and needs of the vessel are not final at this time, however its fuel infrastructure appears to utilize a significant amount of space (a National Aeronautics and Space Administration (NASA) launch pad 60,000 gallon LH_2 tank measures about 17m length, with a 4.25m diameter).[83] Tanks are vacuum-insulated and double-walled to maintain cryogenic conditions and decrease risk of leaks.

In March 2023, the world's first liquid hydrogen-fueled ferry began operation in Norway. The 82.4m length *MF Hydra* can travel with 9 knot service speeds with its 80 cubic meter (m^3) storage tank, two 200kW fuel cells, two 440kW generators, and two Schottel thrusters.[84] In San Francisco, CA a gaseous hydrogen-fueled ferry was delivered but does not appear to have begun operation in its 6-month pilot project. The 22m length *Sea Change* can travel 20 knot service speeds with two 300kW propulsion systems and fuel cells with a total output of 360kW. However, its storage tanks have a capacity of less than $1m^3$ of hydrogen fuel, highlighting that onboard storage continues to be a challenge for implementation.[85]

Year-end analysis of alternative fuel vessels found the hydrogen orderbook to have decreased by one-third from 2022 to 2023, as orders have been canceled. DNV has deemed hydrogen's maritime readiness as "aspirational" for 2024.[86] R&D for near-term deployment may consider its use in dual fuel engines, blended fuels, or combined with supplemental power support.

Life Cycle WtW GHG and Criteria

At present, approximately 95% of hydrogen is gray hydrogen, produced through steam methane reformation (SMR) of natural gas, with no TtW emissions but high WtW carbon

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[82] https://www.unols.org/sites/default/files/201711ficap05.pdf

[83] https://blogs.nasa.gov/groundsystems/2016/12/01/new-liquid-hydrogen-tank-will-support-flights-from-launch-pad-39b/

[84] https://interestingengineering.com/transportation/mf-hydra-worlds-first-liquid-hydrogen-powered-ferry

[85] https://www.bairdmaritime.com/work-boat-world/passenger-vessel-world/ferries/vessel-review-sea-change-hydrogen-fuelled-demonstrator-ferry-for-san-francisco-bay-area/

[86] https://maritime-executive.com/article/dnv-orders-for-alternative-fueled-vessels-grow-with-methanol-in-the-lead

emissions.[87] Natural gas (which is mostly methane) feedstocks are used to make hydrogen via SMR, where high temperature steam reacts with methane in the presence of a catalyst to produce hydrogen. Natural gas is used to generate heat for this process. Upstream emissions from gray hydrogen include natural gas combustion emissions and criteria pollutants, and uncombusted methane leakage from upstream infrastructure or production processes.

The SMR reactions are laid out below with (1) showing the general SMR reaction of methane and water in the presence of high heat and a catalyst to produce hydrogen, (2) showing the water-gas shift reaction (WGSR) whereby additional H_2 is released by the reaction of carbon monoxide (CO) produced by the SMR reaction with water (H_2O), and (3) showing hydrogen produced via the direct steam reforming (DSR) reaction.

$$\text{(1) } CH_4 + H_2O \rightleftharpoons CO + 3H_2$$
$$\text{(2) } CO + H_2O \rightleftharpoons CO_2 + H_2$$
$$\text{(3) } CH_4 + 2H_2O \rightleftharpoons CO_2 + 4H_2$$

Blue hydrogen utilizes the same SMR process as gray hydrogen, but uses CCUS technologies to capture carbon emissions in the exhaust gasses (see Equations (2) and (3)). CCUS technologies address CO_2 emissions, but not CH_4, NO_x, or other pollutants from natural gas combustion to generate heat for the reaction. Production of blue hydrogen has been estimated to capture around 60-85% of CO_2 emissions; fugitive methane emissions remain an issue.[88]

In SMR, 55% of the CO_2 emissions are a byproduct of the reforming and reactions occurring. The remaining 45% are from the combustion of natural gas.[89] Thus, the carbon-intensity of blue hydrogen differs depending on the application of CCUS technology at each of these stages. GHG reduction estimates of gray vs. blue hydrogen vary greatly, between 5-36%, due to the R&D stages and varying assumptions for the CCUS efficiency, cost, etc.[90] Furthermore, there are arguments against the economic feasibility of CCUS because of the high financial costs associated with the energy-intensive CO_2 capture and conversion steps.[91]

A recent study found that blue hydrogen production at scale is not compatible with the Paris Agreement,[92] as carbon capture rates would need to be higher than 40% to have lower GHGs emissions than directly combusting methane as a fuel source. While CCUS

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[87] https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming
[88] https://doi.org/10.1002/ese3.956
[89] https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/
[90] https://pubs.rsc.org/en/content/articlehtml/2022/se/d2se00444e
[91] https://doi.org/10.1016/j.oneear.2022.01.006
[92] A legally binding international treaty on climate change / https://unfccc.int/process-and-meetings/the-paris-agreement

technology is often purported to reduce emissions by more than 90%, real-world conditions result in reductions closer to one-third of total CO_2 emitted, with consequential high-warming methane emissions not addressed.[93] Methane is 27-30 times more potent than CO_2 as a GHG over a 100-year timeframe, and is 82.5 times more potent over the near-term.[94]

Another recent study boldly claimed that blue hydrogen is neither clean nor low carbon. Even with the most conservative emission estimates and an assumed 85% carbon capture rate, the carbon-intensity of blue hydrogen production would be higher than the U.S. DOE's defined "clean hydrogen standard".[95] Surprisingly, some assumptions result in blue hydrogen having a greater warming effect than directly burning coal, natural gas, or diesel oil (thereby, gray hydrogen would too).[96]

Under the Inflation Reduction Act, U.S. Congress initiated incentives for blue H_2 production; Out of the 6-10 H_2 hubs designated for funding, a minimum of two must include blue hydrogen, as stipulated in the legislation.[97] The DOE has previously cited independent projections that blue H_2 could represent 50-80% of total U.S. H_2 production in 2050. Nevertheless, the current administration has stated plans to limit its approvals to deploying carbon capture at existing facilities rather than funding new blue H_2 facilities.[98]

Green H_2 is extracted from a non-hydrocarbon feedstock, usually water (H_2O), through electrolysis using renewable electricity or waste heat, or using polymer electrolyte membrane (PEM) electrolysis. PEM electrolysis is considered to be a promising pathway to green H_2, better suited for backstopping renewable energies,[99] although alkaline electrolysis with sodium hydroxide (NaOH) is considered to be a more mature technology and more commercially viable due to its lower capital costs and longer infrastructure lifetime.[100,101] Other green pathways for hydrogen production from water include thermochemical, photobiological, or photoelectrochemical water splitting, but these technologies are in early development.[102]

Theoretically, there is no carbon consumed or produced in the green hydrogen life cycle, although H_2 combustion in an ICE can release NO_x and water vapors.[103] NO_x is a grouping of toxic and highly reactive nitrogen gasses with negative impacts on air quality.[104] The

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[93] https://doi.org/10.1016/j.egyr.2023.08.021
[94] https://www.epa.gov/ghgemissions/understanding-global-warming-potentials
[95] https://ieefa.org/media/3953/download?attachment
[96] https://doi.org/10.1002/ese3.956
[97] https://www.congress.gov/bill/117th-congress/house-bill/5376/text
[98] https://www.eenews.net/articles/is-there-a-future-for-blue-hydrogen-5-things-to-watch/
[99] Backstopping refers to supporting or mitigating the challenges associated with the intermittent nature of renewable energy sources through its storage and ensuing accessibility
[100] https://thundersaidenergy.com/2023/01/17/green-hydrogen-alkaline-versus-pem-electrolysers/
[101] https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/
[102] https://afdc.energy.gov/fuels/hydrogen_production.html
[103] https://www.researchgate.net/publication/339106527
[104] https://www3.epa.gov/region1/airquality/nox.html

high heat conditions for hydrogen combustion can split apart the stable nitrogen (N_2) naturally occurring in the atmosphere, referred to as "thermal NO_x".[105] Presently, green hydrogen produced via electrolysis predominantly relies on fossil fuel grids, where grid CO_2 emissions can be twice that of SMR because of the inefficiency in the additional step of energy conversion.[106]

The total life cycle GHG emissions from renewable energy sources are significantly lower and generally less variable than those from fossil fuels.[107] Green hydrogen from renewable energies has a fraction of the life cycle emissions associated with gray hydrogen, though it is expected that there would still be GHGs associated with infrastructure development and manufacturing.[108] Apart from emissions, the mining of resources, including those used in renewable energy systems, has the potential to harm ecosystems and communities.[109] Nonetheless, green hydrogen would produce significantly fewer WtW emissions than most other marine fuel options.[110]

Bunkering and Existing Infrastructure

In 2022, global hydrogen demand reached 95 Mt, marking a historical high.[111] However, this demand was primarily concentrated in traditional, non-fuel sector applications. An estimated 10 Mt of hydrogen is currently produced in the U.S., predominantly through brown and gray processes.[112] Global capacity for hydrogen liquefaction is approximately 600 MT per day, equivalent to ~500,000 kW of hydrogen capacity.[113]

Global policies and financial incentives supporting the development of extensive hydrogen infrastructure have been emerging since 2019, with South Korea and Australia being early leaders in making a national commitment.[114] In 2021, the DOE launched the "Hydrogen Shot" aimed at reducing the cost of clean hydrogen production to $1 per 1 kilogram (kg) in 1 decade ("1-1-1") by establishing a framework for blue and green hydrogen pathway solutions at competitive scale.[115] Additionally, the *Bipartisan Infrastructure Law* and *Inflation Reduction Act* led towards the DOE committing $7 billion towards establishing domestic hydrogen infrastructure from production to use.[116]

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[105] https://doi.org/10.1039/D1EA00037C

[106] https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/

[107] https://www.nrel.gov/docs/fy21osti/80580.pdf

[108] https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf

[109] https://climate.mit.edu/ask-mit/will-mining-resources-needed-clean-energy-cause-problems-environment

[110] https://www.researchgate.net/publication/339106527

[111] https://www.iea.org/reports/global-hydrogen-review-2023

[112] https://www.energy.gov/eere/fuelcells/hydrogen-production

[113] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf

[114] https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html

[115] https://www.energy.gov/eere/fuelcells/hydrogen-shot

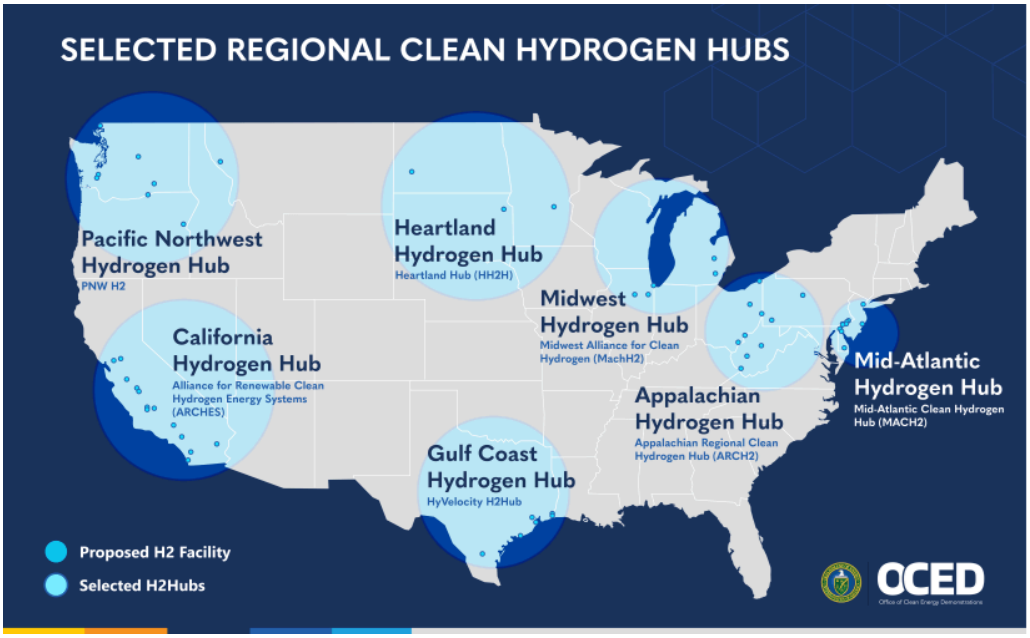
[116] https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations

Seven H_2 Hubs were selected under the *Inflation Reduction Act* to enter into negotiations with the U.S. federal government in the last quarter of 2023 (as shown in Figure 4). Collectively, the DOE aims for these facilities to produce 3 Mt of hydrogen annually.[117] These facilities are expected to require eight to twelve years before reaching operation, according to the DOE timeline. Consequently, it won't be until 2032-2036 that these renewable hydrogen capacities will be added to the market.[118] DOE announced support for these H2 Hubs and development of clean hydrogen technologies under the National Clean Hydrogen Strategy intent for funding announcement.[119]

The Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES),[120] also referred to as the CA Hydrogen Hub was awarded under this legislation. ARCHES seeks to prioritize the production, distribution, and storage of "clean renewable hydrogen" produced exclusively from renewable energy and biomass.[121] ARCHES aims "to reduce CO_2 emissions by 2,000,000 metric tonnes per year." The ARCHES hub has strong emphasis on beneficial engagement with local communities and plans to allocate funding towards 39 clean hydrogen projects across the state, with a view to eventually converting maritime equipment at ports to run on hydrogen.[122,123]

Figure 4

DOE Map of U.S. Clean Hydrogen Hubs Selected for Award Negotiation[124]



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[117] https://archesh2.org/arches-named-regional-h2hub/
[118] https://www.energy.gov/oced/funding-notice-regional-clean-hydrogen-hubs
[119] https://www.energy.gov/eere/fuelcells/articles/doe-issues-notice-intent-funding-advance-national-clean-hydrogen-strategy
[120] https://archesh2.org
[121] https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations
[122] https://archesh2.org/community-benefits/
[123] https://archesh2.org/about/
[124] https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations

Current CA state law requires that a minimum of 33.3% of hydrogen produced for or dispensed by fueling stations funded by the state must be generated from select renewable energy resources. If approved, a recently introduced CA state bill would require that beginning January 1, 2045, all hydrogen produced and consumed in CA for the generation of electricity or fueling of vehicles be green hydrogen.[125]

The 2022 global annual production of clean (blue and green) hydrogen pathways was approximately 726,000 MT, or around 0.76% of global production.[126] By mid-2023, it was estimated to be 740,000 MT.[127] This estimate does not include the 30,000 MT of green hydrogen that went online in summer 2023 across two facilities in China, nor additional facilities that have since, or will soon begin operation.[128,129]

There are global proposals to add approximately 26 Mt of clean hydrogen capacity through 2030; This represents about one-third of the 75 Mt of additional global capacity needed by 2030 to progress towards achieving net-zero emissions across sectors. Only 7% of these proposals have reached the stage of committed capital and/or construction. North America accounts for the largest volume of low-GHG hydrogen production proposals. While there is interest in hydrogen production, interest in developing other upstream infrastructure for distribution is lacking. There is a significant disparity between proposals for hydrogen production and for the development of other crucial infrastructure across the globe for its import and export, such as terminals, large-scale storage, ocean-going tankers, refueling and bunkering stations, etc.[130]

California is the only state in the U.S. to offer hydrogen fueling stations for road-based transportation.[131] Every U.S. state, excluding Kansas, has at least one statute or incentive concerning hydrogen fuel, with California (totaling 55) boasting more than twice the number of relevant regulations compared to its closest competitor.[132] Presently, the major hydrogen-producing states are California, Louisiana, and Texas. The majority of hydrogen is consumed for non-fuel applications close to production sources, due to the lack of distribution infrastructure. There are currently 1,600 miles of pipelines for hydrogen transportation in the U.S. located near petroleum refineries and chemical plants in Illinois, California, and the Gulf Coast.[133] This represents a significant portion of the 2,796 miles of hydrogen pipelines across the globe.[134]

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[125] https://legiscan.com/CA/text/AB1550/id/2708127

[126] https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf

[127] https://hydrogencouncil.com/en/hydrogen-insights-2023/

[128] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/063023-two-green-hydrogen-projects-totaling-30000-mtyear-of-capacity-start-up-in-china

[129] https://www.airswift.com/blog/green-hydrogen-projects-usa

[130] https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf

[131] https://afdc.energy.gov/stations/#/analyze?fuel=HY&show_map=true

[132] https://afdc.energy.gov/data/10376

[133] https://afdc.energy.gov/fuels/hydrogen_production.html

[134] https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf

A key challenge of the hydrogen energy economy is hydrogen's propensity to accelerate the deterioration of many metals and plastics used in conventional infrastructure.[135] In theory, gaseous hydrogen could be transported using the existing natural gas network with infrastructure modifications.[136] In practice, only about 50% of the LNG infrastructure could be reused, and that number decreases if hydrogen-compatible materials were not used in the initial construction, such as with older terminals.[137] Further consideration for infrastructure safety must be given for material compatibility under the extreme cryogenic conditions required for hydrogen distribution and storage.

The first substantial pipeline transition will be attempted in the Netherlands beginning in 2023, with operations anticipated in 2025. The Netherlands' plans to build an approximately 745-mile hydrogen network, 85% of which will involve transitioning existing natural gas pipelines. This real-world project will provide insight into the feasibility of this undertaking, in particular revealing how sections of new construction compare to retrofit in both initial construction and ongoing maintenance.[138]

The most costly incompatibilities for hydrogen transition exist in the conversion of natural gas storage tanks, which are estimated to make up 95% of the total equipment costs at an import terminal.[139] Issues are not limited to material compatibility, but notably, the energy stored by LH_2 in the same volume tank as LNG would be 60% lower due to the lower volumetric density of hydrogen.[140] Therefore, additional tanks for greater capacity would be required even in a theoretical seamless transition of current storage.

Some energy transitions envision blending hydrogen with natural gas in existing infrastructure, with estimates up to a ratio of 1:5 hydrogen to natural gas, safely. At higher concentrations hydrogen can accelerate the cracking and embrittlement of many metals and plastics not designed for hydrogen contact.[141] Some estimates of feasible blend ratios are as low as 1:50, and the differences in compatibility and lack of standardization across countries will be a challenge in its international trade.[142] Careful consideration and international standardization would be necessary to ensure safe integration of hydrogen into existing infrastructure for transportation and storage.

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[135] https://h2tools.org/bestpractices/material-compatibility

[136] https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

[137] https://www.nrdc.org/bio/ade-samuel/hydrogen-ready-lng-infrastructure-uncertain-way-forward

[138] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/102723-netherlands-begins-construction-of-national-hydrogen-pipeline-network

[139] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf?rev=3d707c37462842ac89246f48add670ba

[140] https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf

[141] https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf

[142] https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html

Although compressed hydrogen-natural gas blends can be directly used in ICEs,[143] their gaseous forms are unlikely to be utilized as a fuel due to the substantial volumetric capacity required for gaseous storage. Blending the fuels in their liquid forms, LH_2 and LNG, is a less feasible choice due to the complications of boil-off gas (BOG) from the mixture. Simulations of these blends saw that a 3% LH_2 mixture would have up to 16% hydrogen in the boil-off, introducing the cracking and embrittlement referenced above, and preventing BOG compressor equipment technologies from operating properly.[144] These technologies capture and reliquefy vaporized gasses lost in cryogenic storage, reducing methane slip in the case of LNG, and saving costs by minimizing lost fuel.

Hydrogen is not yet a mature technology, particularly in the maritime industry. The first transoceanic shipment of LH_2 from Australia to Japan[145] left the dock in February 2022.[146] Global uptake of hydrogen energy across all sectors is only estimated to reach 0.5% by 2030 and 5% by 2050, despite net zero emission trajectories accounting for 13% uptake of hydrogen to global energy mix on this timeline.[147] The infrastructure to bunker hydrogen is still novel. Across the globe, the world's first LH_2 bunkering facility for fueling ships was unveiled at the COP26 climate change conference in Glasgow in 2021.[148] However, there are no ports deploying hydrogen bunkering right now.

Through $16 million of funding, including a DOE-awarded grant of $8 million, Hornblower Energy in San Francisco, CA aims to build a floating barge for green hydrogen bunkering. It is expected to be complete in 2025, with its 2023 annual merit review to the DOE reporting "the design is progressing well and on time". However, little has been publicly reported about the project due to proprietary content.[149] The project team aims for the barge to be capable of producing, storing, and fueling up to 530 kg of hydrogen per day (equivalent to 0.53 MT). Its production would be facilitated by utilizing hydroelectric power, showcasing the utilization of zero-GHG hydroelectric energy in water electrolysis to generate green hydrogen.[150]

Costs (CAPEX and OPEX)

CAPEX = capital expenditure, OPEX = operating expenditures

Green hydrogen is not yet cost-competitive with gray hydrogen. However, the price of green hydrogen is expected to decline as the costs of renewable electricity and electrolysis fall, especially with the assistance of regulations and implementation of carbon pricing and tax credits available under the U.S. *Inflation Reduction Act* or by other

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[143] https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/14-317.pdf
[144] https://issuu.com/palladianpublications/docs/lng-october-2022/s/17026993
[145] Liquified hydrogen was transported as cargo, not used as marine fuel to power the vessel.
[146] https://www.iea.org/reports/global-hydrogen-review-2022
[147] https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html
[148] https://www.unitrove.com/media/press-release/2021/11/05/unitrove-unveils-world's-first-liquid-hydrogen-bunkering-facility
[149] https://www.marinelink.com/news/making-hydrogen-work-demo-project-san-508541
[150] https://hydrogen-central.com/hornblower-federal-grant-green-hydrogen-bunker-fueling-station-san-francisco/

nations. The current costs of commercially available electrolyzers, PEM and Alkaline, are \$1800/kW and \$1400/kW respectively. Despite its significant capital and operating costs, electrolysis is less efficient at producing hydrogen than SMR processes; its estimated 70% efficiency is below that of SMR at 74-85%.[151]

Eighty percent of hydrogen fuel costs is a function of the cost of electricity, which drives its extraction and which goes into energy costs to liquefy it for use. Production of hydrogen costs about \$5 per kg, depending on its production pathway: \$2.50-6.80/kg-gray H_2, \$1.50-4.10/kg-blue H_2, or \$2.5-6.0/kg- green H_2.[152] Liquefaction adds approximately \$1.50/kg, regardless of the production pathway.[153] Aforementioned, the DOE Hydrogen Shot seeks to reduce production costs with a goal of \$1 per 1 kg in 1 decade. Similar trajectories are proposed in other nations' climate pledges.[154] The DOE hydrogen goal for \$1/kg by 2031 only considers the capital and operating costs of production and does not include liquefaction, storage, delivery or dispense costs, which will translate to the end-user price.[155,156]

In addition to expensive production costs, hydrogen transportation and storage costs are still economically challenging, both pre- and post-bunkering. One approach to reduce costs is to carry hydrogen within the bonds of ammonia to utilize its properties that are more favorable for storage (e.g. ammonia's liquefaction temperature is -33°C compared to hydrogen's -253°C). It can be cracked or released through catalytic decomposition, with 5.65 kg of ammonia needed to produce 1 kg of hydrogen. Costs of liquefied hydrogen storage in cryogenic tanks are between \$1.67-2.04/kg compared to \$0.91-1.09/kg when hydrogen is carried in liquid ammonia.[157]

Pipeline transportation of gaseous H_2 would cost around 1\$USD/kgH_2 over 1500 km. Prices follow a linear curve, rising with distance, due to a larger number of compression stations required.[158] Due to this, cost-effective long distance transportation would require transporting hydrogen via another energy carrier (i.e. NH_3) or a liquid organic hydrogen carrier (i.e. methylcyclohexane - $CH_3C_6H_{11}$), or instead as LH_2 by tanker (Table 7). However, liquefaction is highly energy-consuming and therefore expensive, but transportation costs for LH_2 are roughly the same as the cost of delivery through pipelines.[159] LH_2 transportation adds 2.5x less end-user costs to the fuel than NH_3 conversion, but loses significantly more energy across its journey.[160]

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[151] https://doi.org/10.3390/en16145482
[152] https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/20004-cost-electrolytic-hydrogen-production.pdf
[153] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf
[154] https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html
[155] https://crsreports.congress.gov/product/pdf/IF/IF12514/62
[156] https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-strategy-roadmap.pdf?Status=Master
[157] https://doi.org/10.3390/en16145482
[158] https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf
[159] https://doi.org/10.3390/en16145482
[160] https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html

Table 7

Comparison of hydrogen carriers [161,162,163,164,165]

Carrier	Storage Cost (USD/kgH_2)	Transportation Cost (USD/kgH_2)	Efficiency	Storage Density (kgH_2/m^3)	Pros	Cons
Liquid Hydrogen (LH_2)	1.67 - 2.04	1.45 - 2.00	30-36% loss in liquefaction 0.05-0.25% loss in boil-off	70.8	Liquefaction commercially mature No purification	High cost for cryogenic equipment Small-scale availability today
Ammonia (NH_3)	0.91 - 1.09	1.40	12-26% loss for synthesis 13-34% for cracking	107	Production and traded in a large global market	High NO_x during shipping Toxic and corrosive Cracking technology still immature
Liquid Organic Hydrogen Carrier (LOHC)	Unclear	0.06 - 2.90	25-35% loss for dehydrogenation 0.1% loss of carrier per storage-release cycle	70	Can be transported as an oil in existing infrastructure	No clear chemical compound to act as "carrier" Possible carriers have a high cost Carriers would likely contain CO_2
H_2 Gas Pipeline	0.19 - 0.27	0.54 - >3.00	10% loss for compression 0.4% leakage loss	10.9-40	No conversion required, only compression Transport and storage are proven at a commercial scale	Material incompatibilities High cost off-shore Low energy density

A comparative study of fuels estimated LH_2 to be the most expensive low-GHG alternative fuel to bunker at $2,738.20/MT.[166] Most vessel designs to date utilize LH_2, which will have substantial costs from cargo revenue losses from its space requirements, and the energy used to maintain cryogenic conditions. Vessel costs are least understood, especially for OGVs. Due to its energy density-limitations, hydrogen is only feasible on short distances especially with ICEs, though use in fuel cells shows some promise for longer distances. Retrofits and new-builds are mainly occurring under R&D conditions and publicly available

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[161] https://doi.org/10.3390/en16145482
[162] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf
[163] https://cleantechnica.com/2022/10/04/the-green-hydrogen-pipeline-shipping-question/
[164] https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf
[165] https://www.energypolicy.columbia.edu/publications/hydrogen-leakage-potential-risk-hydrogen-economy/
[166] https://doi.org/10.1016/j.ijnaoe.2023.100523

data on costs are scarce. The concept of a small, low-speed, minimal-range research vessel had initial investment costs estimates between $76-82 million, and operating costs approximately 8% higher than for an equivalent diesel-fueled vessel; The hydrogen systems comprised ~10% of the total vessel CAPEX.[167]

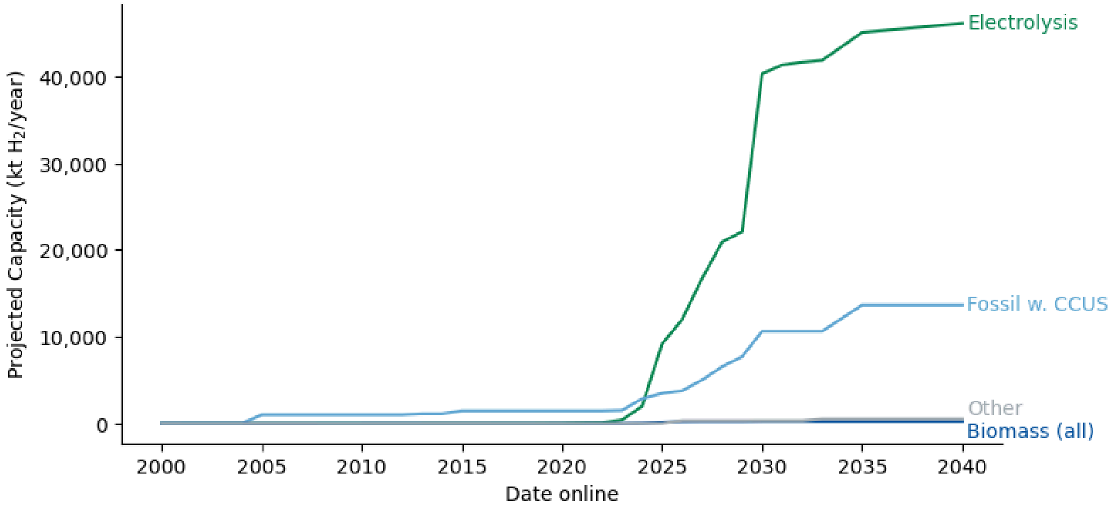
Fuel Availability and Projections: Hydrogen

According to the most recent estimates by the International Renewable Energy Agency (IRENA), global hydrogen production stood at around 75 Mt H_2 per year, with another 45 Mt H_2 per year as part of a mix of gasses. At the end of 2021, IRENA reported that around 47% of hydrogen production was gray (produced from natural gas), 49% was brown (produced from coal or oil), and around 4% was produced through electrolysis.[168]

Estimates from IEA differ from IRENA's, with IEA reporting global hydrogen production at almost 95 Mt in 2022, up 3% compared to 2021 (~92.2 Mt). Similar to IRENA, IEA reports that hydrogen production is dominated by fossil feedstocks, with 62% of hydrogen produced from natural gas without CCUS (gray hydrogen); 21% was produced from coal (brown hydrogen)–much of that in China; and refining byproducts accounted for 16% of global production.[169]

Figure 5

Global Renewable Hydrogen Capacities Projected to Come Online to 2040



Global demand across sectors anticipated at 530 Mt by 2050, 30% feedstock for other fuels (IEA)
Maritime and aviation demand ~110 Mt by 2050 (Hydrogen Council)

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[167] https://doi.org/10.1016/j.ijhydene.2020.06.019

[168] https://www.irena.org/Energy-Transition/Technology/Hydrogen

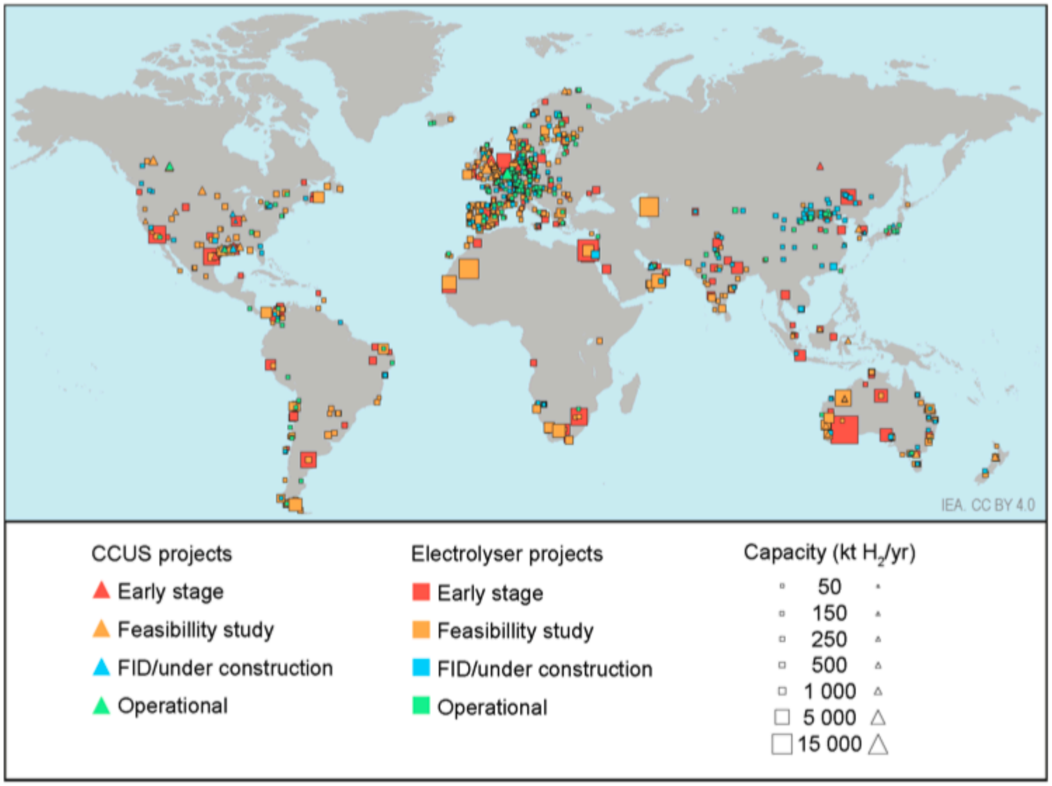
[169] https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf

IEA reports that low-emissions (blue and green) hydrogen production was less than 1 Mt in 2022, equivalent to around 0.7% of global production. Of that total, blue hydrogen (from fossil fuels, with CCUS) made up 0.6% of total production, with green hydrogen (from electrolysis) accounting for 0.1%. Production of hydrogen from electricity amounted to less than 100,000 MT in 2022, but showed 35% growth compared to 2021.[170] The increasing number of proposed blue and green hydrogen facilities are shown in Figure 5.

The IEA Hydrogen Projects Database[171] and 2023 Global Hydrogen Review indicates the potential for low-emission hydrogen production to reach 20 Mt in 2030. Analysis of the Projects Database shows that planned development of hydrogen produced from electrolysis is anticipated to grow significantly, from 203,000 MT in 2023 to 40.97 Mt by 2050. Of these planned and projected electrolysis projects, the vast majority (91.3%) of planned growth (nearly 42.2 Mt by 2050 if all projects are successful) uses dedicated renewables as the primary energy source (Figure 6).[172]

Figure 6

IEA Map of Globally Proposed Hydrogen Facilities with Capacities



Note: Map also includes announced projects starting after 2030.
Source: IEA Hydrogen Projects, (Database, October 2023 release).

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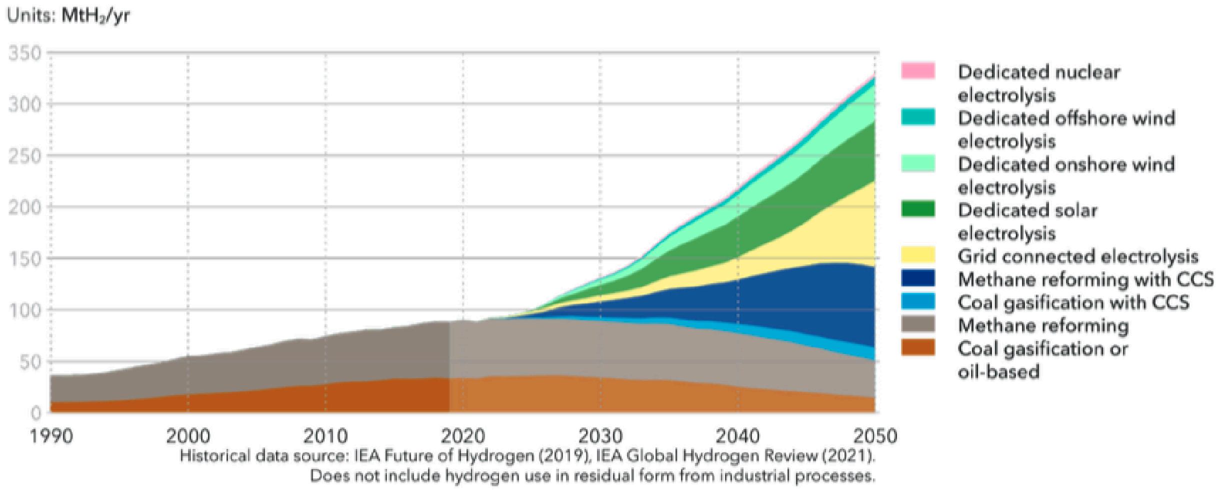
[170] https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf
[171] https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database
[172] NOTE: These estimates are for total potential production listed in the IEA Hydrogen Projects database. These projects are in various stages of development, including, among others, under construction, final investment decision (FID), feasibility study, and concept. We refer to these collectively as potential production and do not otherwise account for project status.

In terms of total proposed H_2 production capacity, Australia is projected to add up to 10.2 Mt (equivalent to 11% of total proposed global capacity) followed by the USA with 9.3 Mts (10.2% of total proposed capacity) and Great Britain with 7.7 Mt (8.4% of proposed capacity). Together, Australia, the USA, and Great Britain account for 30% of proposed global capacity, and the top 10 countries[173] account for 66% of proposed capacity.

The IEA database includes projects totalling up to 60.6 Mt of hydrogen production capacity by 2040, with 76.2% of projects using electrolysis and 22.6% using fossil feedstocks with CCUS. DNV,[174] based on IEA data and projections, projects total hydrogen production could grow to around 330 Mt, with around 85% of production coming from reduced GHG routes (27.5% from fossil sources with CCUS), as shown in Figure 7. IEA's Net Zero by 2050 Roadmap projects that hydrogen demand, for use as molecular hydrogen or as a feedstock in other low-GHG fuels, will need to grow ~6x (to 530 Mt in 2050) in large part to meet transport demand, including from shipping. The Hydrogen Council anticipates 110 Mt of hydrogen demand by 2050 for maritime and aviation fuels.[175]

Figure 7

IEA Total Global Hydrogen Capacities Projected to 2050



Historical data source: IEA Future of Hydrogen (2019), IEA Global Hydrogen Review (2021).
Does not include hydrogen use in residual form from industrial processes.

DNV projects that the cost of electrolysis using dedicated solar or wind renewables could drive towards \$2/kgH_2 (~\$5/kgH_2 today) due to large cost reductions in solar panels (-40%) and wind turbines (-27%) reducing the cost of the electricity used to produce green hydrogen. With expanded renewables and efficiency gains, DNV predicts that electrolyser operating hours will increase, and costs will lower further as perceptions of financial risk are alleviated.

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[173] The top 10 countries by projected hydrogen production capacity by 2050 are: Australia, USA, Great Britain, Netherlands, Spain, Mauritania, Egypt, China, India, and Germany.

[174] DNV (2023) HYDROGEN FORECAST TO 2050.

[175] https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf

Section 4: Methanol

Fuel description and properties

Methanol is one of the most widely available organic chemicals in the world, with over 110 Mt produced in 2022, the energy equivalent of ~55 million tonnes of oil.[176,177] Methanol is a relatively mature marine fuel: engines and fuel systems are available and in use (and more are in development, see Section 2), and interim guidelines for use are available. Vessels have been using methanol as a marine fuel for several years, and many methanol-compatible vessels are on the orderbook.

Methanol is suitable for both two-stroke and four-stroke engines, and a range of vessel types and applications, though it is not a drop-in fuel for use in conventional marine diesel engines. Methanol is appropriate for use in dual fuel spark-ignition engines, and requires dedicated or retrofitted engines with modifications to the engine, fuel storage, and ignition systems.[178,179] As methanol is a liquid in ambient conditions, it is compatible, to an extent, with some existing fuel storage and bunkering equipment. It does not require the use of cryogenic and pressurized fuel tanks. Partly due to comparatively low capital investment costs, methanol is currently considered as having one of the lowest total costs of ownership of various alternative marine fuel options.[180,181]

Methanol is corrosive, and compared to conventional marine fuels, has a low energy density (15.9 MJ/L) (Table 8), requiring ~2.5x the volume for fuel storage. Methane has a low cetane number (5), and a low flash point (11 to 12°C, as compared to 50°C for heavy fuel oil (HFO)), so is more flammable and carries a greater risk of explosion. Methanol burns with a nearly invisible flame in daylight, posing additional risk for visual detection of fires. Methanol is also toxic to humans, though is far less toxic to wildlife, compared to conventional marine fuels. If spilled, methanol is biodegradable. For safety reasons, use of methanol as a marine fuel requires specialized monitoring and control systems, and proper procedures for handling and bunkering (described in following sections).[182,183,184]

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[176] https://www.methanol.org/the-methanol-industry/

[177] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html

[178] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf

[179] https://doi.org/10.1016/j.isci.2020.101758

[180] https://doi.org/10.1016/j.rser.2021.110861

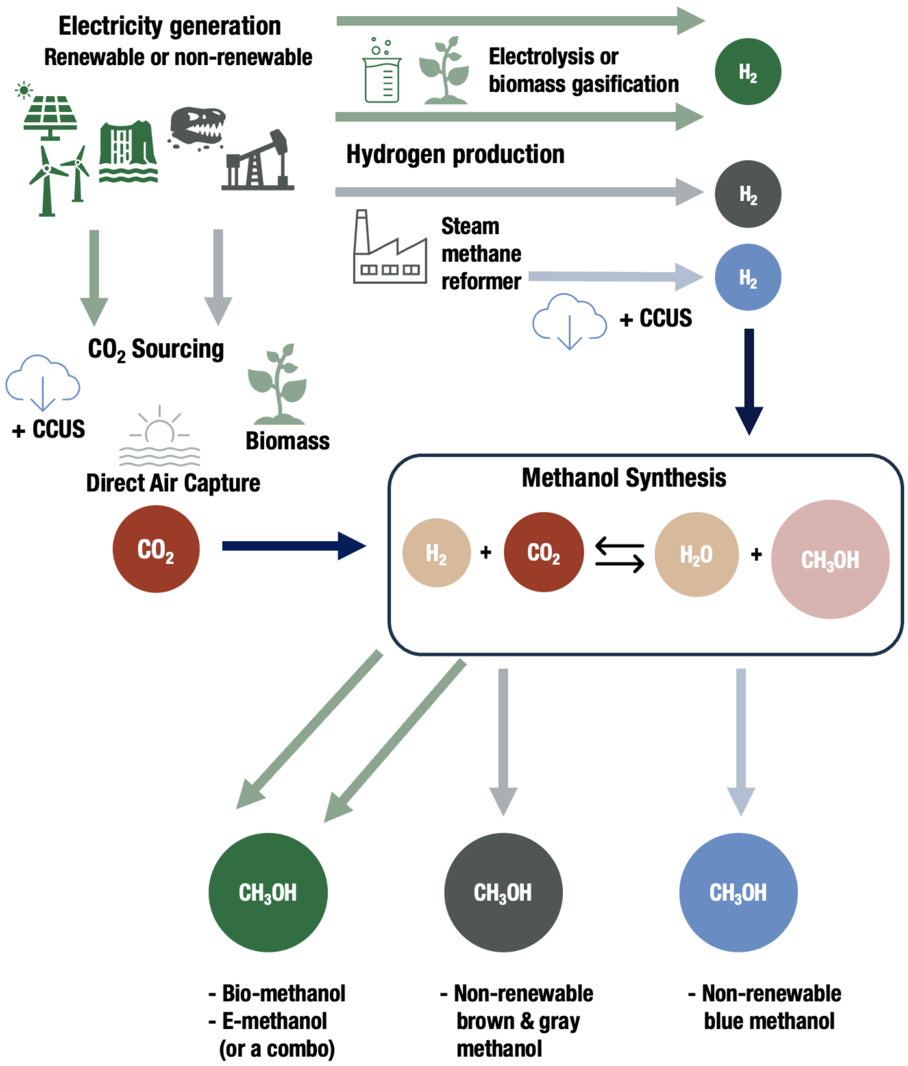
[181] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

[182] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf

[183] https://doi.org/10.1016/j.isci.2020.101758

[184] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html

Figure 8
Methanol production pathways



Methanol can be produced through a number of pathways (Figure 8) from a variety of feedstocks. Currently methanol is typically produced using natural gas and coal—“gray” and “brown” methanol, respectively. Gray and brown methanol are high in carbon-intensity, and may increase GHG emissions compared to conventional marine fuel, on a life cycle (WtW) basis.[185] “Blue” methanol, produced from natural gas and using CCUS, is estimated to be lower in carbon intensity, but non-renewable.[186]

Methanol can also be produced as a renewable fuel by a number of pathways, producing either bio-methanol or e-methanol—“Green” methanol, which is low in carbon intensity. Green methanol fuels may reduce life cycle GHGs by up to 70% to 100%, or may even

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[185] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[186] https://www.methanol.org/wp-content/uploads/2020/04/IRENA_Innovation_Renewable_Methanol_2021.pdf

result in net negative GHG emissions, depending on feedstock (in cases, for instance, where business-as-usual management of feedstocks such as manure would lead to high amounts of GHGs released).[187188,189,190]

Bio-methanol may be produced through gasification of biomass (such as forestry or agricultural residues), followed by fuel synthesis. E-methanol may be produced from CO_2 and H_2, using either point capture (capturing CO_2 emissions from a concentrated source such as a coal or natural gas power plant) and electrolysis, or direct air capture (DAC–directly removing CO_2 from the atmosphere) and electrolysis, to produce e-methanol. E-methanol is considered "green" if produced with renewable electricity.[191]

Table 8

Methanol fuel parameters, costs, and emissions[192]

Methanol Properties	Gray/Brown	Biomethanol	e-methanol
Volumetric Energy Density (MJ/L)	15.9 - liquid		
Storage Density (kg/m^3)	791.4 - liquid		
Technology Maturity	Relatively mature. Engines and fuel systems are available and in use, and bunkering and use has been demonstrated.		
WtW CO_2e (kg per MJ fuel)	0.095 – 0.186	-0.055 – 0.070	0.000 – 0.079*
WtW NO_x (kg per MJ fuel)	0.0003 – 0.0004		n/a
WtW SO_x (kg per MJ fuel)	0.00001 – 0.00002	NC – 0.00003	n/a
WtW $PM_{2.5}$ (kg per MJ fuel)	0.00001 – 0.00002	NC – 0.00002	n/a
Vessel Capital Costs ($/kW)	Propulsion system: $270/kW - $600/kW Fuel Tanks and add-ons: ~$200/kW		
Fuel Cost ($/MT)	310 – 1,280	400 – 1,290	570 - 2,350
Fuel Cost ($/MJ)	0.014 – 0.058	0.018 – 0.058	0.026 - 0.107
MGO Fuel Cost ($/MT) ($/MJ)	890 – 990 $/MT 0.021 – 0.023 $/MJ		

NC = negligible concentration; n/a = not identified here; *estimated typical range

Though green e-methanol and bio-methanol are far less GHG-intensive compared to gray or brown methanol produced from fossil fuels, the technologies are in earlier stages of development, and are more expensive than conventional marine fuels and methanol. Compared to e-methanol, bio-methanol is less expensive, and is also considered a more viable and realistic option in the near-to medium-term (2030 to 2050). Though e-fuels are

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[187] Potential for net-negative GHG emissions is described further in "Methanol WtW GHG Emissions" section
[188] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[189] https://doi.org/10.1016/j.isci.2020.101758
[190] https://www.nature.com/articles/s41560-023-01334-4/tables/2
[191] https://www.methanol.org/wp-content/uploads/2020/04/IRENA_Innovation_Renewable_Methanol_2021.pdf
[192] https://oceanconservancy.org/wp-content/uploads/2023/03/Approaches-Decarbonizing-US-Fleet.pdf

less developed, in the longer term they could theoretically produce a much larger quantity of fuel, as renewable electricity production capacity is limited only by land and equipment, versus feedstock availability limitations for bio-methanol.[193]

Production of green methanol is currently limited (≤ 1 Mt), though over 60 projects are underway worldwide. Green methanol is expected to be available to a larger extent in 2024/2025 (~6 Mt per year), with another ~4.5 Mt available beginning 2026/2027.[194,195] Combined (~10.5 million tonnes methanol), this equates to ~0.2 EJ, or roughly 2% of total estimated energy use in the marine shipping sector (through 2030).[196]

Engine and Fuel System Parameters

Use of methanol as a marine fuel is relatively well-established, with engines and fuel systems developed and demonstrated, IMO interim guidance on use issued (MSC.1/Circ.1621[197]), multiple vessels using methanol, and hundreds of hours of successful bunkering having been demonstrated. Methanol as a marine fuel has recently been recognized as "head[ed] for the mainstream," and commercial development is expected to expand rapidly in the next few years.[198,199]

Methanol has the potential to be used in main engines, auxiliary diesel generators, auxiliary boilers, and fuel cells compatible with methanol.[200] Currently, it can be used in 2-stroke diesel-cycle engines, and 4-stroke lean-burn Otto cycle engines, with additional engine types and concepts in development. Though methanol can be used in spark ignition engines and compression ignition engines, it is more suited to dual fuel engines.[201]

Use of methanol as a marine fuel (including in dual fuel engines) requires a pilot fuel, where conventional fuel such as MGO (or certain biofuels)—about 5% of total fuel content on an energy basis—is required to facilitate ignition.[202] As it is liquid at ambient conditions, methanol can be used with existing systems to an extent. Methanol does not require cryogenic tanks or pressurization. As methanol has a lower energy content than conventional marine fuels, more space (~2.4x to 2.5x) is required for fuel storage compared to MGO or HFO.[203] Methanol tanks can often be stored in the ballast/bottom of the ship,however, where they will not interfere with cargo or passenger space.[204]

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[193] https://doi.org/10.1016/j.rser.2022.113127
[194] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html
[195] https://public.tableau.com/app/profile/mi5716/viz/CurrentandUpcomingMethanolProjects/CurrentAndUpcomingMethanolProjects
[196] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[197] https://www.imorules.com/GUID-38B66B3F-AE5D-42C6-87C3-DFC1D2C333F5.html
[198] https://www.dnv.com/expert-story/maritime-impact/Methanol-as-fuel-heads-for-the-mainstream-in-shipping.html
[199] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[200] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html
[201] https://doi.org/10.1016/j.isci.2020.101758
[202] https://doi.org/10.1016/j.isci.2020.101758
[203] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf
[204] https://www.sciencedirect.com/science/article/pii/S0360128522000624#bib0071

Methanol can also be used with fuel cells, where methanol serves as a hydrogen carrier. While methanol is liquid in ambient conditions, it does not require cryogenic tanks and fuel storage area required for LH_2 fuel (Section 3).[205] In these fuel cell systems, hydrogen is produced from methanol using on-board reformers. Whereas in the past, hydrogen used in certain fuel cells (low-temperature proton exchange membrane fuel cells—LT-PEMFC) had to meet strict (~99.99%) purity requirements, high-temperature HT-PEMFC allow for more impurities, and so may be used successfully with hydrogen made from syngas produced on-board.[206]

HT-PEMFCs using methanol exhibit efficiencies of 45-60%, vs. ~35% for ICEs using methanol.[207,208] SOFCs, compatible with a range of fuels (including methanol), are also seen as a promising technology.[209,210] Direct methanol fuel cells (DMFC) do not require the use of a reformer, as they can use the hydrogen directly from the methanol. DMFC are small in size and power capacity (≤5kW), however, and exhibit lower efficiencies.[211] Other potential fuel cells for use in marine shipping include alkaline, molten carbonate, and phosphoric fuel cells, but these are not considered as promising as PEMFCs and SOFCs.[212]

Safety and Necessary Fuel System Modifications and Precautions

Due to some of its properties, including its corrosive nature, toxicity and flammability, use of methanol as marine diesel fuel requires engine and fuel system modifications. Methanol is toxic to humans, potentially causing blindness, kidney damage or even death. Ingesting around 10 milliliters (mL) can lead to serious complications; and the LD_{50} for humans is around 100 mL.[213] Methanol can be toxic when ingested, but also when absorbed through the skin or inhaled at high concentrations.

Methanol has a low flash point (11°C or 12°C, compared to 50°C for HFO);[214] it is more flammable and poses a higher risk of explosion compared to residual or distillate fuels. Also, methanol fires are nearly invisible to the eye in daylight conditions. And in the case that leaks occur, methanol tends to pool close to the ground and low areas as it is heavier than air, and it does not dissipate in enclosed spaces.[215]

In addition to proper crew training, methanol fuel systems and storage require a number of modifications, controls and safety mechanisms to minimize these risks. As summarized

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[205] https://maritime-executive.com/article/first-methanol-powered-fuel-cell-system-approved-by-rina
[206] https://www.idtechex.com/en/research-article/fuel-cell-boats-and-ships-a-methanol-to-the-madness/28816
[207] https://www.idtechex.com/en/research-article/fuel-cell-boats-and-ships-a-methanol-to-the-madness/28816
[208] https://www.blue.world/markets/maritime/
[209]https://www.idtechex.com/en/research-report/fuel-cell-boats-and-ships-2023-2033-pemfc-sofc-hydrogen-ammonia-lng/907
[210] https://doi.org/10.1016/j.rser.2021.110861
[211] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html
[212] https://doi.org/10.1016/j.rser.2021.110861
[213] LD50 - the amount of an ingested substance that kills 50% of the test sample
[214] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html
[215] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.htm

by DNV, modifications include: systems to segregate fuel, the use of cofferdams around fuel tanks, mechanical ventilation providing regular air changes, gas detection and low oxygen alarms, double-walled pipe in fuel supply systems, the ability to purge systems with nitrogen, a pressure-relief system, venting of fuel tanks, and instruments to monitor temperature, pressure, and fluid level. Manual and automatic fuel supply valves are required. Proper ventilation is required, as is attention to positioning and placement of ventilation to avoid areas near crew or passengers; ventilation should also be monitored, with fuel supply shut down in case of failure.[216]

The IMO has issued Interim guidelines for the use of methanol as a marine fuel (MSC.1/Circ.1621), outlining fuel system requirements. The issuance of MSC.1/Circ.1621 has been noted as an enabler for the recent increase in use of methanol in marine shipping, as shipowners and other stakeholders presumably have more confidence in, and are better versed in, the proper and safe protocols for use of methanol as a marine fuel.[217]

Technology Availability and Use

Engines and technology to use methanol in marine shipping are available and in use (some for several years), with two-stroke engines currently more commonly used; more engine types are in development.[218]

Well-demonstrated methanol-compatible technologies include MAN's methanol dual fuel ME-LEI concept for 2-stroke engines (which has been used in tankers since 2016), and Wärtsilä's methanol dual fuel retrofit concept (Sulzer ZA40S) for 4-stroke engines, used on the *Stena Germanica* ferry in Sweden since 2015. Both of these concepts, which are feasible for retrofits and newbuilds, involve high-pressure injection of methanol into the cylinder chamber; the MAN concept uses two injectors–one for methanol and one for diesel–while the Wärtsilä concept uses one injector to inject both fuels.[219]

Manufacturers are developing and offering new methanol-compatible marine engine concepts. As reported by the Methanol Institute in 2023[220] these include:

- *MAN Energy Solutions*, whose two-stroke ME-LG/M dual fuel engines have been demonstrated in more than 145,000 hours of operation, is now developing 4-stroke engines for the marine sector, and will offer retrofits for 4-stroke engines beginning in 2024;
- *Anglo Belgian Corporation (ABC)* is producing DZC dual fuel engines in 6, 8, 12, and 16 cylinders, with engine power ranging from 600 kW to 10.4 MW;
- *Caterpillar* produces Cat3500E series engines that can run on methanol;

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[216] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.htm
[217] https://www.dnv.com/expert-story/maritime-impact/Methanol-as-fuel-heads-for-the-mainstream-in-shipping.html
[218] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[219] https://www.sciencedirect.com/science/article/pii/S0360128522000624#bib0071
[220] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

- *China State Shipbuilding Corporation (CSSC) Power Research* and partners have developed the 6M320DM engine that can be adapted to various vessels up to 20,000 GT.
- *Hyundai Heavy Industries* has developed 2-stroke engines, with 14 delivered and at least 17 more ordered;
- *Mtu marine solutions (Rolls-Royce)* will launch methanol engines in 2026, and fuel cells in 2028;
- *Nordhavn Power Solutions* offers 13 liter/6 cylinder and 16 liter/8 cylinder marine methanol engines;
- *Wärtsilä* offers marine methanol engines (W32 and W46) and offers 2-stroke retrofits in partnership with MDC; and,
- *WinGD and HSD* are partnering to develop marine methanol engines, with plans to launch in 2024.

As of 2023, more than two dozen vessels were using methanol,[221] including the *Stena Germanica* ferry, tankers, container ships and bulk carriers. The orderbook for methanol-ready ships includes 138 more—including container ships, bulk carriers, tankers, passenger vessels and cruise ships. The Methanol Institute maintains a regularly updated document listing methanol-fueled vessels, projects and partnerships relating to methanol as a marine fuel.[222] Recent developments include (but are not limited to):

- A.P. Moller-Maersk, which already had 24 methanol-fueled ships on the order book, will be adding another 10 to 15 container ships;
- In Japan, two bulk carriers are scheduled to be completed by 2026-2027;
- Four methanol-ready chemical tankers with DWT of 18,500 tons scheduled for 2025 delivery;
- Green-methanol powered container ship launched at Hyundai Heavy Industries in South Korea;
- The world's first methanol-fueled hybrid RO-RO vessels scheduled for 2025 delivery;
- Hitachi will invest in methanol supply system and produce methanol engines;
- World's first methanol dual fuel very large crude carrier—306,000 ton—developed for $107 million, set to be ready by April 2026;
- A.P. Moller-Maersk signed an agreement with Equinor to secure supply of green methanol for feeder vessel from September 2023 to mid-2024; and,
- A Disney cruise ship (6,000-passenger capacity) will be converted to be methanol-ready, and expected in service in 2025.

Methanol fuel cells for the marine sector have also been developed for use in auxiliary power units (APUs)[223]—to provide lighting on vessels, for instance, and for smaller,

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[221] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf
[222] https://www.methanol.org/wp-content/uploads/2023/10/MIs-On-the-Water-On-the-Way.pdf
[223] https://www.blue.world/markets/maritime/

lower-power applications such as tugboats, towboats, and superyachts.[224][225][226][227][228] These technologies are currently at the development and demonstration level, with new pilot demonstrations in Europe, China and the United States beginning in 2023 and 2024; methanol fuel cells are not expected to be available widely as an on-board technology for the marine sector until ~2030.[229]

Availability of Low-GHG Methanol

Most of the methanol used in shipping currently is derived from fossil fuels, and does not cause meaningful reductions in—and may actually increase—life cycle GHG emissions. According to DNV, green methanol (bio-methanol and e-methanol produced from renewable resources) is not available in significant quantities, and has been difficult to source, as it is currently in a small number of locations, in relatively small amounts compared to fossil-fuel derived methanol.[230] Though green methanol is not largely available, projects are developing to produce bio-methanol and e-methanol. The first volumes are expected in 2024/2025, with larger volumes by 2030.[231]

Recent promising developments include *The Cajun Sun* completing an 18-day transatlantic voyage powered by 'zero-carbon' bio-methanol in early 2023, and A.P. Moller-Maersk entering an agreement with several partners to secure 730,000 tons or more of green bio-methanol and e-methanol by the end of 2025;[232] partnerships include producers in North and South America, and China.[233]

Life Cycle WtW GHG and Criteria

Methanol WtW GHG Emissions

Life cycle (WtW) GHG emissions depend upon the type of methanol (e.g. brown, gray, biomethanol, e-methanol), the feedstock and process used to produce the fuel, and study assumptions. Table 9 shows a range of estimates of methanol's WtW GHG emissions, and shows that:

- Brown methanol (derived from coal) is estimated to increase GHG emissions substantially, potentially more than doubling WtW GHG emissions compared to conventional marine fuels.
- Gray methanol (natural gas) is not expected to reduce GHG emissions, and may increase WtW GHGs compared to reference fuels.

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[224] https://www.ship-technology.com/news/success-world-first-methanol-hydrogen-fuel/?cf-view

[225] https://www.methanol.org/wp-content/uploads/2020/01/Methanol-as-a-marine-fuel-january-2020.pdf

[226] https://www.meyerwerft.de/en/press/press_detail/meyer_group_shows_future_of_cruising.jsp

[227] https://www.methanol.org/wp-content/uploads/2023/10/MIs-On-the-Water-On-the-Way.pdf

[228] https://powercellgroup.com/maritime-methanol-to-fuel-cell-power-chain/

[229] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

[230] https://www.ieabioenergy.com/installations/#

[231] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html

[232] Partners include MC ENRIC, European Energy, Green Technology Bank, Ørsted, Proman and WasteFuel

[233] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

- Biomethanol has the potential to reduce WtW GHG emissions by more than 90%, or even to net-negative GHG emissions, depending on feedstock and process. In cases, for instance, where in conventional management practices feedstocks such as manure would degrade into significant amounts of CH_4 and CO_2, avoiding these emissions through the conversion of these feedstocks to biomethanol could result in net-negative emissions (as shown in Table 9, with manure feedstock).[234,235]
- E-methanol is largely expected to produce meaningful reductions in WtW GHG emissions when used as a marine fuel (up to 70-100% compared to reference fuels). If high-carbon electricity is used in production, however, e-fuels emissions could exceed or even double those of fossil-based marine residual and distillate fuels.[236,237]

Note that in some cases, WtW GHG emissions reported in Table 9 are lower than reported TtW (exhaust) emissions; this is because combustion of methanol produces a certain amount of GHG emissions, regardless of feedstocks or process used to produce the fuel. During upstream stages of methanol feedstock and fuel production (Well-to-Tank: WtT), however, net GHG emissions may actually be reduced (as in the case of carbon uptake during biomass feedstock growth, or by avoiding emissions that would otherwise take place–e.g. with manure, described above), effectively "canceling out" a portion or all of the TtW emissions.

Methanol Criteria Pollutant Emissions

Methanol is a relatively clean-burning fuel. Though it is produced through various pathways, using a range of feedstocks and processes, the fuel properties, characteristics, and composition of methanol as an end-product and marine fuel are essentially identical. Estimates of TtW (exhaust) emissions of criteria pollutants from methanol combustion, therefore, may be generalized, no matter the feedstock or production pathways.

Compared to combustion of conventional marine fuels, combustion of methanol is estimated to reduce SO_x emissions by 95-100%, as it is a zero-sulfur fuel. With an estimated 0.3-0.4 g/MJ of NO_x, Methanol decreases NO_x emissions by ~25-80% compared to residual or distillate marine fuel (depending on reference fuel),[238239] and increases NO_x slightly compared to LNG.[240] NO_x emissions may be reduced further by injecting water into supply lines—so-called Water-in-Fuel—a relatively simple approach which may bring NO_x emissions from methanol combustion in compliance with Tier III limits for marine combustion engines, without the need for selective catalytic reduction

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[234] https://doi.org/10.1016/j.pecs.2022.101055
[235] https://www.studiogearup.com/wp-content/uploads/2022/02/2022_sGU-for-MI_Methanol-carbon-footprint-DEF-1.pdf
[236] https://www.sciencedirect.com/science/article/pii/S0360128522000624#bib0071
[237] https://doi.org/10.1016/j.adapen.2021.100008
[238] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[239] https://www.methanol.org/wp-content/uploads/2020/04/IMO-Methanol-Marine-Fuel-21.01.2016.pdf
[240] https://www.sciencedirect.com/science/article/pii/S0360128522000624#bib0071

(SCR) or exhaust gas recirculation (EGR) equipment.[241,242] Methanol reduces PM emissions 60% to nearly 100% compared to conventional marine residual and distillate fuels, and reduces PM emissions compared to LNG. When used in a fuel cell, methanol produces zero exhaust emissions of NO_x, SO_x and PM.[243]

Table 9

Life cycle Emissions for Methanol as Marine Shipping Fuel, by Pathway (kg/MJ)

Fuel Type (Pathway/ Feedstock)	**GHGs**		**Criteria Pollutant Emissions**					
	(kgCO2e/MJ)		**NO_x (kg/MJ)**		**SO_x (kg/MJ)**		**PM2.5 (kg/MJ)**	
	WtW	TtW	WtW	TtW	WtW	TtW	WtW	TtW
Methanol from Fossil Fuels								
Coal/Brown	0.186	0.069 - 0.076	0.00037	0.0003-0.0004	0.00001	NC	0.00001	NC
NG/Gray	0.095		0.00033		0.00002		0.00002	
Biomethanol								
Woody biomass	0.010	0.069 - 0.076	0.00032	0.0003-0.0004	NC	NC	0.00002	NC
Forest Residue	0.070		0.00037		NC		NC	
Landfill Gas	0.025		0.00034		0.00003		NC	
Corn Stover	0.024		n/a		n/a		n/a	
Miscanthus	0.017							
Cow manure	-0.055							
Advanced Feedstocks	0.002 - 0.026							
E-methanol								
Estimated Range	0.000 - 0.079	0.055 - 0.085	n/a	0.0003-0.0004	n/a	NC	n/a	NC
High-carbon electricity	0.176	0.069 - 0.076						
Wind-power electricity	0.003–0.026							

Table sources: Winebrake et al. (2019)[244], Brynolf (2014)[245]; Zhou et al. (2021)[246], Foretich et al. (2021)[247], Lagouvardou et al. 2023[248], IMO/DNV (2016),[249] Aakko-Saska et al. (2023),[250] Mukherjee (2020),[251] Gray et al. 2021,[252] Hamelinck and Bunse[253]
NC = negligible concentration; *n/a = not specified/estimated in identified literature

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[241] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html
[242] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf
[243] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf
[244] https://www.mdpi.com/2071-1050/11/8/2235
[245] https://www.sciencedirect.com/science/article/abs/pii/S0959652614002832
[246] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[247] https://www.sciencedirect.com/science/article/pii/S2666822X21000241?via%3Dihub
[248] https://www.nature.com/articles/s41560-023-01334-4/tables/2
[249] https://wwwcdn.imo.org/localresources/fr/OurWork/Environment/Documents/Report%20Methanol%2021.01.2016.pdf
[250] https://www.sciencedirect.com/science/article/pii/S0360128522000624#bib0071
[251] https://www.sciencedirect.com/science/article/pii/S258900422030955X#sec3
[252] https://doi.org/10.1016/j.adapen.2021.100008
[253] https://www.studiogearup.com/wp-content/uploads/2022/02/2022_sGU-for-MI_Methanol-carbon-footprint-DEF-1.pdf

Methanol Bunkering and Existing Infrastructure

As methanol is a liquid at ambient temperature and pressure, existing infrastructure for bunkering and storage of conventional marine fuels may be used, with minor modifications. As noted above, use of methanol as a marine fuel is associated with safety concerns, due to its toxicity to humans and low flash point.[254] Safety guidelines for the bunkering and use of methanol have been developed, and were approved by the IMO in 2020.[255][256] Detailed safety considerations for safe bunkering of methanol have been described in detail elsewhere, including recent documentation produced by DNV, and include: selecting appropriate locations for bunker stations, ensuring well-ventilated areas or segregated compartments, the ability to disconnect the fuel supply source, self-sealing release for bunkering connections, trays and means of draining to minimize spills, and showers and eyewash stations for safety, among others.[257]

Bunkering of methanol as a marine fuel has been successfully demonstrated in trials and certain applications. For the past several years, tankers using methanol have bunkered using cargo shore pipelines near methanol production facilities. Ship-to-ship bunkering of methanol took place for the first time in 2021 at Rotterdam. In early 2023, ship-to-ship bunkering successfully supplied the world's first methanol-fueled ferry with fuel at the Port of Gothenburg.[258] And in July 2023, the world's first ship-to-container ship bunkering of methanol took place at the Port of Singapore; the *MT Agility* tanker vessel supplied a Maersk container ship with 300 MT of methanol, after loading the fuel at a nearby terminal.[259,260] The world's first green methanol bunkering operation took place at Rotterdam in August 2023.[261]

Until fairly recently, ships using methanol as a fuel were rare, and methanol was used only by tankers involved in methanol shipments (as methanol was readily available for such tankers as a fuel supply, and brought onboard during cargo-loading). In 2023, 27 methanol-compatible ships were in operation, representing less than 1% of the world fleet's gross tonnage.[262] And less than 0.001 EJ of methanol was consumed by ships 5,000 GWT and higher in 2021—as compared to ~9 EJ of total fuel consumed in the shipping sector.[263] Yet the picture is changing rapidly. As of this writing, 138 methanol-fueled (or methanol-ready) ships were on order (114 of which were container

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[254] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

[255] https://www.imorules.com/GUID-38B66B3F-AE5D-42C6-87C3-DFC1D2C333F5.html

[256] https://www.imo.org/en/ourwork/safety/pages/igf-code.aspx

[257] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html

[258] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf

[259] https://www.mpa.gov.sg/media-centre/details/successful-first-methanol-bunkering-operation-in-the-port-of-singapore

[260] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

[261] https://oci-global.com/news-stories/stories/oci-global-completes-first-european-green-methanol-bunkering-in-port-of-rotterdam-the-netherlands/

[262] https://www.dnv.com/Publications/maritime-forecast-to-2050-2023-edition-246744

[263] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf

ships), representing 8% of the world fleet's total tonnage, and exceeding the number of orders for LNG vessels.[264]

As noted in an April 2023 report for the IMO, the increasing number of methanol-compatible ships on the orderbook and their demand for fuel may induce developments in bunkering and infrastructure.[265] Yet bunkering of methanol is still in the early stages, and there is a need for experience and standards,[266] and infrastructure improvements and increased availability of low-GHG methanol.

According to DNV, the foundation for a global network for methanol used in shipping already exists in the form of terminals, storage infrastructure, and large quantities of methanol transported by ship (~30 Mt in 2018).[267] About 90 of the world's largest ports supply methanol as a marine fuel, and have bunkering infrastructure in place (Figure 9).[268,269] Additionally, over 120 ports have methanol storage capabilities and infrastructure available—19 of which are in North America.[270,271] As DNV notes, these terminals may function as a launching point for a methanol distribution network, potentially minimizing 'last mile' distribution costs.[272]

Several green shipping corridors for methanol are in development or feasibility stage; these include a Halifax-Hamburg Port-led initiative, the European Green Corridors Network (with five European Ports[273]), the Rotterdam-Singapore Green and Digital Corridor, and the Great Lakes St. Lawrence corridor.[274]

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[264] https://www.dnv.com/Publications/maritime-forecast-to-2050-2023-edition-246744
[265] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[266] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[267] https://www.dnv.com/Publications/maritime-forecast-to-2050-2023-edition-246744
[268] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[269] https://www.sciencedirect.com/science/article/pii/S0196890422002369#b0060
[270] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf
[271] https://www.dnv.com/Publications/maritime-forecast-to-2050-2023-edition-246744
[272] https://www.dnv.com/Publications/maritime-forecast-to-2050-2023-edition-246744
[273] Port of Rotterdam, Port of Hamburg, Port of Roenne, Port of Tallinn, Port of Gdynia; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (https://www.zerocarbonshipping.com/) is also a partner
[274] https://mission-innovation.net/missions/shipping/green-shipping-corridors/route-tracker/

Figure 9

Global and U.S. ports with methanol bunkering

Map showing global (top) and U.S. (bottom) ports with methanol bunkering. Source: The Methanol Institute,[275] which lists 122 ports globally with methanol bunkering supply/storage (112), or bulk liquid storage (10). Open circles indicate bunkering capacity where known, filled circles indicate unknown capacity. See Wooley et al. for stakeholder developments in favor of methanol.[276]

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[275] https://www.methanol.org/marine/

[276] Wooley et al. Policy Options to Decarbonize Ocean-Going Vessels, May 13, 2024, pageeshttps://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/ocean-going-vessel-decarbonization

Costs (CAPEX and OPEX)

CAPEX = capital expenditure, OPEX = operating expenditures

Marine vessels powered by methanol are generally more expensive than those powered by residual fuel or distillates. Investment costs vary by vessel and engine type, and whether the shift to methanol use involves a new-build ship, or retrofit/conversion.

In general, overall retrofit costs to convert ships from diesel engines to dual fueled methanol/diesel are estimated at $270 to $700/kW, with engine retrofits estimated to reach up to $594/kW.[277,278279] New-build costs are estimated at ~$300 to $600/kW for methanol-compatible engines (as compared to $400/kW for engines using HFO), and ~$200/kW for tanks and add-ons (as compared to $300/kW for HFO with scrubber technology).[280281,282]

Recent case studies[283,284] examining the investment and operational costs of using alternative fuels in a Supramax Bulk Carrier estimated the new-build engine cost for methanol-supporting vessels to be approximately $600/kW.[285,286] Tanks and add-on costs for methanol were estimated at $200/kW. The total cost of a new-build vessel was estimated at $33 million for methanol, vs. $30 million for HFO.

Costs to retrofit a Supramax bulk carrier vessel using HFO to methanol use were estimated at $7.4 million.[287] Costs involved in retrofitting vessels are not limited to engines and components, etc. Ships are retrofitted at a shipyard, and must be taken out of service during that time.[288] Retrofit costs also include the opportunity cost of lost productive time (and lost revenue) for the vessel, as well as shipyard charges; these costs together are estimated at $3.6 million,[289] and are included in the $7.4 million estimate.

Fuel storage presents another opportunity cost. Methanol has a lower relative density and lower energy content than residual or distillate fuels (roughly ½ the energy content on a per-ton basis). This means more space is required for fuel storage–methanol requires about 2.5x the storage space of residual fuel or distillates with an equivalent energy content[290]– and additional weight of the fuel. The increased space and/or weight required to store methanol may present opportunity costs in the form of loss of cargo

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[277] https://www.sustainable-ships.org/stories/2023/methanol-marine-fuel

[278] 1 EUR = 1.08 USD

[279] https://www.emsa.europa.eu/newsroom/latest-news/item/4834-update-on-potential-of-biofuels-for-shipping.html

[280] https://www.sciencedirect.com/science/article/pii/S1361920921003722#f0030

[281] https://doi.org/10.1038/s41560-023-01334-4

[282] https://www.sciencedirect.com/science/article/pii/S1361920921003722#f0030

[283] https://doi.org/10.1038/s41560-023-01334-4

[284] https://www.sciencedirect.com/science/article/pii/S1361920923001451

[285] https://doi.org/10.1038/s41560-023-01334-4

[286] https://www.sciencedirect.com/science/article/pii/S1361920921003722#f0030

[287] https://doi.org/10.1038/s41560-023-01334-4

[288] https://www.sciencedirect.com/science/article/pii/S1361920923001451

[289] https://www.sciencedirect.com/science/article/pii/S1361920923001451

[290] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html

carrying-capacity, and revenue earned. In the case of the Supramax bulk carrier, methanol fuel storage can be integrated into the ship structure, and so loss of cargo capacity is penalized based on weight rather than space.[291] For the Supramax bulk carrier, the opportunity cost has been estimated at $0.3 million over 5 years,[292] or $178/day.[293]

Bayraktar et al. (2023)[294] estimated the costs of converting a container ship (originally diesel engine powered with HFO and MDO) to a methanol-compatible engine, in two scenarios (one lower-power, one higher-power).[295] Estimated costs include an investment cost of $9.7 - $11.9 million, operation-maintenance costs of $146,000 to $178,000, tank retrofit costs of $54,000, control system costs of $7,600, and additional costs of $21,600, for a total estimated cost of $9.9 to $12.1 million.[296,297]

Korberg et al. (2021) report estimated costs for advanced fuels (including methanol) and propulsion systems, conducting case studies for four types of ships: large ferries, general cargo, bulk carriers and container ships. Investment costs for ICE methanol-compatible engines are estimated at $545/kW for 2-stroke engines (e.g. used in bulk carrier and container ships), while costs of 4-stroke ICE methanol engines (e.g. used in ferries and general cargo ships) are estimated at $286/kW. Fuel cells, which derive energy from hydrogen cracked from methanol, are estimated to cost $788/kW to $1,382/kW, and require an electric motor ($270/kW) and gearbox ($92/kW), and are estimated to have half the lifetime (15 years) of ICE engines (30 years).[298,299,300]

Vessels operating on LNG may also be converted to methanol use, with LNG-to-methanol retrofits expected to be relatively simpler and less expensive as compared to diesel-to-methanol—as LNG engines and certain fuel system components (e.g. double-walled fuel distribution) are technically capable of handling methanol.[301] One recent study estimated that LNG-supporting Supramax bulk carrier vessels, for instance, could be converted to methanol use at a cost of $5.1 million (compared to $7.4 for an equivalent VLSFO-to-methanol retrofit).[302] Converting from LNG to methanol could also free cargo space. Methanol requires less space for fuel storage compared to LNG. An estimated $140/day ($0.2 million over 5 years) in opportunity costs of lost storage space and related loss of revenue could be avoided by switching from LNG to methanol.[303]

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[291] https://www.sciencedirect.com/science/article/pii/S1361920923001451
[292] https://www.sciencedirect.com/science/article/pii/S1361920923001451
[293] https://doi.org/10.1038/s41560-023-01334-4
[294] https://doi.org/10.1016/j.spc.2023.05.029
[295] Conversion of vessel using Man-Diesel 7L 70 ME-C to either MAN-Methanol-9S50ME-C9.6-LGIM-EGRBP; or MAN-Methanol-6G80ME-C10-LGIM-EGRTC (higher-power, faster).
[296] https://doi.org/10.1016/j.spc.2023.05.029
[297] 1 EUR = 1.08 USD
[298] 1 EUR = 1.08 USD
[299] https://doi.org/10.1016/j.rser.2021.110861
[300] As compared to, for diesel/HFO ICE, $545/kW for two-stroke and $284/kW for four-stroke engines
[301] https://www.sustainable-ships.org/stories/2023/methanol-marine-fuel
[302] https://www.sciencedirect.com/science/article/pii/S1361920923001451
[303] https://doi.org/10.1038/s41560-023-01334-4

Fuel costs

Methanol fuel costs vary widely depending on the type of methanol and production process used, as shown in Table 10 and Figure 10. Currently, the vast majority of methanol is produced from fossil fuels (~65% from natural gas and ~35% from coal), with less than 1% produced from renewable resources. The technologies to produce methanol from coal and natural gas are well-established, and relatively inexpensive–and may even be less expensive than conventional marine fuels (based on energy content–$/MJ), at an estimated $0.014 to $0.026/MJ.[304] Yet methanol from natural gas or coal (gray and brown, respectively) does not present a viable solution for reducing GHGs in the marine sector.

Biomethanol production processes are more established than those for e-methanol, and in general bio-methanol is expected to be less expensive than e-methanol for the near- to medium-term.[305] Yet production costs of bio-methanol and e-methanol (and estimates of future production costs) vary widely depending on expected state of technological maturity, feedstock and process used, and other variables for which future costs are uncertain, such as costs of inputs of production.

Mukherjee et al. (2023), for instance, estimated the production costs of bio-methanol and e-methanol for “pioneer” plants and “nth” (mature technology) plants, and analyzed the effects of changes in parameters including feedstock costs, electricity costs, capital investment costs, and interest rates.[306] Future biomass prices ($/ton of feedstock), which were estimated to range from ~$45/ton to ~$200/ton,[307] could change the production cost of bio-methanol by over $20 per gigajoule (GJ), equivalent to $0.02/MJ. Assuming future electricity prices ranging from ~$11/MWh to ~$95/MWh (some studies project electricity prices to be on the higher end), estimated production cost of e-methanol could change by up to ~$45/GJ. Interest rates, capital investment costs, and cost of oxygen (an input for e-methanol) could also have a significant influence on production costs.[308]

Another cost associated with purchase of bio-methanol and/or e-methanol as a marine fuel is the anticipated requirement for certification or guarantee of origin for e- or bio-methanol; Mukherjee et al. (2023) estimated these costs at ~$0.03/MWh for biofuels, and $0.004-$0.005/MWh for e-fuels.[309,310]

In recent studies, use of bio-methanol with ICE engines has been estimated to have the lowest total cost of ownership compared to other advanced fuels and propulsion systems

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[304] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[305] https://doi.org/10.1016/j.rser.2022.113127
[306] https://doi.org/10.1016/j.rser.2022.113127
[307] 1 EUR = 1.08 USD.
[308] https://doi.org/10.1016/j.rser.2022.113127
[309] https://doi.org/10.1016/j.rser.2022.113127
[310] 1 EUR = 1.08 USD

in the marine sector, and to have some of the lowest production costs compared to alternatives (e.g. e-methanol, bio-LNG, bio-oil, and dimethyl ether) as well.[311,312]

Table 10

Estimated fuel prices for methanol (lower- to upper-bound) in \$/MJ, \$/GJ, and \$/MT (HFO equivalent and MT of methanol) [313,314,315,316]

Fuel Type	\$/MT (HFOE)	\$/MT (MeOH)	\$/MJ	\$/GJ	Source
VLSFO	450 – 570	n/a	0.011 – 0.014	11 – 14	IMO/Ricardo DNV (2023) (based on numerous sources)
MGO	890 – 990	n/a	0.021 – 0.023	21 – 23	
Brown and Gray methanol	570 – 1,060	310 – 570	0.014 – 0.026	14 – 26	Zhou et al. (2021)[317] (based on review of sources)
Gray methanol	1,020 –2,390	550 – 1280	0.025 – 0.058	25 – 58	Lagouvardou et al. (2023)[318] (based on numerous sources)
Bio-methanol	750 – 1,100	400 – 590	0.018 – 0.027	18 – 27	
e-methanol	1,320 – 4,380	710 – 2,350	0.032 – 0.107	32 – 107	
Biomethanol 2030	980 – 1,470	530 –790	0.024 – 0.036	24 – 36	IMO/Ricardo DNV (2023)[319] (based on numerous sources)
Biomethanol 2050	900 – 2,370	480 – 1,290	0.022 – 0.058	22 – 58	
e-methanol 2030	1,510 – 2,090	810 – 1,120	0.037 - 0.051	37 - 51	
e-methanol 2050	1,060 – 1,430	570 – 770	0.026 - 0.035	26 - 35	
Biomethanol 2050	450 - 1,310	240 - 700	0.011 - 0.032	11 - 32	IRENA and Methanol Institute (2021)
e-methanol 2050	490 - 1,760	260 - 950	0.012 - 0.043	12 - 43	

Note: The large range of estimated fuel prices reflect the many variables and uncertainties described above, as well as the compilation of numerous sources to produce a reasonable range of estimates; currency assumptions (e.g. real vs. nominal, reference year used) used in the original sources may also be a factor.

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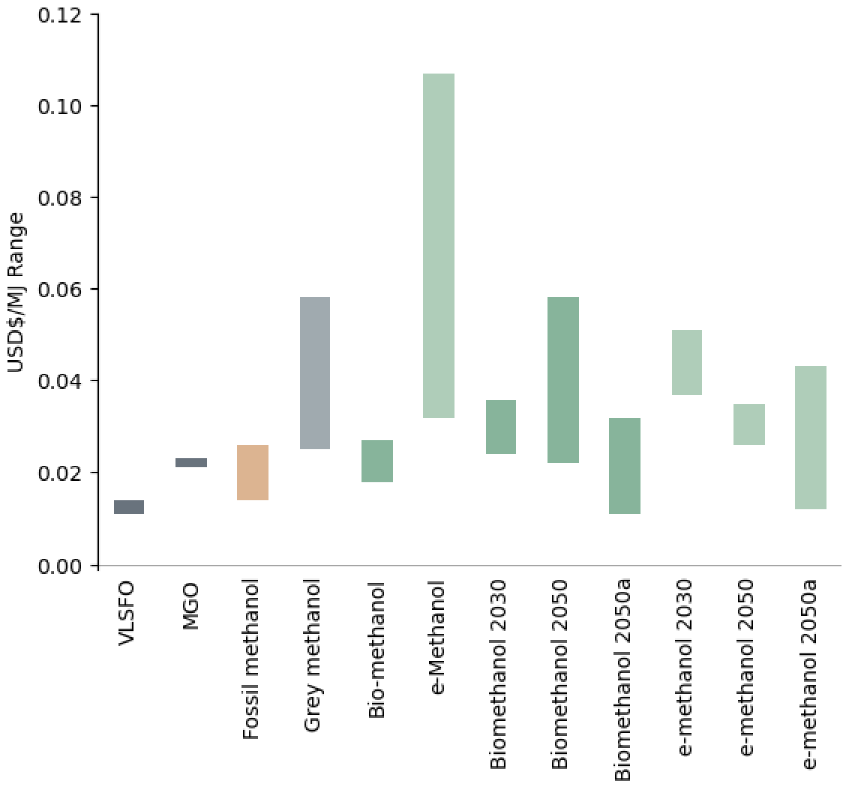
[311] https://doi.org/10.1016/j.rser.2021.110861
[312] https://doi.org/10.1016/j.rser.2022.113127
[313] https://doi.org/10.1038/s41560-023-01334-4
[314] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[315] https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol
[316] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[317] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[318] https://www.nature.com/articles/s41560-023-01334-4
[319] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf

Figure 10

Range of estimated fuel prices and projections for methanol in \$/MJ[320,321,322,323,324]



Fuel Availability and Projections: Methanol

Methanol is widely produced, with 90 production facilities producing ~100 Mt of methanol globally each year, and annual production expected to increase to 500 Mt by 2050.[325] The United States alone has a production capacity of 9.4 Mt a year.[326] Most U.S. methanol plants are located in the Gulf Coast region, near oil and gas and pipeline infrastructure[327] and marine shipping ports including the Port of New Orleans and the Port of Houston (Figure 11).

The vast majority of methanol produced today originates from fossil fuel sources, with renewable (green, low-GHG) methanol production being minimal (< 1 Mt).

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[320] https://doi.org/10.1038/s41560-023-01334-4

[321] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf

[322] https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

[323] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf

[324] The large range of estimated fuel prices in [Figure X] reflect the many variables and uncertainties described here, and the compilation of numerous sources to produce a reasonable range of estimates. Currency assumptions (e.g. real vs. nominal, reference year used) from original sources may also be a factor.

[325] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf

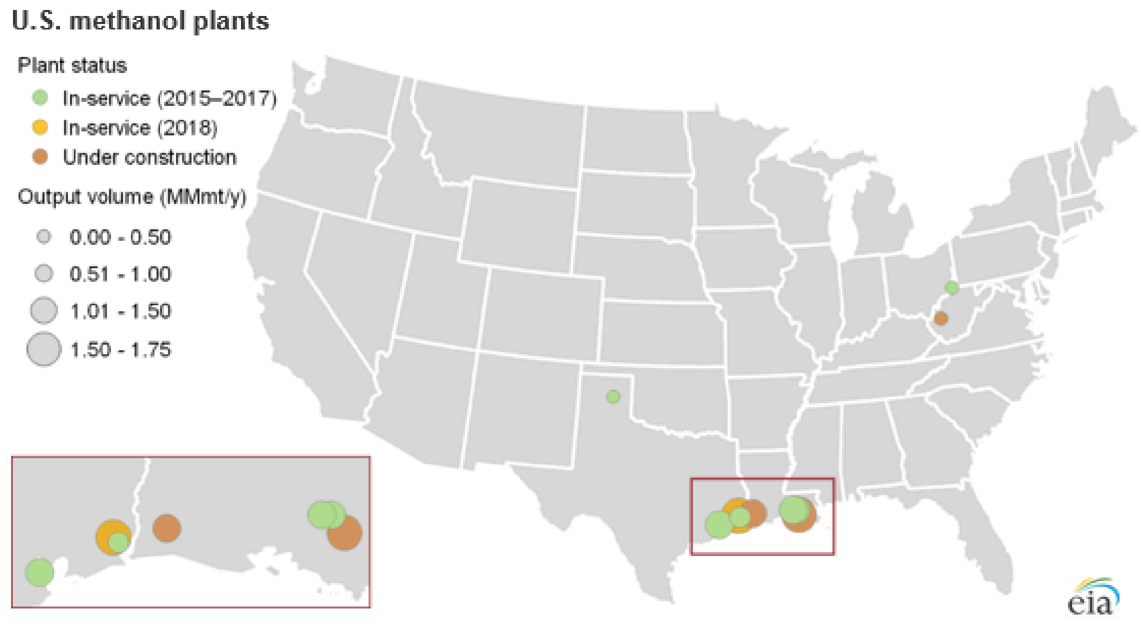
[326] https://www.eia.gov/todayinenergy/detail.php?id=38412

[327] https://www.eia.gov/todayinenergy/detail.php?id=38412

Advances are being made in this area, however, and in the shipping sector. In 2020, for instance, Maersk, DSV Panalpina, DFDS, SAS and Ørsted partnered to develop an industrial-scale facility in Denmark which would provide 250,000 MT of renewable fuel (including methanol) for use as marine fuel and for other modes.[328,329] In 2023, A.P. Moller-Maersk entered an agreement with several partners to secure 730,000 tons or more of green bio-methanol and e-methanol by the end of 2025.[330]

Figure 11

In service and under-construction methanol plants in the U.S.



Source: U.S. Energy Information Administration, based on data from S&P Platts

Map showing in-service, recent, and under-construction methanol production facilities in the U.S. Circle size denotes production output volume. Source: [EIA]

Present and future availability of bio-methanol, like other biofuels, is limited by biomass feedstock availability, as well as competition with other sectors; these issues are discussed in more detail in Section 6 of this report (Biofuels).

Production of significant quantities of green e-methanol will require extensive amounts of renewable electricity–the demand for which also faces competition from other sectors. As noted by Mukherjee (2023), the amount of electricity required to produce a quantity adequate to supply the entire global shipping sector with e-methanol using renewable electricity and DAC technology, for instance, would require over 6,000 TWh of electricity, as compared to total global renewable electricity production in 2021 of 8,300 TWh.[331]

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[328] https://orsted.com/en/media/newsroom/news/2020/05/485023045545315
[329] https://www.sciencedirect.com/science/article/pii/S0196890422002369#b0060
[330] https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf
[331] https://doi.org/10.1016/j.rser.2022.113127

Though e-fuels are less developed, in the longer term they could produce a much larger quantity of fuel, as production capacity is limited only by land and equipment, versus limitations of feedstock availability for bio-methanol.[332]

According to IRENA, renewable methanol production is estimated to reach 135 million tons/year (2.69 EJ) by 2050.[333] Globally more than 80 renewable methanol projects have been announced (or are in planning or development stages), which combined would produce 8 Mt (3 of bio-methanol and 5 of e-methanol) or more of renewable methanol in the next few years (~0.16 EJ, or about 3.8 million tonnes of oil equivalent). These include several projects in the United States, many also located in or near the Gulf Coast Region.[334] OCI, for instance, plans to double green methanol production at its Beaumont, Texas facility, from 200,000 to 400,000 MT. The company will produce bio-methanol and e-methanol.[335] Other producers in Texas, Louisiana and Virginia have announced plans to produce 4.4 million tonnes of green methanol combined.[336] Existing projects or plans for methanol production in California were not identified, though a recent study evaluated the concept of a renewable (bio-methanol) plant in California with the purpose of providing fuel for the marine sector at California ports.[337]

Bio-methanol is less expensive than e-methanol. It is also considered a more viable and realistic option in the near-to medium-term (2030 to 2050). In a recent DNV/Ricardo report to the IMO, expected global availability of bio-methanol was estimated at 0.4 EJ by 2030, 3.6 EJ by 2040, and 7.0 EJ by 2050, meaning in theory these fuels may be able to account for 3.8% of total marine fuel demand in 2030, 27.5% in 2040, and 44.3% in 2050. In practice, competition with other sectors for low-GHG fuels will likely constrain deployment of bio-methanol to the marine sector.

Availability of e-fuels (including e-methanol, but also green hydrogen, e-methane and e-diesel) was estimated at 0.1-1.9 EJ in 2040, and 0.2-5.0 EJ in 2050. Total estimated energy demand for the marine shipping sector, meanwhile, is 10.5 EJ in 2030, 13 EJ in 2040, and 15.8 EJ in 2050.[338] Further incentives and policies to increase e-fuel production will be needed to meet the demand (see *Policy Options to Decarbonize Ocean-Going Vessels*).[339]

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[332] https://doi.org/10.1016/j.rser.2022.113127

[333] https://www.methanol.org/wp-content/uploads/2020/04/IRENA_Innovation_Renewable_Methanol_2021.pdf

[334] https://www.methanol.org/renewable/

[335] https://oci-global.com/news-stories/press-releases/oci-global-to-double-its-green-methanol-capacity-in-the-united-states/

[336] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/shipping/091523-new-us-producers-plan-44-million-mtyear-green-methanol-for-shipping

[337] https://www.sciencedirect.com/science/article/pii/S0196890422002369#b0050

[338] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf

[339] Wooley et al. Policy Options to Decarbonize Ocean-Going Vessels, May 13, 2024, pageeshttps://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/ocean-going-vessel-decarbonization

Use of methanol as a marine fuel is increasing significantly, and may soon be entering the mainstream. Methanol is a relatively clean-burning fuel, and may be effective in reducing criteria pollutant emissions from the shipping sector. Methanol use also has the potential to reduce GHG emissions from marine shipping, but estimated GHG reductions vary widely depending on the type of methanol (green, blue, gray, brown), as well as the specific feedstock and production process used–and in some cases, methanol may actually increase life cycle GHG emissions (i.e. brown or gray) compared to conventional marine fuels.

The anticipated range in GHG emissions reductions associated with methanol's use as a marine fuel points to the importance of avoiding the use of umbrella statements of, and categorizations related to, methanol, and rather to recognize the importance of understanding the emissions associated with methanol production and use by type and source, in context, on a case-by-case basis (e.g. with the use of certification or guarantee-of-origin), as well as how this may change over time.

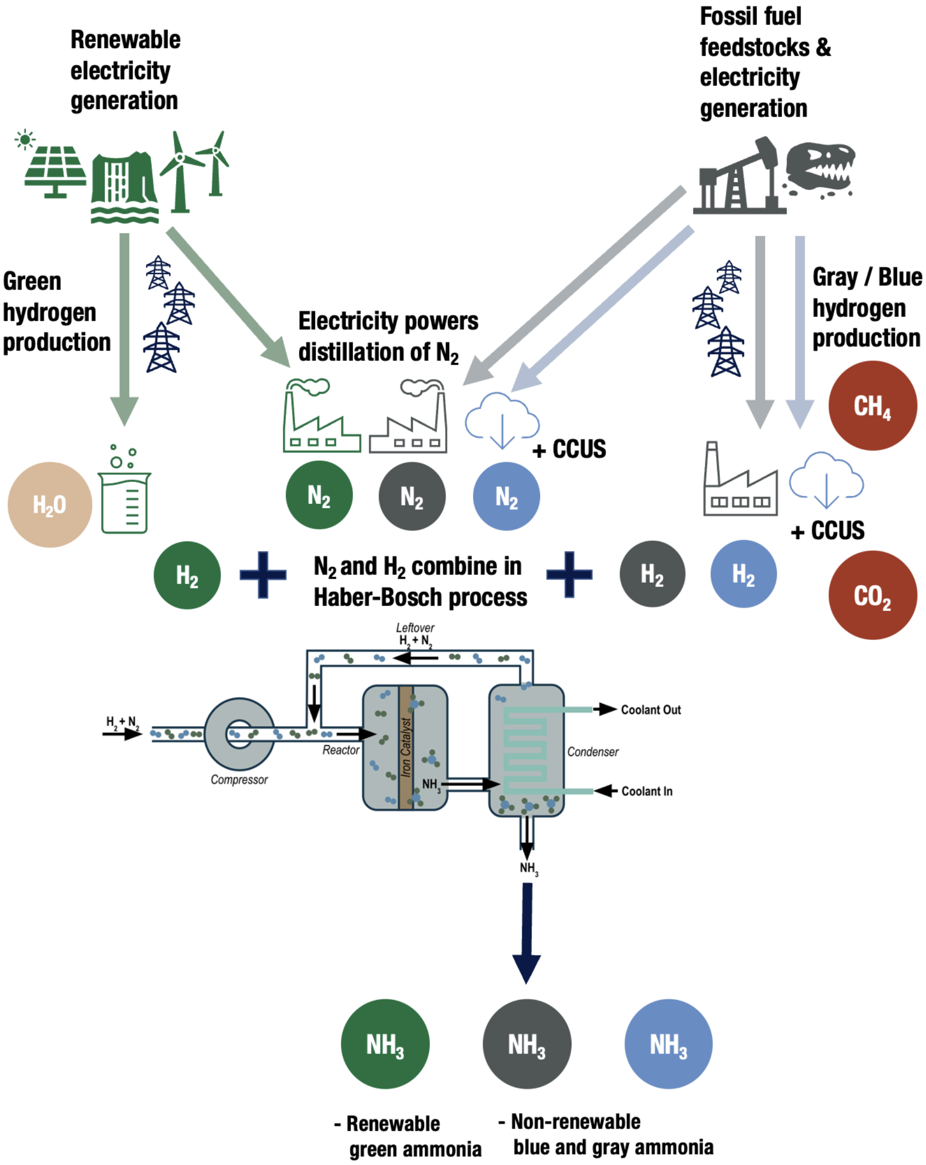
Section 5: Ammonia

Fuel description and properties

Ammonia (NH_3) is carbon- and sulfur-free at consumption. Under ideal conditions, ammonia combustion with oxygen in an ICE should release only molecular nitrogen (N_2) and water vapor, which are non-toxic and naturally abundant in the environment. However, under real-world conditions, significant NO_x formation can result.

Figure 12

Ammonia production pathways



The Haber-Bosch process, which is itself energy-intensive (Figure 12), is the primary method for producing ammonia from nitrogen and hydrogen. The H_2 production pathway, therefore, influences the ammonia pathway (i.e. brown, gray, blue, green). Thus, the two fuels, their technologies and infrastructures are often paired and discussed together.

Similar to H_2 (Section 3), ammonia can be burned in a modified ICE or consumed through a fuel cell. Unlike $H_{2,}$ it does not require cryogenic conditions (boiling point = -33.1°C) and is easier to store than H_2. Ammonia liquefaction is easier and cheaper than H_2 and stores more energy by volume. However, ammonia is more difficult to combust than most alternative and conventional marine fuels. Ammonia requires specialized combustion technologies, including diesel pilot fuels necessary for compression ignition. A key challenge to its development is navigating safe implementation. Exposure can lead to severe health symptoms that include chest pain, eye irritation, cough, headache, and/or death. It can have similarly severe negative effects on aquatic life.

Ammonia's fuel parameters, including energy density, emissions profile, fuel and capital costs, safety issues, and U.S. fuel production, are shown in Table 11.

Ammonia, at 12.7 MJ/L (Table 11), is higher in energy density compared to $LH_{2,}$ though its energy density is less than half the volumetric density of conventional marine fuels. Due to its lower energy content, ammonia requires three to four times more cargo-volume for storage, and weighs twice as much as conventional marine fuels.[340,341] Significant support for ammonia as a future marine fuel comes from its potentially expedited development timeline. Ammonia has existing infrastructure from a well-established industry, primarily its use as a fertilizer.

Ammonia consists of 17.6% hydrogen within its molecular structure. Through a process of breaking the bonds with nitrogen, hydrogen can be extracted and utilized in internal ICE or fuel cells. Leveraging ammonia as a hydrogen energy carrier could potentially offer cost-effective and easier storage and transportation solutions, capitalizing on existing industry knowledge and infrastructure for ammonia while tapping into the diverse applications of hydrogen.

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[340] https://maritime-executive.com/article/with-ammonia-there-s-no-chicken-or-egg-dilemma

[341] https://www.krs.co.kr/eng/Webzine/View.aspx?WMDR=237&WCDR=4090

Table 11

Ammonia fuel parameters, costs, and emissions[342,343,344]

Ammonia Properties	Brown	Blue	Green
Volumetric Energy Density (MJ/L)	12.7		
Technology Maturity	Immature. Commercially available marine engines by 2025/26.		
WtW CO_2e (kg per MJ fuel)	0.113 - 0.194	0.023 - 0.077	0.012 - 0.024
WtW NO_x (kg per MJ fuel)	0.0096		0.008
WtW SO_x (kg per MJ fuel)	0.0031		NC
WtW CH_4 (kg per MJ fuel)	0.0296		NC
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 and/or environment, but can easily be detected by smell without equipment		
U.S. Production (MT)	13 million	~0.7 million*	

NC = negligible concentration

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

Engine and Fuel System Parameters

Ammonia is more efficient when partially decomposed to release H_2 before combustion, as H_2 is more easily ignited. This introduces the potential to capture both the benefits of ammonia during transportation and storage, and those of H_2 at combustion. Ammonia's maritime use in ICEs is near, but not yet at market in its full capacity; its dual fuel application hit waters in 2023, including a 6,014 twenty-foot equivalent unit (TEU) container ship containing two MAN dual fuel engines, the first of its kind.[345]

Wärtsilä aimed to develop a marine engine that runs solely on ammonia in 2023, but after successful testing of a 90% ammonia-fueled engine, believes it will realistically take at

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[342] https://oceanconservancy.org/wp-content/uploads/2023/03/Approaches-Decarbonizing-US-Fleet.pdf

[343] https://doi.org/10.1016/j.fuel.2023.129995

[344] https://www.nordicenergy.org/wordpress/wp-content/uploads/2022/05/LIFE-CYCLE-ASSESSMENT-CAHEMA.pdf

[345] https://maritime-executive.com/article/first-ammonia-ready-containership-delivered-to-cmb

least until late 2025 or early 2026 to reach market.[346,347] WinGD has reported that they are on track to deliver dual fuel ammonia engines in 2025 with vessels on the water in 2026.[348] MAN Energy Solutions aimed to have a commercially-available engine by 2024, with a retrofit package by 2025.[349] MAN completed its first successful ammonia combustion in a maritime two-stroke engine in July 2023 and expects to hold its timeline for the first ammonia engine in 2024 and vessel operations in 2026. Moreover, in 2023, MAN successfully built and tested ammonia bunkering and service-tank facilities with all auxiliary systems to enable a full containment of ammonia in the unlikely event of a leak.[350]

In 2024, a dual fuel vessel in Singapore, Fortescue's *Green Pioneer*, first bunkered ammonia to complete early pilot testing of its ammonia storage systems, associated piping, gas fuel delivery system, retrofitted engines, and seaworthiness. Trials included rigorous safety training for port and vessel crews, and air quality tests for NOx emissions. Successful tests have demonstrated feasibility of ammonia as a marine fuel, signaling progress towards a future where ammonia-powered vessels could be adopted in the global fleet.[351]

A 2023 life cycle study found ammonia ICEs to be more economically viable than fuel cells, while also being cost-competitive for reducing GHG emissions across tankers, small service vessels, and roll-on/roll-off ferries (RoPax). The existing engine, fuel storage, and mechanical space of these three vessel categories were compared to the volume and weight of proposed ammonia systems. The configuration of vessel types may be mass- or volume critical; tankers are mass-limited, whereas RoPax and service vessels are volume-limited. At this stage of R&D, conceptual designs were deemed certainly viable for service vessels and potentially viable for tankers and RoPax. Volume constraints of tankers were incompatible with ammonia systems in their traditional blueprint, however there was ample space available on the deck that may accommodate a new configuration. Ammonia systems are technically feasible aboard RoPax, however have a higher risk in terms of safety.[352]

All manufacturers developing ammonia engines have noted the imperative for safe handling of ammonia–which is toxic–as a critical challenge. However, it's important to note that while ammonia presents safety concerns, it is no more hazardous to transport than

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[346] https://www.argusmedia.com/en/news/2234110-wartsila-targets-ammoniaready-engine-in-2023
[347] https://shippingwatch.com/regulation/article15928061.ece
[348] https://maritime-executive.com/article/wingd-predicts-ammonia-fueled-engines-for-q1-2025-and-in-service-in-2026
[349] https://www.man-es.com/discover/two-stroke-ammonia-engine
[350] https://www.man-es.com/company/press-releases/press-details/2023/07/13/groundbreaking-first-ammonia-engine-test-completed
[351] https://fortescue.com/news-and-media/news/2024/03/15/world-s-first-use-of-ammonia-as-a-marine-fuel-in-a-dual-fuelled-ammonia-powered-vessel-in-the-port-of-singapore
[352] https://doi.org/10.1016/j.apenergy.2023.121773

propane or gasoline.[353,354] Ammonia's hazards have been studied and documented for many decades, through its supply in the chemical sector; its flammability is low, while its toxicity is high.

Pure ammonia (>99%) can also be referred to as anhydrous[355] ammonia. It contains little to no water, causing the compound to aggressively seek out moisture from its surroundings. Its exposure can cause severe burns to skin, eyes, throat, and respiratory tract. Its transport in the chemical sector mandates use of personal protective equipment, emergency water supplies, slow transport speeds, and regular maintenance of equipment.[356] Ammonia cargo spills can cause ecological damage, but disperse over smaller areas and persist for short periods of time, compared to spills of conventional marine fuels.[357]

Current codes and standards governing ammonia usage will need revisions to accommodate its varied applications as an energy carrier. Effective utilization hinges on the use of thoroughly tested equipment and the implementation of proper handling protocols for integrating it into an engine and fuel system.

Manufacturers are also working to address NO_x emissions to follow regulatory requirements through marine dual fuel engine testing. In these tests, when the proportion of ammonia is increased, CO_2, CO, and unburned hydrocarbons (UHC) are reduced, but at the expense of increased NO_x production.[358] This is also referred to as the UHC-NO_x trade-off, which is not exclusive to ammonia combustion, but has also been observed for other fuel types, such as LNG. Currently, available engines using ammonia emit relatively high unburned NH_3 and NO_x emissions. As that share of ammonia fuel increases in the ICE, the NO_x emissions increase significantly due to the fuel-bound nitrogen in ammonia.[359]

Under dual fuel testing, it was found that when the proportion of ammonia is too low, the high-temperature combustion of diesel leads to high NO_x emissions. Conversely, when the proportion of ammonia is too high, the increment of non-reacting ammonia into the exhaust gas (aka “ammonia slip”[360]) increases and thus does NOx emissions.[361] It was found that only when the fuel share of ammonia was less than 40% in the diesel dual fuel

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[353] https://nh3fuelassociation.org/wp-content/uploads/2013/01/nh3_riskanalysis_final.pdf

[354] https://nh3fuelassociation.org/wp-content/uploads/2013/05/riso-ammonia-transport-safety-report.pdf

[355] Anhydrous = containing no water

[356] https://www.mda.state.mn.us/sites/default/files/inline-files/Practice%20Safety%20When%20Handling%20Anhydrous%20Ammonia%20-%20NH3%20%28002%29_0.pdf

[357] https://www.edfeurope.org/sites/default/files/EDF-Europe-Ammonia-at-sea-FullReport.pdf

[358] https://doi.org/10.3390/jmse10010043

[359] https://doi.org/10.1016/j.rser.2023.113631

[360] Ammonia slip refers to the release of unreacted ammonia, stemming from the incomplete combustion of NOx and the reagent

[361] https://doi.org/10.3390/jmse10010043

application that NO_x emissions using the dual fuel operation were lower than those using 100% diesel fuel.[362]

Under testing of a non-marine engine, ammonia combustion in low-load conditions has been shown to rely on mixing diesel fuel or diesel combustion products with the ammonia/air mixture, essentially operating in a diesel flame-driven mode.[363] Comparing the performance in marine dual fuel engines under low-load conditions, high-pressure systems were shown to have higher power and lower emissions than low-pressure applications.[364]

When ammonia acts as a carrier for H_2, use of fuel cells can bypass the pollutants (i.e. NO_x) associated with ammonia fuel use by cracking its energy and then consuming it without burning ammonia. Direct ammonia fuel cells (DAFCs) are still at low technological maturity.[365] These technologies are not considered to be economically viable for maritime use, as they neither compete with the efficiency of H_2 technology nor of ICE use. Additionally, existing fuel cell technology cannot supply adequate power for ships. However, in 2024, a two-megawatt solid-oxide fuel cell powered by NH_3 will supply a portion of energy on the *Viking Energy* supply ship from Norway, in combination with traditional fuels.[366]

Life Cycle WtW GHG and Criteria

The majority of ammonia (~99%) is currently produced from natural gas or coal feedstocks, using SMR to generate H_2. Around 90% of carbon emissions from ammonia production occur during H_2 synthesis.[367] SMR accounts for over 80% of the energy required. As a result, current ammonia synthesis is the largest CO_2 emitting chemical industry process by a significant margin today.[368] The resulting H_2 is then combined with N_2, separated from the air through a cryogenic process, to form ammonia using the Haber-Bosch process with iron catalysts, under high heat conditions (~400-600 °C).

Today's global production of ammonia, across all sectors, is estimated to generate 1-3% of global CO_2 emissions (as it is primarily from fossil fuels).[369] Furthermore, when considering fuel energy densities, the feedstock and conversion emissions of gray ammonia were estimated to be the highest of seventeen marine bunker fuels, including conventional marine bunkers.[370] Therefore, decarbonization of ammonia through

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[362] https://doi.org/10.1016/j.rser.2023.113631
[363] https://doi.org/10.1007/s10494-023-00453-y
[364] https://doi.org/10.1016/j.fuel.2023.128906
[365] https://doi.org/10.1021/acsenergylett.1c02189
[366] https://spectrum.ieee.org/why-the-shipping-industry-is-betting-big-on-ammonia
[367] https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/
[368] https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf
[369] https://www.nature.com/articles/s44160-023-00362-y
[370] https://doi.org/10.1016/j.fuel.2023.129995

upscaling green production is a high priority for it to serve a role in net-zero climate trajectories.

The production of ammonia is energy-intensive, with approximately 60% of the energy put into the production plant being stored into the bonds of ammonia.[371] The reaction between N_2 and H_2 requires high temperatures and pressures that drive up costs and potential GHG emissions. Due to the low volumetric energy density of ammonia compared to conventional hydrocarbons, there is ongoing R&D to reduce the energy intensity of ammonia production without reducing yield.[372]

Ammonia may significantly reduce TtW GHG emissions compared to MDO, but may produce higher WtW emissions, depending on the production pathway.[373] In maritime applications, green ammonia was found to have 83% lower vessel-specific (g/kWh) WtW carbon emissions than very-low sulfur fuel oil, while blue ammonia's was found to be 57% lower; gray ammonia, meanwhile, had 48% greater emissions.[374,375] CO_2 and SO_x emissions occur entirely, while CH_4 and NO_x occur predominantly, from the production of ammonia rather than its combustion phase (upstream, WtT GHG emissions).[376]

Ammonia has a reduced carbon intensity, but still produces considerable NO_x emissions. NO_x emissions contribute to smog and acid rain, and can harm respiratory systems of humans and other living organisms. While the theoretical ideal combustion process for ammonia would not emit NO_x, this is not the case in practical situations involving high temperatures, such as in maritime use. Emissions abatement options include additives to convert ammonia into urea solution to reduce NO_x in the exhaust gas, or SCR technologies. SCR is considered to be economically advantageous with ammonia, but is only efficient at high temperatures.[377]

Bunkering and Existing Infrastructure

The global production capacity for ammonia reached 243 Mt in 2020, although demand was around 75% of that. The existing capacity of renewable ammonia production is only 0.02 Mt per year, equivalent to 0.01% of today's global ammonia production. Over 60 renewable ammonia plants have been announced, with a combined annual capacity of 71 Mt operational by 2040. Not all of these projects are fully committed by final investment decision.[378]

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[371] https://doi.org/10.1016/j.joule.2020.04.004

[372] https://www.krs.co.kr/TECHNICAL_FILE/2021-ETC-01_Report%20on%20Ammonia-Fueled%20Ships.pdf

[373] https://www.nordicenergy.org/wordpress/wp-content/uploads/2022/05/LIFE-CYCLE-ASSESSMENT-CAHEMA.pdf

[374] https://doi.org/10.1007/s11367-022-02091-4

[375] https://safety4sea.com/wp-content/uploads/2021/04/ABS-Setting-the-Course-to-Low-Carbon-Shipping-View-of-the-Value-Chain-2021_04.pdf

[376] https://doi.org/10.1016/j.fuel.2023.129995

[377] https://www.krs.co.kr/TECHNICAL_FILE/2021-ETC-01_Report%20on%20Ammonia-Fueled%20Ships.pdf

[378] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

Ammonia is incompatible with many materials used in conventional systems. It is corrosive to some alloys containing copper and nickel and to some plastics, limiting the materials to design NH_3 systems and the feasibility of transitioning fossil fuel systems. Nevertheless, there is widespread pre-existing infrastructure for ammonia, including for agricultural and industrial purposes.

Ammonia can be transported by pipeline and has existing transportation infrastructure due to its widespread use and production as an agricultural fertilizer and in chemical industries. Most ammonia infrastructure is relatively local;[379] the U.S. possesses 5,000 kilometers of ammonia pipelines (of the ~8,000km global total), though minimal compared to over 490,000 kilometers of high-pressure natural gas pipelines.[380] Expansion of ammonia infrastructure, requiring substantial capital investment, is necessary to fulfill upcoming demands.

In addition to pipeline networks, ammonia can be transported by specialized tank trucks and waterborne tankers; with pressurized systems and low temperatures at -34°C (1 bar) or -20°C (10 bar). For large-scale use, such as in the maritime industry, ammonia storage in its energy dense liquefied form is preferred and is considered to be 99% efficient.[381]

Before its consideration as a fuel, ammonia was already being stored and handled in 120 ports around the world, with the capacity to deliver around 100 million annual tons of ammonia for non-marine sector use.[382] This capacity only moderately increased by 2020, with 132 ports with ammonia terminals (38 export, 88 import, 6 dual-function). Fourteen terminals are located at U.S. ports, with one import terminal located at the Port of Stockton, CA.[383] Terminals are continuing to be established, such as the deepwater-marine ammonia terminal in the Port of Houston becoming fully operational in 2021.[384] Around 18-20 Mt of ammonia is shipped internationally per year. In 2022, the U.S. exported ~19% of its domestically-produced ammonia, while simultaneously importing ~14% of its total consumption.[385]

In 2022, the American Association of Port Authorities (AAPA) labeled ammonia a 'viable fuel', with comments on its easier and cheaper storage, while being a more efficient fuel source than hydrogen.[386] In 2023, the AAPA endorsed the bipartisan Hydrogen for Ports Act[387] supporting the investment and development of hydrogen- and ammonia-fueled

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[379] https://www.nustarenergy.com/Business/AssetSheets?assetid=PL_AMMONIA&assettype=Pipeline

[380] https://kleinmanenergy.upenn.edu/research/publications/ammonias-role-in-a-net-zero-hydrogen-economy/

[381] https://kleinmanenergy.upenn.edu/research/publications/ammonias-role-in-a-net-zero-hydrogen-economy/

[382] https://doi.org/10.1016/j.jpowsour.2008.02.097

[383] https://www.topsoe.com/hubfs/DOWNLOADS/DOWNLOADS%20-%20White%20papers/Ammonfuel%20Report%20Version%2009.9%20August%203_update.pdf

[384] https://financialpost.com/pmn/press-releases-pmn/business-wire-news-releases-pmn/vopak-moda-houston-commissions-its-fully-operational-marine-terminal-in-the-port-of-houston

[385] https://crsreports.congress.gov/product/pdf/IF/IF12273

[386] https://www.bunkerspot.com/global/56101-global-aapa-ammonia-is-a-viable-fuel-source-that-could-prove-cheaper-and-more-efficient-than-hydrogen

[387] https://www.coons.senate.gov/imo/media/doc/ports_hydrogen_infrastructure_initiative2.pdf

equipment at ports and in shipping applications, particularly through a joint feasibility study across relevant federal agencies.[388]

In 2023, there are no established port bunkering facilities or infrastructure to supply ammonia as a maritime fuel.[389] The Port of Rotterdam anticipates the launch of ammonia bunkering trials sometime in 2024; It has joined in a joint study framework with 15 other port and stakeholder organizations to share knowledge for ammonia bunkering, particularly with safety challenges, with the aim to implement and scale ammonia as a marine fuel.[390] An international joint feasibility study is also occurring at the Port of Savannah, Georgia to investigate and build a framework for ship-to-ship green ammonia bunkering, with an undetermined timeline for its delivery.[391]

In November 2023, four very large ammonia carriers were contracted to be built in a ~$498 million dollar deal. Each will be capable of transporting 93,000m^3 of liquid $NH_{3,}$ making them the largest ammonia carriers in the world. These vessels,to be delivered in 2027, will be capable of delivering ammonia and will be built "ammonia-ready" for eventual fueling "upon the shipowner's request".[392]

Costs (CAPEX and OPEX)

CAPEX = capital expenditure, OPEX = operating expenditures

Blue ammonia production pathways are forecast to reach full maturity by mid-2030.[393] Blue ammonia utilizes the SMR process but reduces CO_2 emissions with CCUS technologies. These CCUS technologies have the same limiting parameters as other blue production pathways (e.g. does not address other GHGs, engineering assumptions for capture rate are higher than in practice, wide estimations of economic feasibility, etc.). Blue fuels at their maturity should theoretically have 90% carbon capture rates, but technologies in R&D are not achieving those reductions. The DOE claims new CCUS technologies will greatly reduce costs in production by up to 23%, with a cost of $40/MT CO_2 at 90–97% carbon capture rate. However, they suggest a different approximation of carbon capture than provided in the IRENA report, stating that current capture costs range from $200–1000/MT $CO_{2,}$ which would underestimate the DOE assessment.[394]

The green ammonia market is predicted to grow at a compound annual growth rate of 7.8% from 2021 to 2027.[395] By 2050, the green ammonia production capacity required to meet fuel demand from the maritime sector alone could be five times greater than present

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[388] https://www.aapa-ports.org/advocating/PRDetail.aspx?ItemNumber=22895
[389] https://doi.org/10.1016/j.trd.2023.103666
[390] https://www.offshore-energy.biz/port-of-rotterdam-to-fuel-ships-with-methanol-on-a-regular-basis-from-summer-2023/
[391] https://www.marinelog.com/news/u-s-east-coast-green-ammonia-bunkering-plan-in-the-works/
[392] https://www.offshore-energy.biz/hanwha-ocean-bags-498-million-order-for-worlds-largest-ammonia-carriers/
[393] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[394] https://doi.org/10.1016/j.jclepro.2022.135696
[395] https://doi.org/10.1007/978-981-16-8717-4_10

total global production of ammonia, regardless of pathway, ranging from 670-946 million tons per year. The scale of green ammonia market growth is assumed to have a profound impact on its technology costs, reducing the capital costs of electrolyzers through scaling up unit capacity and manufacturing volumes.[396] Furthermore, commitments by nations to reduce the production costs of green H_2 will translate to the production costs of green ammonia. Therefore, projected future costs should decrease as production scales up.

Comparing the production and transportation pathways of other alternative, low-GHG fuels, ammonia was found to be 31-32% cheaper than hydrogen and 15-18% cheaper than methanol.[397,398] Green ammonia has the lowest upstream, WtT energy costs by a significant margin, compared to other low-GHG fuel sources originating from renewable energies.[399] Hydrogen is an input to ammonia production, so hydrogen and ammonia production costs are intertwined. The additional losses of energy conversion makes ammonia production more vulnerable to fluctuations in the price of electricity than H_2.[400]

Ammonia's primary economic advantage over H_2 comes from its cheaper and easier transportation. Ammonia can be liquefied using only a small fraction of the stored energy, while liquefying hydrogen requires almost 50% of the stored energy. Ammonia also holds its stored energy over extended periods of time, with negligible losses over a six-month storage period, compared to LH_2 losing 60% over that same period.[401] Ammonia has lower energy losses from boil-off of its liquid state than LNG and $LH_{2,}$ and can be transported efficiently for both energy and costs over long distances overseas.[402]

The costs of transporting ammonia were similar regardless of the mode of transportation, with each being cost-effective and competitive per kilogram. The transportation costs per gigajoule, thus considering energy-dense fuel equivalencies, of a marine carrier vessel were higher for ammonia ($1.09) than for LNG ($0.74) and methanol ($0.68), but half the cost of LH_2 ($3.24). However, ammonia has a lower transportation cost per kilogram ($0.02/kg) and the capital cost of an LNG tanker is 15% higher than for ammonia.[403] The pipeline transportation costs per kilogram of ammonia ($0.03/kg) were cheaper than for H_2 ($1.51/kg) or CH_4 ($0.10/kg).[404] The price of ammonia pipeline transport is approximately 1% of its delivered cost, depending on the global region.[405]

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[396] https://www.ammoniaenergy.org/articles/maritime-decarbonization-is-a-trillion-dollar-opportunity/
[397] https://www.krs.co.kr/eng/Webzine/View.aspx?WMDR=237&WCDR=4090
[398] https://doi.org/10.1016/j.joule.2019.07.005
[399] https://doi.org/10.1016/j.joule.2019.07.005
[400] https://doi.org/10.1016/j.apenergy.2023.121773
[401] https://kleinmanenergy.upenn.edu/research/publications/ammonias-role-in-a-net-zero-hydrogen-economy/
[402] https://doi.org/10.1016/j.ccst.2022.100056
[403] https://doi.org/10.1016/j.egyr.2020.07.013
[404] https://doi.org/10.3389/fmech.2020.00021
[405] https://doi.org/10.1016/j.isci.2021.102903

Using 2020 and 2021 economic conditions and literature estimates, the simulated bunkering price of ammonia was approximately $539.30/MT, which was lower than the bunkering costs reported of LNG or MGO. Due to its lower energy density (18.6 MJ/kg), more metric tons of fuel are required to power the vessel over the same journey.[406] Recent global events, such as COVID-19 and the Russia-Ukraine war, have led to increased market prices of ammonia. The long-term average price is approximately $300/MT, though this rose to as high as $1,350 at the start of 2022 (non-marine sector).[407]

In 2023, global ammonia prices fell 50%, which may sound economically advantageous in terms of its competition; however, it was connected to the fall in feedstock natural gas prices. Thus, this price drop widened the cost and demand gaps between conventional and low-GHG ammonia. Consequently, it led to the suspension of and additional challenges to securing final investment decisions for low-GHG ammonia projects. Uncertainties in pricing for these new ammonia projects have required contracts to lock in export demand to secure financing.[408]

Ammonia engines are relatively new technologies, and engine and storage costs are not readily available. Costs of a new-build ammonia vessel are estimated to be 25-30% higher than a comparable conventional vessel.[409] Estimates, which may vary in the application of different vessels, put additional costs around $13.3 million for an ammonia vessel with a 30 megawatt (MW) engine ($443/kW), including fuel storage tanks, engine, and fuel system.[410,411] Other estimates of an ammonia engine system vary greatly, between $400-847/kW CAPEX.[412,413,414] Its operating costs are estimated to be $227-262/MWh, but anticipated could be reduced to $162/MWh soon.[415,416] Estimated by shipping company Grieg Star, retrofit costs of an ammonia system on a dry-bulk carrier were found to be greater than 50% of the fair market value of a new-build ship.[417]

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[406] https://doi.org/10.1016/j.ijnaoe.2023.100523

[407] https://www.dtnpf.com/agriculture/web/ag/crops/article/2022/03/15/russia-ukraine-war-drives-world

[408] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/081523-global-ammonia-prices-fall-50-on-year-sparking-concerns-over-future-low-carbon-ammonia-market

[409] https://www.globalmaritimeforum.org/content/2021/06/The-Nordic-Green-Ammonia-Powered-Ship-_Project-Report.pdf

[410] 1 EUR = 1.08 USD

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

[412] 1 EUR = 1.08 USD

[413] https://doi.org/10.1016/j.rser.2021.110861

[414] https://doi.org/10.1016/j.enconman.2023.117497

[415] 1 EUR = 1.08 USD

[416] https://doi.org/10.1016/j.ijnaoe.2023.100523

[417] https://www.ammoniaenergy.org/articles/retrofitting-vessels-for-ammonia-fuel-new-technical-study-from-grieg-star/

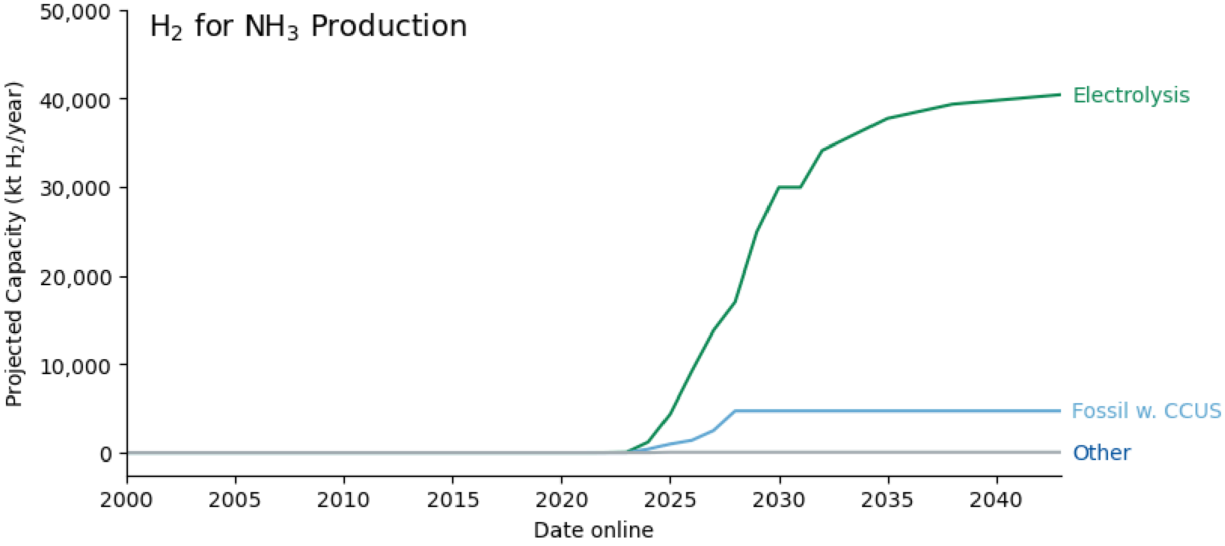
Fuel Availability and Projections: Ammonia

Ammonia is produced in large quantities globally to support agriculture and industrial processes. In 2021 global ammonia production stood at around 183 Mt.[418] Ammonia is a hydrogen-based fuel and so hydrogen production pathways dominate the greenhouse gas intensity of ammonia. IEA's Hydrogen production projects database also includes hydrogen production facilities with the end-goal of providing feedstocks for ammonia production (Figure 13).

The IEA projects data show projects totaling 45.2 Mt of hydrogen for ammonia production, which could provide feedstocks for up to 250 Mt of ammonia.[419] Much of the projected production is using electrolysis, which accounts for 89.4% of total production by 2043, with fossil-with-CCUS accounting for 10.5% of projected capacity.
The IEA data do not list any additional fossil-with-CCUS projects beyond 2028. This is likely due to a paucity of upcoming data, rather than a moratorium on new projects beyond 2028. Hydrogen production through electrolysis is projected to be dominated by projects using dedicated renewables, which account for 87.0% of proposed capacity in 2030 and 90.4% in 2043, the last year of IEA project data. Grid and Grid+Renewables account for 4.3% in 2043, with the remaining 5.3% of electrolysis from unknown origin (Figure 13).

Figure 13

Global Renewable H_2 Capacities Allocated for Ammonia Production Projected by 2043



Global demand of NH_3 for the maritime sector is anticipated between 128-245 Mt by 2050 (IEA)

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[418] IEA (2022) Ammonia Technology Roadmap.
[419] Assuming around 178 kg of hydrogen are needed to produce 1,000 kg of ammonia. Molecular mass of H = 1.01, N = 14.01, NH_3 = 17.04

Of the around 183 Mt of ammonia produced globally, around 20 Mt are traded internationally.[420] As a result, there exists a developed network of around 200 ports and associated infrastructure and experience with transporting and handling ammonia. Ammonia may be used directly in marine engines, or transported as ammonia and then cracked to yield molecular hydrogen.

IEA's Sustainable Development and Net Zero scenarios both include significant uptake of ammonia as a marine fuel by 2050, with global maritime demand for ammonia reaching 128 Mt and 245 Mt under those scenarios, respectively.[421] Rapid uptake of green hydrogen production is needed to meet ammonia demand under these scenarios.

Ammonia production was spread across 35 plants in 16 states in the U.S. in 2022. Total U.S. production in 2022 is estimated at around 13 Mt with 60% of U.S. production in the Gulf region, in Louisiana, Oklahoma, and Texas.[422] The U.S. imported an additional 2.1 Mt for domestic consumption, predominantly from Trinidad and Tobago (58%) and Canada (40%). Agricultural markets dominate ammonia demand in the U.S. with around 88% of domestic ammonia consumption for fertilizer use.

The disparity between renewable ammonia production and projected demand in a net-zero future presents a significant challenge to achieving global and local emissions targets. As noted earlier, life cycle emissions of gray ammonia were estimated to exceed those of conventional fuels when accounting for the quantities required to replace their energy, mainly due to its lower energy density (later discussed in Section 8: Technology Readiness).[423] Consequently, should various sectors transition to ammonia infrastructure, without proper regulation and economies concurrently securing renewable production levels to meet their demand, the potential reliance on gray ammonia could inadvertently steer the world farther from its climate targets.

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[420] IEA (2021) Ammonia Technology Roadmap.

[421] IEA (2021) Ammonia Technology Roadmap. Box 2.2.

[422] U.S. Geological Survey, Mineral Commodity Summaries, January 2023. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-nitrogen.pdf

[423] https://doi.org/10.1016/j.fuel.2023.129995

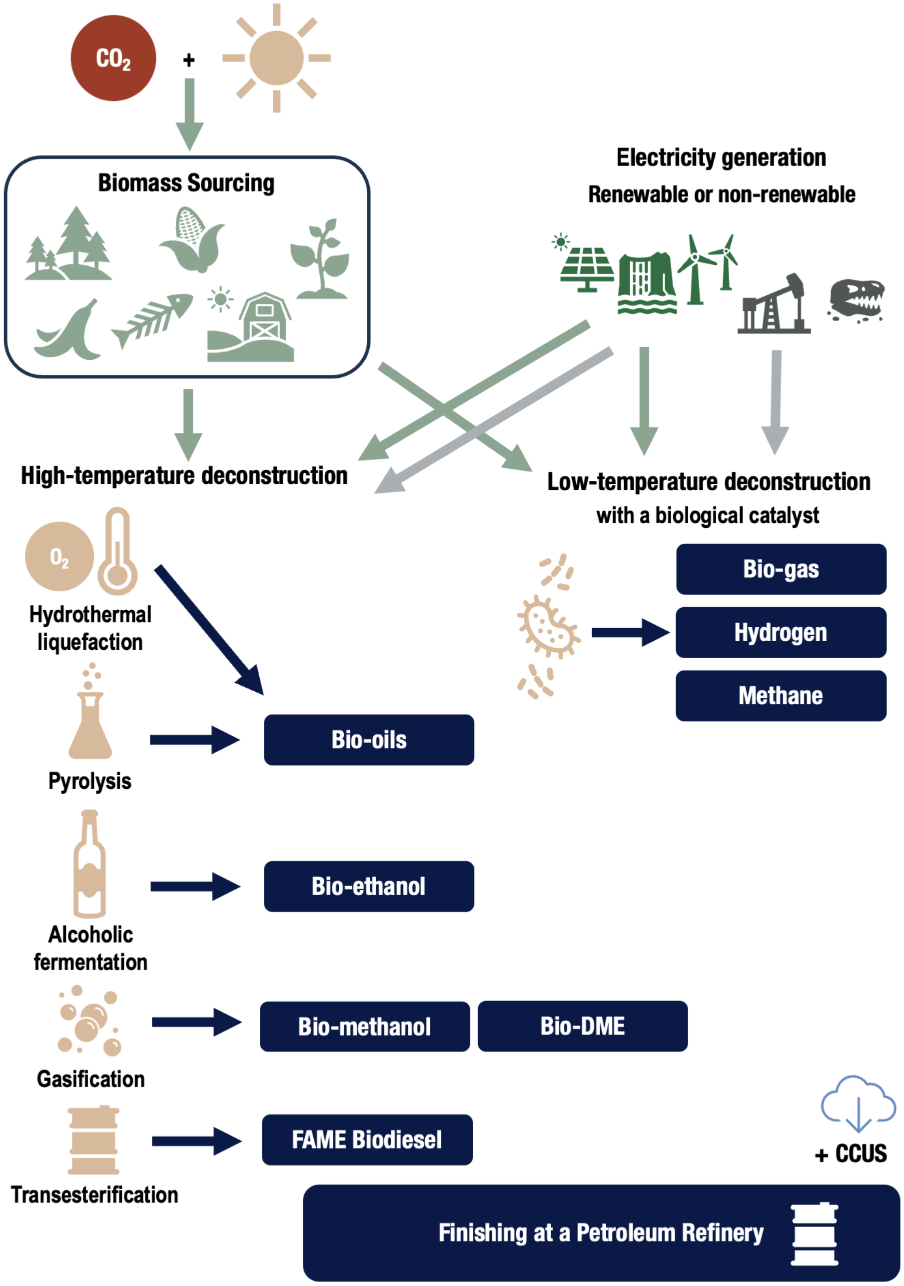
Section 6: Biofuel

Fuel description and properties

Biofuels encompass a variety of liquid fuels derived from biological sources, with a wide range of potential feedstocks and fuel types available. The term "biofuels" denotes a diverse array of fuels with unique characteristics and suitability for different vessels.

Figure 14

Biofuel production pathways



Options of biofuels available–or expected to be available–for use as a marine fuel include biodiesel (or Fatty Acid Methyl Ester–FAME), hydrotreated vegetable oil (or HVO–also known as renewable diesel), dimethyl ether (bio-DME), straight vegetable oil (SVO), bio-oil, bio-crude, Fischer-Tropsch diesel (FT-Diesel), bio-methanol (Bio-MeOH), lignin ethanol oil (LEO), and liquefied natural gas (bio-LNG).[424,425,426,427]

Several biofuels have been found to be relatively similar to each other in terms of technology status, availability, GHG mitigation, costs, and compatibility with marine vessels.[428,429] In general, biofuels are seen as a promising short-to mid-term solution for decarbonization in the marine sector, as many biofuels are “drop-in” fuels, meaning they can be blended with conventional marine transport fuels (e.g. HFO and MGO), and may be used without requiring major modifications to engines, pumps, fuel storage or other fueling infrastructure.[430,431]

So-called “first-generation” biofuels are made from food crop feedstocks such as corn, soybeans, and canola. Due to their impacts on land use and food supply, first-generation biofuels have not been shown to decrease net GHG emissions on a life cycle basis, and may even increase net GHG emissions. First-generation biofuels are generally seen as unsustainable due to effects on land use patterns and food supply, among others.[432]

“Second-generation” or advanced biofuels are produced from non-food feedstocks including forest residues and waste streams (e.g. agricultural waste, oils and greases, manure and sludge, landfill gasses and municipal wastes). Second-generation pathways are comparatively less mature than first-generation pathways, and are currently associated with higher costs and uncertainties. They are, however, generally expected to cause significant GHG emissions reductions——potentially reaching zero- or even below-zero GHG emissions on a life cycle basis—and are expected to have minimal impacts on land use and food crops.[433,434] This report focuses on biofuels produced through second-generation feedstocks and pathways.

Third- and fourth-generation biofuels, including those produced from feedstocks including algae and genetically-engineered algae, are developing. They are not yet technologically viable, but are expected to be so years, or even decades in the future.

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[424] https://farmdocdaily.illinois.edu/2023/02/biodiesel-and-renewable-diesel-whats-the-difference.html
[425] https://pubs.acs.org/doi/10.1021/acs.est.0c06141
[426] https://doi.org/10.1021/acs.est.3c00388
[427] https://onlinelibrary.wiley.com/doi/pdf/10.1002/bbb.2350
[428] https://doi.org/10.1016/j.rser.2022.113127
[429] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[430] https://doi.org/10.1016/j.rser.2022.113127
[431] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[432] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[433] https://doi.org/10.1016/j.rser.2022.113127
[434] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf

Biofuels are produced through various processes–including esterification, hydrothermal liquefaction (HTL), fast pyrolysis (FP), Fischer-Tropsch (FT) process, hydrotreating, and fermentation–all of which are compatible with specific feedstocks and fuels, and are associated with specific properties, costs, and emissions profiles on a life cycle basis.

This section focuses on the biofuels identified as having the most promise in feasibly reducing life cycle GHG emissions in marine transport: FAME or biodiesel, HVO or renewable diesel, FT-Diesel, and bio-DME.[435] We also include bio-oils, recognized as having particular promise and viability in mitigating GHG emissions in the marine sector in the longer- term.[436,437,438,439] Bio-methanol, another promising biofuel, is covered separately in Section 4.

Fatty Acid Methyl Ester (FAME/Biodiesel)

Biodiesel, or FAME, is produced through transesterification–where fats and oils are reacted with alcohols and catalysts, with methanol typically used as a reactant—to produce fatty acid esters that have similar properties to conventional diesel.[440] FAME has been produced primarily through first-generation feedstocks, (i.e. food crops), which does not produce meaningful GHG reductions. FAME produced from second-generation feedstocks, however, has the potential to reduce life cycle GHG emissions upwards of 70%.[441442] FAME, like other biofuels, is not expected to be used as a neat (100%, or B100) fuel in marine shipping, but is used in blends (most often up to B20–20% FAME), though successful trials using B30 (30%), 50:50 blends (B50) and even B100 (100% biodiesel) have been conducted. Expected GHG emissions reductions compared to conventional fuels are, of course, dependent on the biofuel blend ratio.

FAME is largely considered a "drop-in" fuel and may be blended with existing petroleum fuels. FAME blends can be used with most existing marine engines, bunkering infrastructure and fueling systems, with only minor modifications. FAME has a relatively high energy density (as compared to other alternative fuels), is higher cetane than diesel, and has a higher flashpoint than petroleum diesel, with a lower flammability and explosion risk. It may also improve lubricity, reducing engine wear. FAME is nontoxic to humans and wildlife, and spills degrade two to four times faster than petroleum diesel. On a life cycle

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[435] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[436] https://doi.org/10.1016/j.rser.2022.113127
[437]https://cms.zerocarbonshipping.com/media/uploads/documents/Using-bio-diesel-onboard-vessels_v6_2023-06-19-113010_zomk.pdf
[438] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[439] https://doi.org/10.1021/acs.est.3c00388
[440] https://farmdocdaily.illinois.edu/2023/02/biodiesel-and-renewable-diesel-whats-the-difference.html
[441] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[442] https://doi.org/10.1016/j.pecs.2022.101055

(WtW) basis, FAME (produced from second generation feedstocks) generally reduces GHG, SO_x, and $PM_{2.5}$ emissions[443,444,445]

Disadvantages of FAME include a slightly lower energy content (about 7%) per volume compared to petroleum diesel fuels, leading to higher fuel consumption. FAME's higher oxygen content limits storage time (≦ 2 months) due to corrosion effects. FAME is corrosive with fuel systems using certain metals (copper, bronze, zinc, tin, and brass), but most marine shipping engines and fuel systems are constructed from aluminum and stainless steel, which are compatible with FAME. FAME may also degrade rubber and plastic parts, and otherwise damage engine components, reducing engine performance. FAME increases the susceptibility of microbial growth and fouling, which can lead to corrosion of fuel tanks, and clogged fuel lines and injectors. FAME's cloud point, the temperature where waxes in the fuel begin to solidify, is higher than that of petroleum diesel (e.g. -3 to 15°C, vs. -8.9°C). Temperatures below the cloud point can lead to gelling, where the fuel solidifies and no longer flows freely through fuel lines, filters may become clogged, and mechanical failures may result.[446] FAME is also less stable as a fuel, and may form emulsions with water, or deposits and sludge. For the most part, technical disadvantages of FAME can be largely addressed through relatively simple modifications to fueling systems and components, and/or through the use of fuel testing and additives (the cloud point and cold filter plugging point [CFPP] of FAME, for instance, may be lowered through crystallization filtering technique and/or adding a cold flow improver).[447] As described later in this section, FAME blends have been used successfully in many trials and voyages, where minor modifications have been employed.

In addition to technical challenges, FAME is more expensive than its petroleum counterparts, while supply of second-generation feedstocks required for FAME production is limited.[448,449,450,451]

HVO (Hydrotreated Vegetable Oil)

HVO, also called renewable diesel or green diesel, is produced through catalytic hydrodeoxygenation of vegetable oils or animal fats, including waste fats, oils and greases (FOGs) such as used cooking oil (UCO). HVO has characteristics similar to diesel, and can be used as a drop-in fuel in marine engines as an MGO replacement with little or no modifications to engines or systems. HVO has an energy density competitive with HFO and MGO (and relatively high as compared to other biofuels),[452] a high cetane number

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[443] https://farmdocdaily.illinois.edu/2023/02/biodiesel-and-renewable-diesel-whats-the-difference.html
[444] https://doi.org/10.1016/j.martra.2021.100033
[445] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[446] https://doi.org/10.1016/j.martra.2021.100033
[447] https://doi.org/10.1016/j.martra.2021.100033
[448] https://farmdocdaily.illinois.edu/2023/02/biodiesel-and-renewable-diesel-whats-the-difference.html
[449] https://doi.org/10.1016/j.martra.2021.100033
[450] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[451] https://link.springer.com/article/10.1007/s10098-023-02501-7
[452] https://www.sciencedirect.com/science/article/pii/S2666822X21000241?via%3Dihub

(80-99) and high flashpoint. It performs well in cold temperatures, exhibits reduced abrasiveness and low tendency for deposits, is nontoxic and stable, and can be stored for long periods.[453,454,455]

Like FAME, HVO is unlikely to result in meaningful GHG reductions when produced using first-generation feedstocks from food crops (HVO has been primarily produced from palm oil in the past), yet when produced from UCO, HVO is estimated to reduce life cycle GHGs by more than 80% compared to conventional marine fuels.[456,457,458]

Challenges with use of HVO as a marine fuel include limited availability of, and growth potential for, second-generation feedstocks (e.g. waste FOGs such as UCO): Total HVO production was only 6.6 to 7.7 Mt in 2020, compared to projected global fuel consumption in the marine sector of 330 Mt annually.[459] The estimated global potential for known HVO feedstocks would produce ~440 petajoules per year of fuel, approximately 4.9% of the marine sector's current energy demand of ~9 EJ (2050 projected consumption of 15.8 EJ).[460] Competition from other transportation sectors (road and aviation) is also an issue for HVO fuel. HVO is a higher quality biofuel, and closer in price to the conventional petroleum fuels in these sectors. HVO is also relatively expensive, at around 1.5x to 2.4x the cost of fossil marine fuels.[461,462,463]

Fischer-Tropsch (FT) Diesel

FT-Diesel is a well-established technology when produced from coal and natural gas, though this approach does not reduce GHG emissions compared to conventional marine fuels. FT-Diesel can be produced through a less mature technology, Biomass-to-Liquid (BtL), using widely available feedstocks such as municipal and agricultural waste products and landfill gas. Production of FT-Diesel as a biofuel involves gasification followed by FT-synthesis, which can produce a range of fuel products tailored to the end use. The end product for the marine sector is a drop-in fuel with a high cetane number and characteristics very similar to diesel, requiring little-to-no engine or fuel system modifications.

FT-Diesel can be used as a neat fuel (100%), or blended with existing fuels with no restrictions. FT-Diesel produced from wastes can produce very low to even net-negative

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[453] https://doi.org/10.1016/j.martra.2021.100033
[454] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[455] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[456] https://doi.org/10.1016/j.martra.2021.100033
[457] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[458] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[459] https://www.maritime.dot.gov/sites/marad.dot.gov/files/2020-10/TroyatArgonnejournalarticle.pdf
[460] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[461] https://doi.org/10.1016/j.martra.2021.100033
[462] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[463] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf

GHG emissions on a life cycle (WtW) basis, when accounting for co-products of the FT-process, and/or compared to the GHG production of these wastes otherwise.[464,465,466,467]

The technology to produce FT-Diesel from biomass is still at a relatively early stage of development, and costs are high (~1.5x to 4x the cost of conventional fossil marine fuels).[468][469] Yet in comparison to other low- or zero-GHG marine fuel alternatives, FT-Diesel's higher fuel costs may be offset by the drop-in nature of the fuel, and avoiding costs of retrofits or engine upgrades or replacement. FT-biofuels are not expected to be viable for the marine sector in the near term due to costs and stage of technological maturity, but are expected to have long-term potential.

DME (Dimethyl Ether)

DME, like FT-Diesel, can be produced from fossil fuels, though DME produced from fossil fuels is not expected to reduce GHG emissions. DME (bio-DME) may also be produced through gasification of a wide range of biomass feedstocks, including lignocellulosic feedstocks such as forest residues. Bio-DME can be produced directly, through catalytic dehydration of methanol, or indirectly through methanol synthesis (following gasification), followed by dehydration. DME has a high cetane number and relatively clean combustion (with low levels of PM, NO_x, and CO emitted). Bio-DME has been estimated to reduce life cycle GHGs by over 90% compared to petroleum marine fuels (i.e. Zhou et al. 2021 estimated 1.1 to 7.7 gCO2e/MJ, using GREET),[470] though research in this area is limited.

Disadvantages of DME include a relatively low energy content, low viscosity and lubricity, and a low flash point. DME is a gas at room temperature, but can be liquefied by pressurizing above 5 bar (75 psi). As DME behaves similarly to propane (LPG), it is expected that LPG distribution and infrastructure can be used.[471][472] Pressurized tanks are required for DME storage.[473] DME is more compatible with conventional marine engines than other alternatives (e.g. methanol), and can be used in a variety of engine types. It can be blended with MGO or MDO at up to 20-30% (v/v) with minor engine modifications (with larger amounts requiring dedicated engines and additional fuel tanks and systems), and can be used as a drop-in fuel with LPG dual fuel engines, in theory up to 100%.[474] As with FAME, limits on DME blends will likewise reduce achievable GHG and other emissions reductions. When used neat, use of DME as a marine fuel would require a dedicated

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[464] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[465] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[466] https://doi.org/10.1016/j.pecs.2022.101055
[467] https://doi.org/10.1021/acs.est.3c00388
[468] https://www.energy.gov/sites/default/files/2023-05/beto-18-project-peer-review-sdi-est-apr-2023-kass.pdf
[469] https://theicct.org/publication/the-potential-of-liquid-biofuels-in-reducing-ship-emissions/
[470] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[471] https://doi.org/10.1016/j.isci.2020.101758
[472] https://doi.org/10.1016/j.jpowsour.2005.05.082
[473] https://afdc.energy.gov/fuels/emerging_dme.html
[474] https://www.emsa.europa.eu/newsroom/latest-news/item/4834-update-on-potential-of-biofuels-for-shipping.html

engine. Though it has been tested on smaller marine engines, understanding of DME's compatibility with large marine engines is still in early stages.[475,476,477]

Though bio-DME shows promise in several respects, production and use is currently in relatively early stages of development compared to other biofuels (e.g. FAME, HVO, FT-Diesel), and far from commercialization, while its future technological readiness is uncertain, and DME engines are not available on the market for the maritime sector.[478,479] Production of bio-DME is extremely limited globally (and unknown/nonexistent in the United States).[480] Meanwhile, in contrast to other biofuels and low-GHG alternatives, there are few indications that DME is being seriously considered by stakeholders for maritime use (as confirmed by experts in a 2023 report to the IMO).[481] Therefore, in this report we present information for bio-DME to the extent it is relevant and available, but focus more on biofuel alternatives where technological development, production, and/or industry interest and potential demand are more certain.

Bio-Oils (Pyrolysis Oil and HTL Biocrude):

Bio-oils are produced by thermochemical conversion of biomass to liquid fuels, most commonly through pyrolysis or HTL. Bio-oils may be produced through various second-generation (or advanced) feedstocks, including woody biomass, manure, and sludge, and the resulting fuels are appropriate as a replacement for HFO in low-speed engines. Pyrolysis oil is a more established technology, while HTL biocrude is a higher quality fuel.

Bio-oils, particularly when produced through pyrolysis, contain higher levels of oxygen and acids, and require upgrading and treatment before being viable as drop-in fuels. The corrosiveness of pyrolysis bio-oils is of particular concern.[482] Biocrude can be used in existing engines in small amounts as a drop-in fuel. Exact properties and composition of bio-oils vary depending on feedstock and process, and the extent to which the fuel has been upgraded, and are difficult to generalize. Bio-oils tend to be highly acidic, have a high oxygen content, and are relatively unstable. Pyrolysis oil tends to have a lower energy content and higher moisture content than HTL biocrude. Bio-oils also tend to be prone to engine deposits and carbon residues.[483,484,485,486]

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[475] https://pubs.acs.org/doi/10.1021/acsomega.1c03885
[476] https://www.ieabioenergy.com/wp-content/uploads/2018/02/Marine-biofuel-report-final-Oct-2017.pdf
[477] https://www.e3s-conferences.org/articles/e3sconf/pdf/2019/42/e3sconf_asee18_00048.pdf
[478] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[479] https://www.sciencedirect.com/science/article/pii/S0360128522000624
[480] https://www.ieabioenergy.com/installations/#
[481] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[482] https://www.energy.gov/sites/default/files/2023-05/beto-18-project-peer-review-sdi-est-apr-2023-kass.pdf
[483] https://doi.org/10.1016/j.rser.2022.113127
[484] https://doi.org/10.1016/j.martra.2021.100033
[485] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[486] https://doi.org/10.1016/j.pecs.2022.101055

Transforming bio-oils into usable fuel first requires upgrading: initial processes such as filtration, emulsification, or addition of solvents reduce ash content and viscosity while improving the ability for bio-oils to be blended with conventional fuels.[487] Additional upgrading may be done through chemical or catalytic processes, including hydro-deoxygenation (HDO) and catalytic cracking. Upgrading produces a higher-quality fuel, one showing promise as a future drop-in fuel for marine shipping. However, upgrading also increases energy use, costs, and life cycle GHG emissions. HDO requires the use of hydrogen, which increases costs and emissions, while catalytic cracking produces lower yields, and produces bio-oils with a lower energy content.[488,489,490,491]

Potential availability and cost of feedstocks are relative advantages of bio-oils compared to other biofuels. Advanced feedstocks for bio-oils are not nearly as limited as are second-generation feedstocks for FAME and HVO, for instance. Bio-oils from waste feedstocks are also expected to be relatively less expensive as compared to other biofuels, and may be obtained at zero or even negative cost. Bio-oils and biocrude are at a relatively early stage of technological development, and commercial production is not expected in the near-term, but show promise as a zero-carbon (or even net-negative) carbon fuel for the marine sector in the future, as a long-term option.[492,493,494,495]

Engine and Fuel System Parameters

Much of their promise for use as a marine fuel in the short-term, lies in their ability to drop-in, reducing the risk of stranded assets.[496] Biofuel blends have been demonstrated and used in marine shipping somewhat extensively, with only minor modifications to systems necessary.

FAME blends (B20-B30,[497,498,499] B50,[500] and even B100[501]) have been used in a series of successful trials in the marine shipping sector. It is expected that FAME blends of up to B20 or B30 will require no modifications of marine engines or fuel systems, and trials have indicated that higher blend ratios of FAME may be used with no major modifications to

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[487] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[488] https://doi.org/10.1016/j.rser.2022.113127
[489] https://doi.org/10.1016/j.martra.2021.100033
[490] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[491] https://doi.org/10.1016/j.pecs.2022.101055
[492] https://www.energy.gov/sites/default/files/2023-05/beto-18-project-peer-review-sdi-est-apr-2023-kass.pdf
[493] https://doi.org/10.1021/acs.est.3c00388
[494] https://onlinelibrary.wiley.com/doi/pdf/10.1002/bbb.2350
[495] https://cms.zerocarbonshipping.com/media/uploads/documents/Using-bio-diesel-onboard-vessels_v6_2023-06-19-113010_zomk.pdf
[496] https://doi.org/10.1016/j.martra.2021.100033
[497] https://vesselperformance.info/2023/02/21/one-announces-successful-completion-of-biofuel-trial/
[498] https://www.oocl.com/eng/pressandmedia/pressreleases/2022/Pages/28Sep2022.aspx
[499] https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-and-maersk-tankers-carry-out-successful-marine-biofuel-trials.html
[500] https://pubs.rsc.org/en/content/articlehtml/2022/se/d1se01495a
[501] https://www.fuelsandlubes.com/flo-article/csl-completes-worlds-longest-running-trial-of-b100-biodiesel/

equipment necessary. A trial using B100 in main and auxiliary engines, with over 30,000 hours of operating time, reported successful results using FAME from second-generation feedstocks (waste plant material) with no major modifications to existing systems.[502]

In practice, it is expected that due to some of its challenging properties (cold flow, etc.), use of high blends of FAME would require minor fuel system modifications, cleaning and maintenance, and minor engine modernization, including hoses, filters and seals, and fuel filtration and treatment.[503] Another challenge of FAME, its relatively short shelf life and tendency to degrade more quickly than conventional fuel, is not expected to be a problem for shorter routes, or if a ship using FAME were able to reach the next bunkering location in less than eight weeks, especially if fuel is stored in a suitable temperature range (between 14°C and 43°C) or stability additives are used.[504]

HVO and FT-Diesel are compatible with marine engines and fueling systems, and can be used neat (100%) with no issues expected.[505,506,507]

DME is compatible with existing engines and fuel systems as a blend. As noted earlier, with similar properties and characteristics to LPG, it is expected that DME can be used in LPG distribution and infrastructure. DME is more compatible with marine engines than other alternatives (e.g. methanol), and can be used in a variety of engine types; it can be blended with MGO or MDO at up to 20-30% (v/v) with minor engine modifications, and as a drop-in fuel with LPG engines in limited amounts (up to 30%--additional amounts would require testing, as well as additional storage tanks and fuel supply systems).[508]

DME has been tested in up to a 40% blend on a 4-stroke marine engine,[509] but use as a neat fuel would require retrofits or a dedicated engine. Though DME-dedicated engines for the marine sector are unavailable on the market,[510] Zhou et al. (2021) note that MAN has developed a liquid-gas-injection (ME-LGI) concept, available as a new engine or retrofit for slow speed engines; it was developed for use with LPG and methanol, though other low-flashpoint fuels such as DME and ethanol can be used.[511,512] As noted earlier, the technological readiness of bio-DME as a marine fuel, particularly for larger,

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[502] https://www.fuelsandlubes.com/flo-article/csl-completes-worlds-longest-running-trial-of-b100-biodiesel/
[503] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[504] https://doi.org/10.1016/j.martra.2021.100033
[505] https://doi.org/10.1016/j.martra.2021.100033
[506] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[507] https://www.cell.com/iscience/pdf/S2589-0042(20)30955-X.pdf
[508] https://www.emsa.europa.eu/newsroom/latest-news/item/4834-update-on-potential-of-biofuels-for-shipping.html
[509] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[510] https://doi.org/10.1016/j.pecs.2022.101055
[511] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[512] https://www.man-es.com/docs/default-source/document-sync/b-w-me-lgi-engines-liquid-gas-injection-methanol-and-lpg c58e7846d76a4eac98b1b6b9bd843dc1.pdf?sfvrsn=a4e4362b_0

slow-speed engines, is uncertain, and stakeholder interest in DME as a marine fuel is lacking.[513]

Bio-oils (pyrolysis oil and HTL biocrude) may be used as drop-in fuels in smaller amounts, for use in large, slow-speed engines, as a replacement for HFO,[514] with upgraded HTL-biocrude being more compatible than pyrolysis oil. When used as a blend with HFO, corrosion from HTL-biocrude is not an issue.[515] As discussed above, bio-oils are still in relatively early stages of technological development. Research is being conducted to understand and address quality concerns that may cause compatibility issues with existing engines and systems (e.g. corrosion, stability), and to refine the upgrading process to minimize these.[516]

As noted by Foretich et al (2021), in the short-term, fuel stability issues may be less of a concern for large deep-sea ships, as they often have more fuel tanks with the ability to isolate unstable fuels; larger deep-sea ships may also be equipped with fuel purification systems, and they may have more resources to devote to necessary fuel stability additives. Bio-oils are seen as holding promise to achieve meaningful GHG reductions in the marine shipping sector in the long-term, but additional R&D is required before these fuels may be used in significant amounts.

Life Cycle WtW GHG and Criteria

Estimated life cycle (WtW) GHG emissions of biofuels vary widely (Table 12), and depend not only upon fuel type (e.g. FAME vs. HVO vs. Bio-oils), but also upon feedstock and process used, and assumptions regarding transportation of feedstocks and fuels, co-products generated, and whether CCUS is used. The expected quantity of GHG emissions that would have resulted during the business-as-usual management of the feedstock is another factor which may significantly influence WtW GHG estimates.

Conventional management of sewage sludge and landfill gas, for instance, are GHG-intensive. One study estimated that HTL conversion of sewage sludge to marine biofuel produced one-third the GHG emissions expected from conventional management.[517] Yet another factor is the extent to which a fuel has been treated or upgraded to improve compatibility with marine engines[518,519] (in Table 12, GHG estimates for biocrude are provided for fully upgraded fuels).

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[513] https://fft.wpdev.ws/wp-content/uploads/2023/04/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[514] https://doi.org/10.1016/j.martra.2021.100033
[515] https://www.energy.gov/sites/default/files/2023-05/beto-18-project-peer-review-sdi-est-apr-2023-kass.pdf
[516] https://www.energy.gov/sites/default/files/2023-05/beto-18-project-peer-review-sdi-est-apr-2023-kass.pdf
[517] https://doi.org/10.1016/j.rser.2022.113127
[518] https://doi.org/10.1021/acs.est.3c00388
[519] https://www.energy.gov/sites/default/files/2023-05/beto-18-project-peer-review-sdi-est-apr-2023-kass.pdf

Table 12

Life Cycle Emissions for Low-GHG Marine Biofuel Pathways (kg/MJ)

Fuel Type (Pathway/ Feedstock)	GHGs		Criteria Pollutant Emissions					
	(kgCO2e/MJ)		NO_x (kg/MJ)		SO_x (kg/MJ)		$PM_{2.5}$ (kg/MJ)	
	WtW	TtW	WtW	TtW	WtW	TtW	WtW	TtW
Conventional Fuels								
HFO	0.095 - 0.097	0.082	0.00034	0.00031	0.00006-0.0014	0.00005 - 0.0013	0.00007-0.00016	0.00006-0.00016
MDO	0.092 - 0.094	0.079	0.00034	0.00031	0.00006-0.00093	0.00005 - 0.00092	0.00002-0.00009	0.00002-0.00008
MGO	0.089 - 0.090	0.075	0.00033	0.00030	0.00001 - 0.00047	0.00046 - 0.00046	0.00002-0.00005	0.00002-0.00005
FT-Diesel (NG)	0.088	0.073	0.00033	0.00030	0.00002	NC	0.00002	0.00002
LNG*	0.094	0.074	0.00025	0.00023	0.00001	NC	0.00001	0.00001
Low-GHG Biofuels								
Bio-Oil (Woody Biomass, Pyrolysis)	0.001 - 0.020	0.100	0.00032-0.00139	0.00030	0.00002-0.00008	NC	0.00001-0.00002	0.00002
FT-Diesel (Biomass)	0.003 - 0.007	0.073	0.00032	0.00030	0.00001	NC	0.00002	0.00002
HVO (UCO)	0.016	0.074	0.00031	0.00030	0.00001	NC	0.00002	0.00002
FAME/ Biodiesel (Range)	0.032 (0.014 - 0.100)	0.077	0.00033	0.00030	0.00002	NC	0.00002	0.00002
DME* (biomass)	0.0011-0.0077	0.068	na	na	na	NC	na	na
Zero-GHG Biofuels (Future/Long-Term Pathways)								
Biocrude HTL (Manure, Full Upgrade)	-0.046	na	0.00130	0.0012	0.00009	NC	0.00001	NC
Biocrude HTL (Sludge, Full Upgrade)	-0.003	na	0.00124	0.0012	0.00003	NC	NC	NC
FT-Diesel (Landfill Gas)	-0.022	na	0.00121	0.0012	0.00003	NC	NC	NC

* Note that including methane slip can significantly increase WTW emissions from LNG
na = not available or specified; NC= negligible concentration /
Sources: Tan et al. 2021[520],[521] and Masum et al. 2023[522] (GREET), Lagouvardou et al 2023,[523] Zhou et al. 2021,[524] Aakko-Saska et al. 2023,[525] Kass et al. 2023,[526] Carr et al. 2022[527]

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[520] https://pubs.acs.org/doi/10.1021/acs.est.0c06141
[521] https://pubs.acs.org/doi/suppl/10.1021/acs.est.0c06141/suppl_file/es0c06141_si_001.pdf
[522] https://doi.org/10.1021/acs.est.3c00388
[523] https://www.nature.com/articles/s41560-023-01334-4
[524] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[525] https://doi.org/10.1016/j.pecs.2022.101055
[526] https://www.energy.gov/sites/default/files/2023-05/beto-18-project-peer-review-sdi-est-apr-2023-kass.pdf
[527] https://oceanconservancy.org/wp-content/uploads/2023/03/Approaches-Decarbonizing-US-Fleet.pdf

Biofuels' GHG emissions reductions in marine shipping vary due to multiple factors, making precise estimations challenging. Biofuels certification systems (such as ISCC[528]) allow for the measurement and verification of GHG emissions reductions for biofuels used in marine shipping, and ensuring traceability, and verification of other sustainable and socially responsible management practices in fuel production.[529,530]

Emissions of Criteria Pollutants from Biofuels

Table 12 presents estimates of TtW and WtW emissions, by fuel type, recognizing that the literature has shown discrepancy with regards to expected effects of biofuels on emissions of criteria pollutants. These estimates are specific to fuel type and blend, engine type and conditions, conventional fuel displaced, and are dependent on study assumptions and limitations. Literature on emissions specific to biofuels used as marine fuel is limited. Existing studies tend to use life cycle analysis, lab tests, or focus on smaller, medium-speed, 4-stroke marine engines, while the vast majority of marine fuel consumption and GHG emissions are produced by vessels with large 2-stroke engines.[531]

Below we provide an overview of general findings regarding effects of biofuels on criteria pollutants (SO_x, NO_x and PM) from lab tests and on-board measurements, while estimates from life cycle analyses are shown in Table 12. Table 13, in the following section, shows results of a study conducting on-board measurements of biofuel use on a bulk-carrier with a large 2-stroke engine.

SO_x Emissions

Biofuels are generally sulfur-free fuels, so exhaust (TtW) SO_x emissions are reduced drastically, if not entirely eliminated for practical purposes, with use of most biofuels. The low sulfur emissions measured in on-board testing result from conventional fuel used as a pilot fuel, or lubricating oil.[532] Most biofuels will not be used neat, however, due to availability and technical constraints, and rather will be used as blends. SO_x emissions reductions are a function of the relative content of biofuel in the blend (i.e. B30 = ~30% reduction in SO_x; B50 = ~50% reduction). FAME, HVO, FT-Diesel, and DME (from bio-feedstocks) are all expected to reduce SO_x by practically 100%.[533,534]

NO_x Emissions

Studies have estimated that FAME biodiesel may increase or decrease NO_x emissions, depending on baseline fuel comparison and engine type and load, etc. In general, use of FAME leads to NO_x emissions increasing slightly at lower loads, and decreasing slightly at

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[528] International Sustainability and Carbon Certification
[529] https://www.dnv.com/services/iscc-sustainable-bio-energy-and-product-certification-3820
[530] https://www.iscc-system.org/markets/sustainable-marine-fuels/
[531] https://doi.org/10.1039/D1SE01495A
[532] https://doi.org/10.1016/j.pecs.2022.101055
[533] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[534] https://doi.org/10.1016/j.pecs.2022.101055

higher loads.[535,536,537,538] However, Lloyd's Register Maritime Performance Services conducted sea trials for FAME blends from B20-100, in both two- and four-stroke marine engines at varying engine loads, ultimately concluding that FAME blends do not significantly increase NO_x compared to conventional fuels. Although specific NO_x measurements may have tested higher under certain conditions, overall, they remained within the margins of trial consistency and the variations were insignificant. Upon contacting other engine manufacturers and industry stakeholders, each reported that their independent testing corroborated these findings.[539]

Paraffinic fuels such as HVO and FT-Diesel have generally been shown to reduce NO_x emissions, with on-board measurements showing decreased NO_x (1-13%) with a 50% HVO blend when compared to ultra-low sulfur diesel (ULSD). Lab testing has estimated a 0-20% decrease in NO_x emissions with HVO compared to MGO, and 3-20% reductions with FT-Diesel.[540] Results for bio-oils (pyrolysis oil) have shown both increases and decreases in NO_x emissions, with increases at higher loads.[541] Lab-testing of DME in a 4-stroke engine (20-40% blend) found a 20-26% increase in $NO_{x,}$ as compared to HFO. Literature on DME use as a marine fuel is limited.

PM Emissions

FAME biodiesel tends to reduce PM emissions (38-90%) compared to conventional marine fuels, depending on reference fuel. One study found lower PM emissions at high load (25% increase with 50:50 blend), with increased PM at lower loads.[542543] Research is limited on emissions of HVO and FT-Diesel compared to distillate fuels. HVO effects on PM emissions range from a 38% decrease (on-board testing vs. ULSD) to a 30% increase (lab testing vs. MGO); FT-Diesel effects range from a 16% decrease to a 18% increase in lab testing vs. MGO (and 24% decrease in the life cycle analysis model (LCA)). In lab testing in a 4-stroke engine (at 20-40% blend), DME was shown to reduce PM by 23% to 58% compared to HFO.[544,545]

Exhaust (TtW) Emissions- Large, Slow-Speed, Two-Stroke Engine

Many estimates of effects on emissions of biofuels used in marine shipping have focused on smaller, 4-stroke engines, and/or have used lab-testing or LCA approaches. Stathatou et al. (2022) measured emissions from a dry-bulk vessel (the *Kira Oldendorff*)[546] powered

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[535] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[536] https://www.mdpi.com/1996-1073/16/12/4647
[537] https://doi.org/10.1016/j.pecs.2022.101055
[538] https://doi.org/10.1039/D1SE01495A
[539] https://www.lr.org/en/knowledge/research-reports/nox-from-marine-diesel-engines-using-biofuels/
[540] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[541] https://doi.org/10.1016/j.pecs.2022.101055
[542] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[543] https://doi.org/10.1016/j.pecs.2022.101055
[544] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[545] https://doi.org/10.1016/j.pecs.2022.101055
[546] 81,280 DWT capacity, 9,932 kW engine–MAN B&W 6560ME-C8.5

with a 50:50 blend of MGO and biodiesel produced from UCO, under several load conditions (see Table 13), and compared to similar conditions with the vessel powered solely with low-sulfur MGO (LSMGO).[547] Exhaust emissions of NO_x and CO_2 were measured on-board, SO_2 emissions were estimated based on fuel sulfur content;[548] WtW emissions were calculated based on prior studies estimating life cycle emissions.[549]

CO_2 emissions in operation at low loads were slightly higher for the biofuel blend (0.4% and 5% higher for 1st two slow-speed operating modes), and slightly lower at higher loads, with an overall reduction in CO_2 exhaust emissions of 1.2%. Similarly, NO_x emissions were higher in the first two (lower-load) operating modes for the biofuel blend (10% and 2% increase) as compared to LSMGO, and lower in the three higher-load modes, with an overall weighted NO_x reduction of 3%. Emissions at all loads met Tier II NO_x limits.[550] SO_2 emissions were estimated to decrease by 50%, as would be expected with the fuel sulfur content and estimation method. Life cycle (WtW) CO_2 emissions were estimated to be reduced by 40% with the 50:50 biofuel blend. A subsequent study (Chountalas et al. 2023), examining the effects of using B30 on a bulk carrier, found that NO_x emissions increased slightly–7% compared to MGO, and 3.5% compared to HFO–but remained compliant with legislation.[551]

Table 13

Comparison of Exhaust (TtW) emissions from 50:50 biodiesel/MGO blend and LSMGO, on bulk carrier *Kira Oldendorff* with large slow-speed, two-stroke engine

		CO_2 TtW [g/kWh]		NO_x TtW [g/kWh]		SO_2 TtW [g/kWh]	
Mode and Description	**Engine Load**	**B50**	**LSMGO**	**B50**	**LSMGO**	**B50**	**LSMGO**
1. Dead Slow Ahead	20-23%	427.9 ± 33.2	426.5 ± 24.8	11.1 ± 0.3	10.1 ± 0.3	0.14 ± 0.05	0.27 ± 0.03
2. Slow ahead	32-37%	535.9 ± 22.1	511.9 ± 18.9	12.6 ± 0.3	12.3 ± 0.3	0.20 ± 0.08	0.32 ± 0.04
3. Half ahead	41-44%	548.7 ± 21.7	558.8 ± 19.7	13.2 ± 0.3	13.9 ± 0.4	0.18 ± 0.07	0.35 ± 0.04
4. Full ahead	61-67%	589.5 ± 19.6	599.5 ± 20.2	12.5 ± 0.3	12.6 ± 0.31	0.19 ± 0.07	0.37 ± 0.04
5. Full ahead	90%	604.5 ± 18.1	610.7 ± 18.9	9.9 ± 0.3	11.5 ± 0.3	0.20 ± 0.07	0.38 ± 0.04
Weighted emission factors	All modes	5.71 ± 0.12	5.78 ± 0.12	12.23 ± 0.19	12.62 ± 0.19	0.19 ± 0.04	0.36 ± 0.02

Sources: Stathatou et al. 2022[552]; Stathatou pers. comm. (2023)

Previous studies have found similar results when comparing biodiesels to conventional marine fuels (i.e. NO_x emissions either increase or decrease slightly, and differ according to load). These studies, however, have tended to focus on vessels with medium-speed, 4-stroke diesel engines with much lower power ratings (~400kW or less). Stathatou et al. (2022) were the first to study emissions on a vessel with a large slow-speed, 2-stroke

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[547] LSMGO = Low-sulfur marine gas oil, maximum sulfur content of 0.1%

[548] as per ISO 1878

[549] https://doi.org/10.1039/D1SE01495A

[550] The Kira Oldendorff's design and performance met IMO Tier II regulations.

[551] https://doi.org/10.1016/j.energy.2023.127845

[552] https://doi.org/10.1039/D1SE01495A

main engine (9,932 kW); as the authors note, bulk carriers represent a large share of global shipping energy consumption and CO_2 emissions, making up 21% of the global merchant fleet, and accounting for ~47% of shipping CO_2 emissions.[553]

Bunkering and Existing Infrastructure

Biofuel Bunkering and Infrastructure

One of the primary advantages of biofuels in the marine sector is their ability to be used, in the near-term, as drop-in fuels, and used with existing engines and systems with little-to-no modifications needed. Likewise, biofuels can also be blended with conventional marine fuels (MDO/MGO/HFO depending on biofuel), and can use existing infrastructure for fuel storage and bunkering.[554] It is expected that bio-DME, given its similar properties to LPG, could utilize existing LPG infrastructure.

Biodiesel (FAME) is currently the most common biofuel used in marine shipping, and viability of bunkering has been established in practice. Numerous successful trials and pilot projects of biofuels bunkering and use have been conducted,[555] including a recent trial with FAME produced from UCO, a second-generation feedstock.[556] In Port of Singapore and Port of Rotterdam (the world's two largest ports) alone, 0.93 million tonnes of blended biofuels were bunkered in 2022—an estimated 0.28 million tonnes of pure biofuel, equivalent to ~0.1% of total marine shipping sector fuel consumption. Over 90 biofuel bunkering operations, more than those for LNG, took place at Port of Singapore in 2022, where biofuel blended with VLSFO was delivered via bunker barges for the first time as well.[557]

Costs (CAPEX and OPEX)

CAPEX = capital expenditure, OPEX = operating expenditures

As biofuels are drop-in fuels, and can be used with existing engines, fuel systems and infrastructure without requiring major modifications, capital costs are minimal. Additional costs associated may include bunkering costs due to lower energy content of biofuels, fuel testing, and cleaning, maintenance, monitoring of fuel and systems. These costs are also expected to be relatively minor.[558] Fuel costs for biofuels, however, may come at a premium compared to conventional fuels.

Anticipated fuel costs for biofuels vary widely (Table 14), and involve uncertainty. Estimated fuel costs vary by fuel type, feedstock, production process used, and

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[553] https://doi.org/10.1039/D1SE01495A
[554] https://greenvoyage2050.imo.org/wp-content/uploads/2023/08/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[555] https://eto.dnv.com/maritime/publications/biofuels-in-shipping-white-paper-download.html
[556] https://www.reuters.com/business/sustainable-business/decarbonisation-centre-finishes-two-trials-biofuel-bunkering-2023-02-21
[557] https://greenvoyage2050.imo.org/wp-content/uploads/2023/08/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf
[558] https://www.emsa.europa.eu/newsroom/latest-news/item/4834-update-on-potential-of-biofuels-for-shipping.html

assumptions regarding a number of variables including feedstock prices, size and technological maturity of production facilities, transportation costs, and energy costs, among others.

Feedstock prices—which in many cases are uncertain, and dependent on a number of factors—can have a significant impact on biofuel prices. Mukherjee et al. (2023),[559,560] for instance, estimated the cost of production of bio-DME. Conducting a sensitivity analysis assuming a range of woody biomass feedstock prices (~$43 to ~$189/ton), resulting bio-DME production prices could vary by up to ~$0.02/MJ depending on plant maturity and production process. In the case of sludge and manure (used as feedstocks in HTL biocrude), costs may be negative, as tens of millions of tons of these feedstocks currently impose costs in business-as-usual practices in the form of management, disposal and tipping fees. These feedstocks, therefore, may be obtained by biofuel producers at a negative cost, as this may alleviate the expenses incurred under conventional management practices.[561] (The lower range of estimated HTL biocrude prices in Table 14 assume negative feedstock prices; the higher assume zero-cost feedstock).

The technological maturity of the production plant (i.e. whether a “pioneer” or first-of-its-kind plant, or an “nth”—plant, where the technology is well-established) also influences cost estimates.[562][563] Mukherjee et al. (2023)[564] estimated a difference in cost of $0.005 to $0.022/MJ to produce bio-DME in a pioneer plant vs. a mature plant, depending on production process. Assumed CAPEX of the plant also influenced estimated production costs by ~$0.022/MJ, or even ~$0.043/MJ for a pioneer plant. Interest rates influenced the estimated production price of bio-DME by $0.005 to $0.032/MJ.[565]

Another factor affecting biofuel price estimates is the consideration of co-product credits; the production of FT-Diesel from landfill gas, for instance, produces co-products of hydrogen and wax, while production of FP (fast pyrolysis) bio-oil may produce acetone and methyl-ethyl-ketone; the sale of co-products on the market may reduce the minimum viable selling price for biofuels.[566] The degree to which the fuel has been processed or upgraded influences production price; higher end fuel price estimates for HTL biocrude, Table 14 assume fully upgraded fuel, and non-negative (zero) feedstock costs.[567]

Biofuel prices are influenced not only by production costs but also by market dynamics such as feedstock prices, supply and demand, and the cost of alternative or substitute

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[559] 1 EUR = 1.08 USD
[560] https://doi.org/10.1016/j.rser.2022.113127
[561] https://doi.org/10.1021/acs.est.2c03960
[562] https://doi.org/10.1016/j.rser.2022.113127
[563] https://doi.org/10.1021/acs.est.2c03960
[564] 1 EUR = 1.08 USD
[565] https://doi.org/10.1016/j.rser.2022.113127
[566] https://doi.org/10.1021/acs.est.2c03960
[567] https://doi.org/10.1021/acs.est.2c03960

fuels. The primary driver for the price of biodiesel (FAME) and HVO in recent years, for instance, has been the price of petroleum diesel.[568]

Finally, as estimated GHG reductions from biofuels vary significantly by fuel and process, certification or guarantee-of-origin (such as ISCC)[569] is another anticipated cost associated with the use of biofuels. It has recently been estimated at $0.03/MWh for biofuels.[570,571]

Table 14

Biofuel Price Estimates in $/MJ and $/MT(HFOE)

	$/MJ		$/MT (HFOE)	
Fuel	**Low**	**High**	**Low**	**High**
VLSFO	0.011	0.014	450	570
MGO	0.021	0.023	890	990
FT-Diesel (Landfill Gas)*	0.025*		1,020*	
FT-Diesel (Biomass)	0.024	0.066	980	2,700
FT-Diesel (Advanced feedstocks)	0.038	0.105	1,020	4,300
FAME/Biodiesel (UCO)	0.020	0.035	820	1,430
FAME/Biodiesel	0.026	0.049	1,090	2,000
Bio-DME[572]	0.016	0.049	650	2,000
HVO (Vegetable Oil, Waste FOGs)	0.024	0.061	980	2,500
Bio-Oil, FP (Woody Biomass)*	0.016*		650*	
Bio-Oil, CFP (Woody Biomass)	0.023	0.027	940	1,100
Biocrude, HTL (Sludge)	0.003	0.018	100	740
Biocrude, HTL (Manure)	0.006	0.017	240	700

CFP= Catalytic Fast Pyrolysis, FP= Fast Pyrolysis, HTL= Hydrothermal Liquefaction. HFOE=Heavy Fuel Oil Equivalent

* Note that the lack of range in estimates (single-point estimate) presented for FT-Diesel (Landfill Gas) and Bio-Oil, FP (Woody Biomass) does not indicate a lack of uncertainty in price/cost estimates for these fuels, but rather the point estimates were the only ones identified in this review.

Sources: Derived from estimates in Tan et al. 2021,[573] Li et al. 2022,[574] Lagouvardou et al. 2023,[575] Zhou et al. 2021,[576] Korberg et al. 2021,[577] Kass et al. 2023,[578] Mukherjee et al. 2023,[579] and Carr et al. 2022[580]

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[568] https://afdc.energy.gov/fuels/prices.html
[569] https://www.iscc-system.org/markets/sustainable-marine-fuels/
[570] https://doi.org/10.1016/j.rser.2022.113127
[571] 1 EUR = 1.08 USD
[572] 1 EUR = 1.08 USD
[573] https://pubs.acs.org/doi/10.1021/acs.est.0c06141
[574] https://pubs.acs.org/doi/10.1021/acs.est.2c03960
[575] https://doi.org/10.1038/s41560-023-01334-4
[576] https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf
[577] https://doi.org/10.1016/j.rser.2021.110861
[578] https://www.energy.gov/sites/default/files/2023-05/beto-18-project-peer-review-sdi-est-apr-2023-kass.pdf
[579] https://doi.org/10.1016/j.rser.2022.113127
[580] https://oceanconservancy.org/wp-content/uploads/2023/03/Approaches-Decarbonizing-US-Fleet.pdf

Fuel Availability and Projections: Biofuels

As established infrastructure and systems are available for biofuel blending and bunkering, technical and logistical barriers to biofuels use as a marine fuel (downstream of production) are limited. According to stakeholders in the shipping sector, the need for establishing supply chains or adapting fuel systems for biofuels is of little concern.[581]

Rather, limitations for use of low- or zero-GHG biofuel in shipping are anticipated to lie in availability of fuels and advanced feedstocks. The marine shipping sector consumes approximately 280 Mtoe (million tons of oil equivalent) annually[582]—or 9 EJ in 2022 (projected to reach 10.5 EJ in 2030, and 13 EJ by 2040).[583] In contrast, the global capacity for production of sustainable biofuels is estimated at ~11 Mtoe currently, with planned projects indicating production will reach 23 Mtoe by 2026.[584]

This means total global expected sustainable and low-GHG biofuels production (e.g. using second-generation feedstocks) will reach only 4-8% of marine sector fuel consumption in the near future —before accounting for the demand and consumption of biofuels from all other sectors, including road and aviation.[585]

As we explore the viability of biofuels, it's crucial to consider the challenges of sustainable biofuel supply. Despite technical readiness, there are growing concerns regarding the availability and integrity of biofuel sources. With global production of low- and zero-GHG biofuels lagging behind the projected demand, supply limitations loom and are exacerbated by issues such as fraud. In Europe, fraudulent schemes are surfacing that involve mislabeling cheaper traditional biofuels as more expensive varieties made from waste. These revelations underscore weaknesses in EU regulations and the challenges of effectively tracking these supplies.[586,587] The U.S. and other nations must also address their policies and supply certifications to prevent fraud and ensure the sustainability of biofuel trade, aligned with climate goals.

Sustainable biofuel production is increasing significantly, but scaling up is necessary for biofuels to contribute meaningfully to shipping decarbonization, as noted in a recent DNV report. DNV estimates the total, economical and sustainable potential of global biofuel production could be 400 - 600 Mtoe in 2030, and 500-1,300 Mtoe by 2050; they note that 250 Mtoe of sustainable biofuels would be necessary if shipping were to decarbonize primarily through biofuels,[588] while recognizing that there is significant demand for biofuels from other sectors as well.

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[581] https://www.ieabioenergyreview.org/transport-biofuels/

[582] https://eto.dnv.com/maritime/publications/biofuels-in-shipping-white-paper-download.html

[583] https://greenvoyage2050.imo.org/wp-content/uploads/2023/08/Readiness-of-Low-Zero-Carbon-Marine-Fuels-Technology-Full-Report-v1.pdf

[584] https://eto.dnv.com/maritime/publications/biofuels-in-shipping-white-paper-download.html

[585] https://www.lr.org/en/knowledge/research-reports/zero-carbon-fuel-monitor-oct-2023/

[586] https://www.occrp.org/en/investigations/how-biofuels-scams-have-undermined-a-flagship-eu-climate-policy

[587] https://www.euractiv.com/section/agriculture-food/opinion/new-data-shows-commission-maladministration-is-an-open-door-to-palm-oil-fraud/

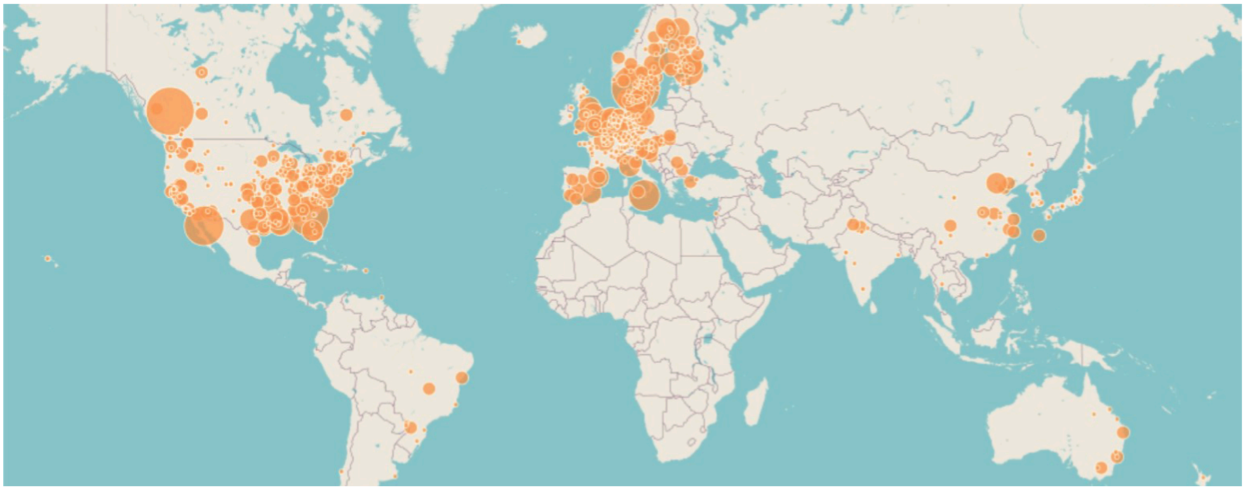
[588] https://eto.dnv.com/maritime/publications/biofuels-in-shipping-white-paper-download.html

Though currently the majority of biofuels are produced from first-generation feedstocks, many projects are in development (i.e. plans to be operational in the near future) which plan to use advanced feedstocks such as forestry residues. Current global biofuel production capacity from advanced feedstocks was recently estimated at 5.1 Mt/year, which if all were directed to marine shipping would provide only 1.5% of shipping fuel needs.[589]

Global biofuel demand reached 4.3 EJ in 2022, with approximately 9% produced from second-generation feedstocks such as waste and residues (in 2021),[590] or roughly 0.39 EJ produced from advanced feedstocks. In the past several years, facilities producing advanced biofuels have increased in both number and size; commercial-scale facilities are planned (i.e. plans to be operational by 2026) or have become operational, particularly in Europe (Figure 15) and the United States (Figure 16).[591,592]

Figure 15

Existing and planned advanced biofuel production facilities



Map of existing and planned biofuel production facilities that use second generation feedstocks. Source: DNV[593]

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[589] https://www.ieabioenergy.com/wp-content/uploads/2021/11/Progress-towards-biofuels-for-marine-shippingT39-report_June-2021_Final.pdf
[590] https://www.iea.org/energy-system/low-emission-fuels/biofuels#tracking
[591] https://www.ieabioenergy.com/installations/
[592] https://eto.dnv.com/maritime/publications/biofuels-in-shipping-white-paper-download.html
[593] https://eto.dnv.com/maritime/publications/biofuels-in-shipping-white-paper-download.html

As of 2023, the United States had capacity to produce 6.9 Mt[594] of biodiesel/FAME,[595] and ~8.9 Mt of renewable diesel/HVO.[596,597] The United States produced 5.4 Mt of biodiesel and 4.4 Mt of renewable diesel (HVO) in 2022, with 0.08 billion gallons of "other" biofuels produced.[598,599] The U.S. consumed 5.5 Mt of biodiesel, and 5 Mt of HVO in 2022,[600] slightly more of these biofuels than it produced. A relatively small share of biofuels in the U.S. are currently produced from advanced feedstocks.[601]

California consumed approximately 3 billion gallons of gasoline equivalent (GGE) of biofuel fuel in 2022, including ~3.8 Mt of renewable diesel (HVO) and ~0.99 Mt biodiesel (FAME).[602] An increasing share of California's renewable diesel is being produced from second-generation feedstocks such as waste FOGs. In 2022, 1.6 billion gallons of wastes and residues such as UCO, tallow (animal fat) and distiller's corn oil (an agricultural byproduct) were used in the production of California's renewable diesel and biodiesel.[603]

In 2022 California produced less than 15% of the biofuel it consumed, by volume. The total volume of biofuels produced in California has increased from ~122 million GGE in 2010 to ~525 million GGE in 2022 (including 80 million gallons of biodiesel [~0.27 Mt tonnes], and 259 million gallons [~0.76 Mt] of HVO/renewable diesel).[604,605] Of the renewable diesel produced in California, only a small share is derived from residues vs. crop feedstocks.[606] Several plants to produce biofuels including HVO in the United States and California are planned or in-progress, such as the *Aemetis Carbon Zero 1* project in Riverbank California, that when operational (est. 2025) is expected to produce 90 million gallons per year of renewable diesel, jet fuel, and byproducts, using agricultural residues (such as waste wood from local orchards) as feedstocks.[607] Yet increased production of biofuels in California may not equate to increased availability of fuels for the marine shipping sector. Substantial demand and consumption of biofuels already exists (and is expected to increase) in other sectors such as road transportation and aviation.

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[594] Megatonnes (or million tonnes)

[595] EIA provided fuel quantity estimates in gallons, which were converted here to million tonnes based on ~300 gallons biodiesel per metric tonne, and 338 gallons HVO per metric tonne.

[596] https://www.eia.gov/biofuels/renewable/capacity/

[597] https://www.eia.gov/biofuels/biodiesel/capacity/

[598] Excluding ethanol

[599] https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T10.04A#/?f=A&start=2001&end=2022&charted=5-20-21

[600] https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T10.04B#/?f=M

[601] https://www.eia.gov/biofuels/update/

[602] CARB provided fuel quantity estimates in GGE (gallon of gasoline equivalent), which were converted to million metric tonnes (MMT) here.

[603] https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard

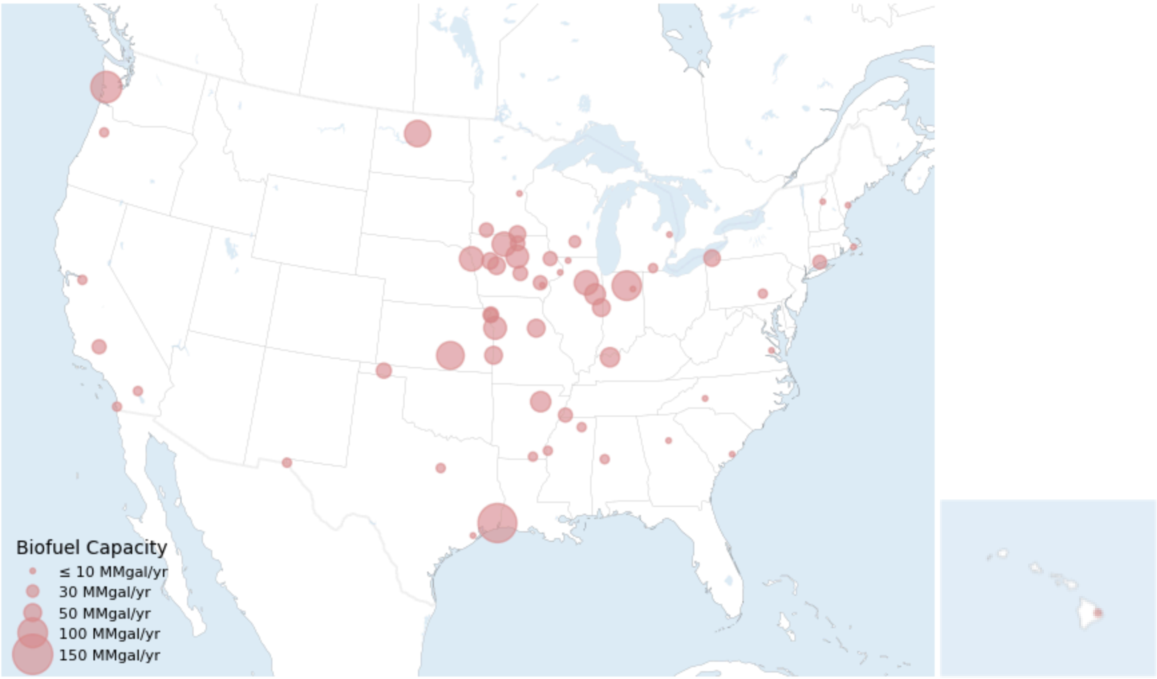
[604] https://www.eia.gov/biofuels/renewable/capacity/

[605] https://www.eia.gov/biofuels/biodiesel/capacity/

[606] https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard

[607] https://www.ieabioenergy.com/installations/

Figure 16
Biodiesel plants and capacity in the U.S.



Map of biodiesel production facilities in the U.S.. Marker size corresponds to production capacity in millions of gallons per year (MMgal/year). Source: EIA.[608]

IEA estimated global biofuel demand to increase by 6% (or 9,100 million liters) in 2022 compared to 2021, and estimated total global demand in 2022 at 170 billion liters. [609][610] The U.S. accounted for the largest share of estimated growth in demand (3,124 million liters), with the majority of projected growth in renewable diesel (2,831 million liters, or 90.6% of U.S. demand).

Under IEA's main case scenario, U.S. biofuel consumption rises to 70.6 billion liters per year in 2027, driven by demand for renewable diesel, biojet fuel, and policies like the Inflation Reduction Act, Renewable Fuel Standard, and state-level low-GHG fuel standards.

IEA projects total biofuel demand to reach 192 billion liters in 2027 under their main case (240 billion liters under the accelerated case). The United States, Canada, Brazil, Indonesia, and India make up 80% of the projected global expansion in biofuels demand, and IEA projects that state-level policies will lead to biofuels' share in transport fuel consumption rising from 4.3% in 2022 to 5.4% in 2027.

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[608] https://atlas.eia.gov/datasets/eia::biodiesel-plants-1/about
[609] https://www.iea.org/reports/renewables-2022/transport-biofuels
[610] https://www.iea.org/energy-system/low-emission-fuels/biofuels

Despite this significant growth in biofuel production and demand, total global projected biofuel energy production/demand in 2027 is around 7.1 EJ to 8.9 EJ,[611,612] or 68 - 85% of projected marine energy demand in 2030 (10.5 EJ). Around 10% of global biofuels are produced from second-generation feedstocks, therefore the data indicate that all projected low-GHG biofuel production could theoretically meet around 7 to 8.5% of global maritime fuel demand in 2030. However, the marine sector faces stiff competition from other transport sectors for fuel, and is unlikely to be able to command all available biofuel, meaning the share of second-generation biofuels in the marine sector will likely remain low until availability scales significantly.

As with other alternative fuels in the marine sector, the potential for significant GHG reductions from biofuels is dependent not only on the quantity of biofuel produced and consumed, but the relative GHG intensity of the biofuel. As discussed earlier, the estimated GHG-intensity of biofuels varies considerably by fuel type, feedstock, production process, and other key factors. This points to the importance of understanding the GHG-intensity of biofuels in context, on a fuel-specific basis, and in measuring and accounting for this with certifications and/or guarantee-of-origin, to ensure that the use of biofuels is achieving the intended objective of reducing GHG emissions from shipping.

Section 7: Supplemental Power Systems

Advancements in ship propulsion technology can contribute to emissions reduction in maritime transportation. Various zero-GHG technologies are under development and there are examples of zero-GHG ships operating commercially, including RoPax ferries up to 11,000 GT, tugs up to 70 BP, a bunker ship and a container ship. Although efforts are underway for establishing standards for absolute zero GHG technologies, the development of absolute zero-GHG maritime supply chains is in early stages.[613]

Supplemental power systems, which can include wind, solar, and battery, could play an important role in enhancing energy efficiency, reducing ship GHG emissions, and decreasing operational and maintenance costs of OGVs. These technologies are typically integrated alongside traditional fossil-fuel burning engines, but could also supplement alternative fuel systems.

Large sails, wings, and rotors, for example, can be used to harness wind energy to assist in propulsion. Solar cell and photovoltaic (PV) technologies can be incorporated to supplement energy systems, and batteries can be used to store energy. Combining wind, solar, and battery technologies holds promise for improving efficiency and reducing carbon emissions from OGVs.

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[611] Assuming biofuel energy density of 37 MJ/L
[612] https://www.iea.org/reports/renewables-2023/transport-biofuels
[613] https://zestas.org/wp-content/uploads/2024/01/MEPC-81-INF.5-ZESTAs.pdf

A benefit unique for supplemental power systems, in contrast to alternative fuels, is their constant weight so that the vessel will not need to take on water ballast, as traditional ICE ships must to offset fuel consumption. The practice of water ballast weighting has introduced invasive species in foreign ecosystems, an issue discussed by IMO in its MEPC 80 updates. IMO considers ballast water to be a substantial pathway for nonindigenous marine species with potentially serious ecological, economic, and health issues from an array of microscopic bacteria, viruses, eggs, and more. Consequential events of invasion are occurring across the globe; The ongoing issue is anticipated to have devastating consequences due to the alarming rate of invasion, largely due to growing trade volumes.[614] Thus, supplemental power systems offer a dual-benefit by not only reducing GHGs and climate warming, but also due to the reduced volumes of ballast water transported to foreign ecosystems.

With the evolution of IMO GHG emissions targets,[615] supplemental fuel systems may become more attractive, especially as costs for solar, wind, and battery technology decrease as technology advances over time. Supplemental power systems may also prove beneficial for reducing emissions from near-port operations.

While there have been demonstrations of small to medium-sized ships that use wind, solar, or battery as their sole propulsion system, the widespread application of these technologies to large OGVs has yet to be seen. This is partially because the full energy demand of these large vessels can not be met by solely relying on the currently available wind, solar, or battery systems. However, wind, solar, and battery have been used to supplement traditional propulsion systems, reducing fuel consumption and the resulting emissions of combustion.

There are few full-scale demonstrations of battery propulsion of large OGVs, and even fewer for wind and solar propulsion systems. The following sections provide an overview of ongoing efforts to incorporate wind, solar, and battery propulsion systems into commercial shipping, with discussions of the feasibility and economics of such efforts.

Wind

Wind-assisted propulsion can help reduce carbon intensity of OGVs by harnessing power from winds to supplement ship momentum. Additional benefits can include increased range, reduced noise, lowered risk of fuel supply chain disruptions, and lower operating and maintenance costs due to lower fuel consumption and stress on the engine. There are several different types of wind-assisted propulsion, but among the most tested are wing sail, kite sail and Flettner Rotor.

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[614] https://www.imo.org/en/ourwork/environment/pages/ballastwatermanagement.aspx
[615] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

The efficiency of wind-assisted propulsion hinges on a variety of physical and technological factors, including design, wind speed and direction, wave resistance, and shipping route.[616] The application of wind-assisted ship propulsion in a modern commercial maritime setting is still in early stages, but has been growing (Figure 17).

Figure 17

Number of ships with wind propulsion systems

* Indicates planned installment. Source: European Maritime Safety Agency[617]

There are a few full scale demonstrations of wind power across wing sail, kite, and Flettner rotor categories, including BAR Technologies WingWings on *Pyxis Ocean,* SkySails on *MS Beluga SkySails*, and Flettner rotors on *E-Ship 1*, described in detail in sections below. Other ongoing demonstrations include Michelin's WISAMO wing sail, Airsea's Seawing kite sail, and vessels equipped with Flettner rotors, such as *MS Viking Grace*, *Maersk Pelican*, and *MV Afros*.

Wing Sail

The wing sail concept emerged following increasing oil prices in the 1980s, which resulted in a federal government-commissioned study of using wind-assisted propulsion as a means of reducing the operating costs of ships in the U.S. merchant marines.[618] The preferred wing sail system consisted of solid sails that automatically adapted to changes in wind direction. This rigid wing sail system underwent testing on a small vessel, and it was estimated to yield fuel savings in the range of 15%-25%. Ultimately, this specific

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[616] https://doi.org/10.1109/OCEANSChennai45887.2022.9775386
[617] https://www.emsa.europa.eu/publications/reports/item/5078-potential-of-wind-assisted-propulsion-for-shipping.html
[618] https://hdl.handle.net/2027%2Fmdp.39015000478001

design did not achieve widespread adoption, possibly due subsequent declines in oil prices resulting in a lack of interest in further wing sail development.[619]

Since then, there have been many efforts to improve upon the wing sail concept. Some emerging technologies have potential applications for container ships, such as Michelin's WISAMO and BAR Technologies' WingWings. Other developing wing sails include Advanced Wing Systems' wing sails and Ayro's Oceanwings. Estimates of potential fuel savings for wing sails in this category vary widely, with a general range of 2-30%.[620,621,622]

Figure 18

Pyxis Ocean sails its maiden voyage with WindWings

The bulk grain carrier, *Pyxis Ocean*, sails her maiden voyage equipped with WindWings. Photo BAR Technologies.

In August 2023, the first cargo ship retrofitted with wing sails made its maiden voyage.[623] *Pyxis Ocean*, chartered by Cargill, is retrofitted with two rigid wings called WindWings, engineered by BAR Technologies (Figure 18). BAR Technologies estimates WindWings could reduce a ship's lifetime carbon emissions by 30% depending on whether the installation is a retrofit or part of a new build.[624] Cargill has estimated that WindWings can save about 1.5 tonnes of fuel per WindWing per day on an average global route.[625]
The large (~125 feet, or 11.5 stories) wings are fitted to the deck of bulk cargo ships. The number of wings varies, contingent on a variety of factors, including vessel size and route.

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[619] https://www.bunkerist.com/en/sail-assisted-propulsion/
[620] https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=2e08a7250c8d8485eb07f6c9a55677cae47d117c
[621] https://doi.org/10.1016/j.oceaneng.2023.115349
[622] https://www.tandfonline.com/doi/full/10.1080/23311916.2018.1543564
[623] https://www.popsci.com/technology/cargo-ship-wind-wings/
[624] https://www.bartechnologies.uk/project/windwings/
[625] https://www.cargill.com/2023/cargill-bar-technologies-wind-technology-sets-sail

BAR Technologies has reported signing two contracts to integrate WindWings on new vessel builds.

Michelin is testing an inflatable wing sail system called WISAMO (Wing Sail Mobility). The system is outfitted with an inflatable fabric envelope and an extendable mast, designed for mobility around harbors and bridges, operated with an automated control system.[626] WISAMO, which is marketed as a tool to help decarbonize maritime transport, can be retrofitted to existing vessels or included in new builds.

The latest tested WISAMO prototype, which covers approximately 100 m^2 (1,076 ft^2), was installed on Compagnie Maritime Nantaise's roll-on/roll-off (RO-RO) ship, *MN Pelican*, in June 2023. The wing is fully automated and adjusts to wind and storm conditions. The 100 m^2 prototype marks a step towards Michelin's envisioned full-scale wing sail, which is expected to have a span of 800 m^2. According to Michelin, WISAMO is estimated to reduce fuel consumption by up to 20%, and is suitable for use across maritime shipping routes. Michelin anticipates further testing before going into production.[627]

Kite Sail

Kite sails have a history of being used as a means of wind-assisted propulsion for various types of vehicles, including small boats, buggies, and in watersports. The kite sail operates by attaching it to the bow of a ship and adjusting its angle based on wind speed and direction and ship speed. This adjustment generates lift and drag to propel the vessel forward.

Modern kite systems aboard ships are automated to respond to these variables to maximize propulsion. Kite sails are nimble systems which can be retrofitted to almost any vessel, and are most effective on slower-speed ships when wind speeds greatly exceed ship speed.[628] The sails typically include automated launch and recovery systems to manage the use of the sail,[629,630] which makes them relatively easy to deploy.

The effectiveness of a kite sail, like other wind-assisted propulsion technologies, is largely contingent upon wind conditions. A commonly used metric to measure the efficiency of kite sail propulsion is the reduction in fuel usage.[631,632,633] A modeling study found that a 320 m^2 kite on a 50,000 DWT tanker yields dramatically different fuel savings depending on wind conditions. Fuel savings were estimated at about 10% for a wind velocity of

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[626] https://wisamo.michelin.com

[627] https://www.autoevolution.com/news/michelin-is-testing-its-groundbreaking-sailing-wing-on-a-commercial-ship-218545.html

[628] https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/ogv_tech_report.pdf?_ga=2.150505470.974679874.1607353296-2132954763.1524507134

[629] https://www.cargo-partner.com/trendletter/issue-10/sails-and-kites-support-cargo-ships

[630] https://skysails-yacht.com

[631] https://newatlas.com/marine/airseas-seawing-cargo-ship-kite/

[632] https://www.springwise.com/innovation/mobility-transport/fuel-saving-auto-kite/

[633] https://skysails-marine.com

around 9.8 m/s (19 kts, or Beaufort Level 5) and about 50% for a wind velocity of around 15.7 m/s (30.5 kts, of Beaufort Level 7), not accounting for sea state.[634] Several empirical studies have been conducted to measure fuel savings of emerging products such as SkySails and Seawing, elaborated on below.

The *MS Beluga SkySails* (shown in Figure 19) was the first ship partially powered by a computer-controlled kite sail in 2007.[635] An EU study found that the 160 m^2 kite sail reduced fuel use by 5% on average, which equates to about 165 tonnes/year of fuel (530 tonnes CO_2/year). Fuel savings were higher on North Atlantic and North Pacific routes (10%-12%) and could be scaled with a larger sail in the future (~600m^2).[636]

Figure 19

Kite sail providing supplemental power to the *MV Beluga Skysails*

The *MV Beluga Skysails*, a heavy lift cargo carrier, operating with kite sail. Photo: Captain John Konrad, NOAA Mariners Weather Log.[637]

A similar kite system, the Airseas Seawing, combines deck, flight, and bridge equipment with eco-routing software and a digital twin model of the wing to automate the operation of their 1,000 m^2 sail.[638] Airseas has tested the Seawing on commercial voyages across the Atlantic Ocean, and plans to open a production factory in 2026 with a target delivery date of 2031.[639] The Seawing is estimated to reduce fuel consumption by 20% on average. The serviceable obtainable market includes 8,500 vessels, according to Airseas.[640]

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[634] https://doi.org/10.1016/j.renene.2015.08.036
[635] http://news.bbc.co.uk/2/hi/europe/7201887.stm
[636] https://webgate.ec.europa.eu/life/publicWebsite/project/details/2650
[637] https://www.vos.noaa.gov/MWL/apr_09/skysails.shtml
[638] https://airseas.com/en/seawing-system/
[639] https://airseas.com/en/new-technical-milestone-seawing-kite-tows-ships/
[640] https://cinea.ec.europa.eu/system/files/2021-11/7%20-%20SEAWING-%20ECOMONDO%20-%20AIRSEAS%20Pitch.pdf

Flettner Rotor

Flettner rotors are vertical-standing cylinders on the deck of a ship that harness wind power to develop lift due to the Magnus Effect.[641] The Magnus effect, often observed in sports like baseball and soccer, is a phenomenon where a spinning object moves through an airstream, causing sideways force on the object.[642] Flettner rotors use the Magnus effect to help drive a ship forward as the wind blows across them. A main advantage of using Flettner rotors over kite and sail systems is the ability to harness wind energy regardless of wind direction. A drawback is that the tall rotors can present challenges when navigating under bridges and around other overhead obstacles.

Figure 20

Flettner rotors installed on the *Buckau* and *E-Ship 1*

First Flettner rotor ship, Buckau, 1925 (left) compared to the modern Flettner rotor ship, E-Ship 1 (right). E-Ship 1 photo: Alan Jamieson

The Flettner rotor was developed in the early 1900s and the first rotor ship to use Flettner rotors, *Buckau*, (Figure 20) sailed across the Atlantic in 1925.[643] Despite the early success of Flettner rotors on *Buckau*, significant interest in Flettner rotor technology was not seen until the early 2000s, coinciding with growing concerns about climate change and energy conservation.

The increasing interest in fuel efficiency led to the development of *E-Ship 1* (Figure 20), a roll-on lift-off (RO-LO) cargo ship designed by Enercon, a wind energy company based in Germany.[644] *E-Ship 1* is 130 m long, and the four 27-meter-tall Flettner rotors assist the two diesel engines in propelling the ship to speeds up to 17.5 knots.

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[641] https://glomeep.imo.org/technology/flettner-rotors/
[642] https://www.seattleu.edu/scieng/physics/physics-demos/thermodynamics/magnus-effect/
[643] https://books.google.com/books?id=W99NAAAAMAAJ
[644] https://www.imcbrokers.com/the-e-ship-1-a-flettner-ship/

According to Enercon, *E-Ship 1* experiences up to 25% fuel savings, with over 15% attributable to the Flettner rotors.[645] Other technologies, like a streamlined propeller and helm, also help reduce overall fuel consumption. *E-Ship 1* made its first commercial operation in 2010 and has since been used to transport Enercon's wind turbine components.[646]

Wind Assist: Economic and Feasibility Overview

With advancements in engineering and design, wind propulsion systems could offer a compelling pathway to harnessing renewable energy sources to drive efficiency and environmental stewardship in the maritime sector. Although wind-powered sailing has a history spanning thousands of years,[647] it is still in development phases within the realm of modern-day commercial shipping.

The motivations for developing wind propulsion technology have evolved, with current efforts being driven by objectives to reduce GHG emissions and achieve fuel savings. *The 2023 IMO Strategy on Reduction of GHG Emissions from Ships* has an ambition of reducing carbon intensity of international shipping by at least 40% by 2030 respective to 2008,[648] and wind propulsion could become an important factor in meeting these reductions.

Large commercial ships can be good candidates for wind systems due to their ample deck space and voyages on open seas routes with high wind speeds. However, these ships have higher fuel consumption than smaller ships, which may cause lower relative economic savings at the current cost of wind technology. The relative fuel savings required to break even could reduce over time as wind technology becomes cheaper.[649]

Actual fuel savings estimates vary depending on experiment setup, technology, crew training, sailing conditions, and many other factors. It is also difficult to estimate fuel savings for ships sailing unknown routes ("tramp trades"),[650] which can be common for some OGVs. As a result, fuel savings estimates for commercial ships vary considerably across empirical and theoretical studies, but have been recorded within the general ranges as follows:

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[645] https://wind-works.org/wp-content/uploads/2023/03/PM_E-Ship1_Ergebnisse_DBU_en.pdf

[646] https://www.stg-online.org/onTEAM/shipefficiency/programm/06-STG_Ship_Efficiency_2013_100913_Paper.pdf

[647] https://www.lifeofsailing.com/post/sailing-history

[648] https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

[649] https://emsa.europa.eu/publications/item/5078-potential-of-wind-assisted-propulsion-for-shipping.html

[650] https://www.marineinsight.com/maritime-law/what-are-liner-services-and-tramp-shipping/

- Wing sails - 2%-30% average fuel savings on a per-voyage basis, with several modeling studies estimating fuel savings of less than 10%[651,652,653,654,655]
- Kite sails - up to 32% fuel savings,[656] with trial estimates at around 16%[657]
- Flettner rotors - 3%-35% average fuel savings on a per voyage basis,[658,659,660,] with a case study estimating about 22%[661]

As technology improves, wind-assisted propulsion technologies may observe greater fuel reductions, especially when combined with other technologies that maximize fuel efficiency.

From an economic perspective, fuel savings will also be subject to fluctuations based on variability in fuel prices, changes in environmental policy, and other external factors.[662,663] Upfront cost estimates of developing wing sail, kite sail, and Flettner rotor technologies are limited due to the proprietary nature of the technology, and installation on relatively few vessels. However, one can use the early estimated costs of SkySails as a point of reference, with a price range spanning from $540,000 to $2.7 million,[664] and an estimated $1 million price for a 320 m^2 kite.[665,666] At a fuel consumption rate of 275 tonnes/day (68,750/year, assuming 250 days at sea), and a fuel price of $616/MT, the SkySail could pay for itself by offsetting around 1.3-6.4% of fuel consumption over a single year (2.6% for the $1 million, 320 m^2 sail). The scaling of SkySails projects could cause reductions to price, but more recent price estimates are not available.

In addition to complying with emissions regulations, ship owners may be incentivized to invest in wind-assisted propulsion to reduce operational costs. Operational cost savings are maximized at optimal wind and sailing conditions, which often occur at low speeds when wind speed is much greater than vessel speed. In contrast, fast-moving ships derive less advantage of wind assistance, resulting in diminished reductions in operational costs and carbon emissions.[667,668]

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[651] https://iopscience.iop.org/article/10.1088/1757-899X/788/1/012062/meta
[652] https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=2e08a7250c8d8485eb07f6c9a55677cae47d117c
[653] https://jurnalmekanikal.utm.my/index.php/jurnalmekanikal/article/view/440
[654] https://wisamo.michelin.com
[655] https://robbreport.com/motors/marine/cargo-ship-pyxis-ocean-1234886926/
[656] https://doi.org/10.17818/NM/2021/2.6
[657] https://maritime-executive.com/article/seawing-kite-completes-validation-testing-demonstrating-fuel-savings
[658] https://doi.org/10.1016/j.oceaneng.2018.02.020
[659] https://maritime-executive.com/article/flettner-rotor-trial-delivers-real-world-fuel-savings
[660] https://www.evwind.es/2013/07/30/enercon-rotor-sail-ship-e-ship-1-saves-up-to-25-fuel/34733
[661] https://doi.org/10.1007/s11356-021-12791-3
[662] https://doi.org/10.1016/j.oceaneng.2018.02.020
[663] https://doi.org/10.3390/su13041880
[664]https://www.mundomaritimo.net/noticias/high-tech-sail-may-cut-cargo-ship-costs
[665] 1 EUR = 1.08 USD
[666] https://webgate.ec.europa.eu/life/publicWebsite/project/details/2650
[667] https://doi.org/10.1016/0167-6105(85)90023-6
[668] https://doi.org/10.1016/j.trd.2020.102380

Solar

Solar power is gaining popularity as a clean energy source with applications in various sectors, including residential energy systems, transportation, and electricity generation. The maritime industry is beginning to explore using solar power to provide power to ship operations. Full reliance on solar PV power for large OGVs is not currently considered feasible using current technology and foreseeable advancements. However, solar PV can be used for auxiliary and supplemental power with the inclusion of an electric motor.

There are two broad approaches for utilizing solar energy on ships: passive and active systems. Passive systems are engineered to directly use solar heat or light. Active systems convert solar energy into a usable form such as electricity, which can then supplement propulsion or be used for other purposes like electrical systems. Passive systems can be beneficial for reducing energy use aboard ships by harnessing natural heating and lighting.

PV systems, which convert solar energy into electricity, are the most commonly used systems on solar-enabled ships. Generating sufficient electricity from solar panels requires a substantial area for installation. Ships with ample non-cargo deck space can more easily accommodate solar panels, making them good candidates for solar power integration.[669] However, retrofitting solar panels on other ships may present difficulties due to the spatial requirements for installation.

Additionally, the panels must be carefully designed to take advantage of solar energy while being resistant to the factors at sea, such as adverse weather conditions and salt spray. When panels are receiving little sunlight at night or during periods of inclement weather, ships need to make use of traditional engines and battery storage for power.

Available Technologies

Innovations in solar-powered shipping have taken place throughout the 2000s, beginning in 2007, when the first solar-powered ship to cross the Atlantic, *Sun 21*, completed its voyage from Chipiona, Spain to New York City, U.S.[670] The voyage took 52 days at a speed of 5-6 knots, powered entirely by solar energy.

The *Sun 21* catamaran is relatively small (14m long)[671] compared to a typical ocean-going cargo vessel (hundreds of meters long),[672] and therefore requires a relatively modest amount of energy to propel the vessel. A typical cargo vessel could not reasonably receive enough energy to operate using a similar solar power retrofit. Nevertheless, the

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[669] https://glomeep.imo.org/technology/solar-panels/
[670] https://newatlas.com/worlds-first-solar-powered-transatlantic-crossing-a-complete-success/7262/
[671] http://www.transatlantic21.org/boat/
[672] https://www.marineinsight.com/types-of-ships/the-ultimate-guide-to-ship-sizes/

transatlantic voyage marked the beginning of a potential movement towards fuel and emissions reductions through the usage of solar energy in commercial shipping.

In 2008, the world's first solar-assisted cargo ship, vehicle carrier *Auriga Leader*, set out on its maiden voyage.[673] *Auriga Leader*, approximately 200m long and 60,213 GT, was developed by Nippon Yusen Kaisha and Nippon Oil Corporation in 2008 as an experimental vessel to determine how solar power could be used to power ships at sea.[674] Over seven months of the two-year experiment (2,600 hours of operation), the solar panel system produced 32,300 kWh of electricity, which contributed 0.05% of the propulsion power and 1% of the electricity used for other operations. These fuel savings equate to around 13 tons/year. At a fuel price of 550 USD/ton, it would take over 190 years to pay off the reported $1.37 million investment cost[675] of the solar installation. The fuel savings experienced by the *Auriga* Leader (Figure 21) were considerably lower than the much smaller, solar-powered *Sun 21*, which demonstrates the challenge of scaling up solar energy to power large OGVs.

Figure 21

Solar panels installed on the *Auriga Leader*

Auriga Leader sails, assisted by solar power, in 2008.

The power generated at sea was 1.4 times the amount that was generated on land in Tokyo, where the developers are headquartered. The solar power system was also reported to operate well despite adverse weather and sailing conditions, such as storms and large waves.[676]

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[673] https://www.eneos.co.jp/english/newsrelease/noc/2009/pdf/090902.pdf
[674] https://shipnext.com/vessel/9402718-auriga-leader
[675] https://www.engadget.com/2008-08-28-japanese-firms-to-partially-propel-cargo-ship-via-solar-panels.html
[676] https://www.eneos.co.jp/english/newsrelease/noc/2009/pdf/090902.pdf

The widespread adoption of solar-assisted technology in shipping has not yet been seen. However, recent projects signal the prospect of growing adoption of solar energy systems by OGVs. These projects include Eco Marine Power's EnergySails, which combine rigid wing sails with solar panels to supplement ship propulsion and electricity demands;[677] the testing of solar panels on Berge Bulk's Berge K2 carrier;[678] and the development of an electric cruise ship equipped with solar sails, planned to launch in 2030.[679]

Economic and Feasibility Overview

Guidance for the materials, electronics, and placement of solar PV systems are recommended to tolerate extreme winds, humidity, salt, and other harsh conditions and environmental factors at sea. The European Committee for Electrotechnical Standardization has developed an ingression protection rating, for which marine PV systems must meet a minimum rating to reduce harm of short-circuits and corrosion to the mechanical parts of the converters. Furthermore, all metal surfaces of the system must be galvanized or covered by special anti rust coatings. Fixing points shall meet quality standards for metal grading. The installation of these systems should not impede cargo or human transfer, cover places of financial impact, and should be stored away from areas of high activity to prevent electrical shock or physical damage.[680] To the best of the authors' knowledge, there are no international or U.S. regulations or guidelines explicit to marine solar systems. Regulation for PV systems at sea will be interconnected with those of marine battery systems, due to the energy storage needs of solar power.

A 2021 study evaluated the performance of a theoretical solar PV system for a 208-meter-long RO-RO ship and estimated its performance with respect to energy efficiency and criteria pollutant and greenhouse gas emissions. The study was performed based on routes between Pendik, Turkey and Trieste, Italy.

The solar PV system was estimated to supply 334,063 kWh/year to the main AC grid (assuming 7.76% energy efficiency) and 7.38% of the fuel requirement of the vessel. The fuel savings resulted in a decrease in CO_2 emissions by 232.4 tons, NO_x emissions by 3.9 tons, and SO_x emissions by 0.3 tons. Based on an assumed unit value of 4.5 \$/watt,[681] the investment cost of the solar system was estimated to be approximately \$192,000, with a simple payback period of ~7 years (~11 years with discounted payback period).[682]

The second IMO GHG study evaluated the performance of a theoretical 270-meter-long tanker outfitted with solar panels. Energy conversion efficiencies were estimated at 13% for average 2009 solar-cell technology, 30% for best 2009 solar-cell technology, and 60%

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[677] https://www.ecomarinepower.com/en/energysail
[678] https://www.bergebulk.com/berge-bulk-begins-solar-power-pilot/
[679] https://www.hurtigruten.com/destinations/norway/the-original-norwegian-coastal-express/sea-zero/
[680] https://doi.org/10.1155/2013/831560
[681] https://doi.org/10.1109/PVSC.2011.6186448
[682] https://doi.org/10.1016/j.solener.2020.07.037

for future (post-2009) solar-cell technology. The nominal power produced by the 13%, 30%, and 60% energy efficiency panels were estimated at about 600 kW, 1,400 kW, and 2,800 kW of energy respectively.[683]

Both studies signify that only a fraction of the power needs of OGVs can feasibly come from solar PV, even with the latest technology and a large quantity of solar panels. Additionally, solar panels can be ineffective when adequate sunlight is unavailable, underlying the importance of combining different supplemental power systems (e.g. wind, solar) in addition to battery storage systems to maximize fuel efficiency.

Electrification

The process of electrifying a fleet involves two main components: providing shore power infrastructure while the vessels are berthed and installing electric propulsion systems and batteries on the vessels themselves.

Shore Power

Shore power, sometimes referred to as cold ironing or alternative maritime power (AMP), allows ships to "plug-in" to shoreside electrical systems while at berth. Shore power allows vessels to turn off auxiliary diesel engines at berth, which significantly lower vessel emissions while at berth, but shifts emissions to the local grid.

There are currently 10 U.S. ports serving cruise, container, and refrigerated vessels with shore power. Shore power systems can be divided into two main categories: high voltage shore connections (HVSC) that operate at 6.6 or 11 kV and serve large OGVs; and low-voltage shore connections (LVSC) that operate at 220-480 V and service smaller vessels including fishing, tug, ferries, harbor craft, and service vessels. HVSC fall under the IEC/ISO/IEEE 80005-1:2019/AMD:2022 industry standard.[684]

Shore power is available at around 65 berths in California, which fall under the state's new At Berth Regulation.[685] As of 1 January 2023, the At Berth regulation requires 100% of calls by container, cruise, and refrigerated cargo vessels to plug in to shore power at regulated terminals. RO-RO vessels will be added on 1 January 2025, and the regulation will expand to tankers on 1 January 2025 at the San Pedro Bay ports and on 1 January 2027 at all other ports.

The Regulation does allow for CARB Approved Emission Control Strategies (CAECS) that provide at least equivalent emissions abatement. An employed CAECS must reduce the

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[683] https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/SecondIMOGHGStudy2009.pdf

[684] ISO. IEEE 80005-1:2019/ AMD 1:2022. Utility Connections in Port – Part 1: High Voltage Shore Connection (HVSC) Systems – General Requirements – Amendment 1. February 2022. / https://www.iso.org/standard/82252.html

[685] https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessels-berth-regulation

vessel’s at berth criteria pollutants (e.g. NO_x and PM) below a set threshold and emit no more carbon than if powered by the CA grid. Vessels and terminals may apply for vessel incident event (VIE) or terminal incident event (TIE) exemptions for a limited number of calls where vessels or terminals were unable to reasonably use shore power.

The benefits of shore power are clear: potentially lower wear on auxiliary engines turned off at berth and reduced at berth emissions in port areas, which are often co-located with vulnerable populations. CARB estimates that the new At Berth Regulation will save 237 lives, yield $2.31 billion in public health benefits, and reduce NO_x emissions by 17,500 tons and CO_2e emissions by 356,000 MT,[686] and may reduce cancer risk by 55%,[687] with other studies also finding significant health benefits.[688] Barriers to shore power include berth availability, compatibility of vessel and shoreside systems, physical alignment of vessel and fixed shoreside systems, and high local grid loads.[689] CARB estimates that the new At Berth Regulation will cost around $2.23 billion, providing avoided adverse health outcomes valued at $2.32 billion. When distributed across the individual freight units, the costs of the new At Berth regulation are low: around $1.14 per TEU, $4.65 per cruise passenger, $7.66 per vehicle on auto carriers, and less than $0.01 per gallon of finished oil product transported.[690]

Shore Power: Technologies

As of 2022, there were ~4,500 commercial vessels larger than 5,000 GT in the global fleet outfitted for shore power connections. With regulatory requirements for shore power implementation in California and Chinese ports, a considerable number of these vessels are operating in the Pacific region.[691]

Shore power systems are composed of three main components: the electrical substation; an interface system; and the vessel’s electrical equipment. Electricity from the grid is converted to a compatible voltage and frequency for shore power vessels at the substation. The interface system includes a set of cables and plugs, typically installed on the berth apron, that may be fixed, movable, or barge-mounted and can then be plugged into the vessel’s receptacle sockets.

When a vessel arrives dockside, power and control cables are connected from the shore power supply to the vessel's onboard electrical system through the interface system. Once connected, the vessel's electrical load is gradually transferred from its onboard generators to the shore power supply. After the connection is established, the vessel's

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[686] https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/ogvatberth2019/uid.pdf

[687] https://ww2.arb.ca.gov/sites/default/files/2020-08/External%20At-Berth%20Fact%20Sheet%20August%202020%20ADA_0.pdf

[688] https://pubs.acs.org/doi/10.1021/acs.est.5b04860#

[689] https://www.epa.gov/ports-initiative/shore-power-technology-assessment-us-ports

[690] https://ww2.arb.ca.gov/sites/default/files/2020-08/External%20At-Berth%20Fact%20Sheet%20August%202020%20ADA_0.pdf

[691] https://aapapowers.com/wp-content/uploads/2023/04/Shore-Power-Technology-Assessment-2022-Update.pdf

engines can be gradually shut down, synchronizing with the grid, matching in frequency, phase, and voltage, to avoid excessive currents which might damage the infrastructure.

Once the load transfer is complete and the vessel is receiving power from the shore, the onboard engines can be safely shut down. With the engines turned off, the vessel relies entirely on the shore power supply to meet its electrical needs while berthed at the port. This practice significantly reduces emissions, noise pollution, and fuel consumption during the vessel's time at berth, contributing to cleaner air and a more sustainable port environment.

Before departure, the reverse process occurs, the vessel's electrical load is gradually transferred back from the shore power supply to its onboard generators. Once complete and the vessel's engines are running and synchronized with the onboard electrical system, the cables are disconnected from the shore power supply, and the vessel is ready to depart.

Shore Power: Emissions

Auxiliary engine exhaust emissions are zero while using shore power. However, to understand the true emissions profile, it is necessary to consider the local grid or shoreside power source. Where renewable energy sources, such as wind or solar, are used, shore power emissions may reasonably be assumed to be zero (not accounting for technology production life cycle emissions). In other cases, where local electricity grids provide power, shore power emissions will mimic the local grid generation mix (Table 15).

Estimates compiled for EPA's "Shore Power Technology Assessment" show NO_x abatement of up to 99%, PM reductions of 53% - 97%, and SO_x abatement of 55% - 80% at U.S. ports, dependent on the local grid generation mix. CO_2 abatement ranged from 26% - 55%.[692]

EPA's Shore Power Emissions Calculator can be used to calculate the potential for emissions abatement using shore power. Comparisons with EPA's eGRID[693] regional emission factors are shown in Table 15. Table 15 shows that, with a few highlighted exceptions, shore power enables ships to substantially reduce emissions at berth compared to using conventional marine fuels.

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[692] See prior footnote

[693] https://www.epa.gov/egrid

Table 15

EPA eGRID shore power emission factors compared to marine engine emission factors

	Regional Emission Factors g/kWh)			
eGRID Subregion Name	**NO_x**	**SO_2**	**CO_2eq**	**$PM_{2.5}$**
ASCC Alaska Grid	2.48	0.50	474.00	0.093
ASCC Miscellaneous	3.50	0.31	239.03	0.355
WECC California	0.21	0.02	226.20	0.014
ERCT All	0.25	0.38	424.60	0.021
FRCC All	0.16	0.13	424.63	0.029
HICC Miscellaneous	3.46	1.80	507.60	0.420
HICC Oahu	1.59	3.63	763.21	0.262
NPCC New England	0.18	0.06	239.30	0.021
WECC Northwest	0.26	0.17	291.82	0.017
NPCC Upstate NY	0.06	0.04	115.16	0.008
RFC East	0.15	0.22	326.58	0.022
RFC Michigan	0.36	0.59	599.28	0.029
RFC West	0.37	0.42	532.53	0.048
SERC Mississippi Valley	0.28	0.44	389.35	0.020
SERC South	0.22	0.13	468.77	0.016
SERC Virginia/Carolina	0.20	0.12	339.07	0.023
	Marine Engine Emission Factors			
Higher than NO_X Tier III	2.00			
Higher than MGO (0.10%S)	7.70	0.424	705.00	0.174
Higher than MDO (0.50%S)	7.70	2.121	705.00	0.299

Shore Power: Costs (CAPEX and OPEX)

Costs associated with shore power fall under two categories: initial vessel, berth, and substation capital expenditures; and ongoing operational energy expenditures. Costs described in this section are largely derived from EPA's Shore Power Technology Assessment and CARB's new At Berth Regulation rulemaking.

Mobile shore power berth connections cost around $250,000 to $600,000. Vessel retrofit and newbuild costs are generally around $500,000 - $900,000 for container ships to add shore power capability, including the necessary upgrades to the vessel electrical system.[694] Other estimates have found retrofitting vessels for shore power to cost about $174 per TEU.[695]

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[694] https://ww2.arb.ca.gov/resources/documents/berth-draft-cost-analysis-appendixb-sria-august-2019

[695] https://oceanconservancy.org/wp-content/uploads/2021/11/Maritime-Port-Clean-Energy-Infrastructure-Jobs-Study-Final-Draft-11.1.21.pdf

When considering the additional infrastructure upgrades necessary, including substations, project costs are highly dependent on the infrastructure. The Port of Los Angeles spent around $15 million to install shore power at the South Terminal, and the Port of Hueneme spent $14 million to electrify three container/reefer berths and upgrade the necessary substations. In Seattle, expansion of the Pier 66 Bell Street Cruise Terminal is expected to cost the Port of Seattle approximately $30 million, including the cost of laying a high-voltage submarine cable to provide power to the berth. To the south, the Port of San Diego announced plans to spend $4.6 million to electrify two berths, doubling the capacity of the port, and enabling two cruise vessels to plug in concurrently. Adding shore power to the Brooklyn Cruise Terminal in Red Hook, which provides shore power to one vessel, cost a total of $19.3 million. The Port of Long Beach reports it has spent over $185 million on infrastructure to facilitate shore power.[696]

For the new At Berth Regulation, CARB estimates that the total cost to retrofit a berth for shore power is around $7 million for container and reefer berths, and around $2 million to add an additional shore power vault when retrofitting. Additional cost estimates are shown in Table 16. There are ongoing federal and state funding sources to support and offset the costs associated with shore power infrastructure, including but not limited to: $3 billion committed by the federal Inflation Reduction Act,[697] $653 million committed by the federal Port Infrastructure Development Program,[698] $1.2 billion committed by the CA Port and Freight Infrastructure Program,[699] and the CA Carl Moyer Memorial Air Quality Standards Attainment Program, which continues to provide over $60 million in funding each year.[700]

Table 16

CARB shore power costs from new At Berth Regulation

Infrastructure	Unit	Cost
Container/Reefer Berth	Cost per berth upgrade	$7.010 million
Container/Reefer Berth	Cost per new vault	$1.993 million
Cruise Berth	Cost per berth upgrade	$83.200 million
Tanker Berth	Cost per berth upgrade	$31.983 million
Container/Reefer vessel	Cost per vessel upgrade	$0.879 million
Cruise vessel	Cost per vessel upgrade	$1.630 million
RO-RO vessel	Cost per vessel upgrade	$3.164 million
Tanker vessel	Cost per vessel upgrade	$2.504 million

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[696] https://polb.com/environment/shore-power/#shore-power-program-details
[697] https://www.epa.gov/ports-initiative/cleanports
[698] https://www.transportation.gov/briefing-room/biden-harris-administration-invests-more-653-million-ports-strengthen-american-supply
[699] https://calsta.ca.gov/subject-areas/freight-rail-border
[700] https://ww2.arb.ca.gov/our-work/programs/carl-moyer-program-infrastructure

Ongoing maintenance costs are also an important consideration. Regular maintenance, and stocking critical parts, can minimize service interruptions and increase vessel connectivity rates. CARB estimates annual equipment maintenance costs around $10,000 per year per vessel, $24,285 per year for maintenance at container/reefer berths, and $50,000 per year at cruise berths.[701]

Expanding shore power infrastructure development across ports also contributes to economic development through creation of high-quality jobs. Shore power infrastructure requires specialized construction, electrical engineering and utility crews. Analysis of the Pier C container shipping facility's shore power development process found that the employment needs during shore power construction at a single terminal was 60 job-years. Construction of shore power at Port of Tacoma's TOTE terminal sustained an estimated 50 manufacturing and local installation jobs for the period of construction.

Operational energy costs vary widely by port. Most ports differentiate between peak and off-peak connections, charging energy rates ($/kWh) that reflect time of day differences. Energy rates vary widely, from $0.0555/kWh (off-peak) in Juneau, Alaska to $0.133/kWh in San Francisco. In many cases ports and terminals negotiate their own energy and demand rates with the local utility. It is also common for ports to include demand charges ($/max. kW), which factor in maximum demand in a fashion similar to many commercial and industrial rate structures. In contrast, the Port of Oakland charges a flat rate of $267/hour + $31/hour maintenance, regardless of energy demand.

Battery

The variable nature of weather results in lulls in availability of solar and wind energy. Batteries play a pivotal role in storing excess energy when these resources are abundant, and releasing power during energy lulls to support ship functions, from lighting to propulsion. Additionally, batteries have the potential to store energy obtained from shore power.

Batteries are different from fuel cells, which do not store chemical energy in their components, although their chemical processes are similar. Batteries are more energy-efficient, using 80-90% of the chemical energy they store, while fuel cells only transform 40% to 60% of the potential energy stored in fuels.[702] Battery systems can become key to reducing GHG emissions in shipping, but the environmental benefits of using battery systems depend upon the upstream emissions associated with the electricity mix of the source energy.

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[701] https://ww2.arb.ca.gov/resources/documents/berth-draft-cost-analysis-appendixb-sria-august-2019

[702] https://www.powermag.com/fuel-cells-vs-batteries-whats-the-difference/

This presents an opportunity to reduce GHG emissions, with the extent of reductions dependent upon several factors, including the energy sources making up the electricity supply and the capacity of the systems. Battery systems, typically based on lithium technology, can partially or fully supply energy for vessel propulsion. Active R&D in battery technology has led to lower costs and improved energy storage density and round-trip efficiency for battery systems. These developments are helping batteries become an economically sustainable resource for storing renewable energy,[703] but developments in sustainable and equitable mining[704] and battery recycling is necessary to promote sustainable use of rare earth metals.[705]

The energy-density of alternative fuels has been a major limitation for their onboard implementation in marine shipping, especially in regard to the larger space requirements for their fuel systems and the storage requirements to offset this power imbalance. With the current energy-capacity of battery technology, there is a potential market for supplemental power for OGVs and even full battery power for smaller vessels. It has been assumed large OGVs would require stacks of batteries that are miles high for full-power substitution. For a small neo-Panamax container ship (~7650 TEUs), representing an average container ship in the global fleet, a route of 20,000 km[706] would require 2,500 TEU equivalents for batteries, or 32% of the ship's cargo carrying capacity.[707]

Bunkering availability and speed can also influence power selection, especially for OGVs operating within defined travel routes or aiming to reduce downtime (e.g. potential for extra port fees and revenue loss). In this area, battery charging times can reduce ship operation efficiency greatly. Megawatt-scale charging infrastructure will be required dockside to meet the large energy requirements of battery-electric container ships without disrupting normal port operation. For example, an estimated 6,500 MWh is required for a small neo-Panamax container ship to traverse a 5,000 km route, which may take 24 hours to recharge using a 220 MW charger.[708] For comparison, average container vessel dwell times at the top 25 U.S. container ports was estimated at 32 hours in 2021, and between 34-37 hours in the first half of 2022.[709]

Battery: Technologies

Hybrid electric propulsion is currently a more feasible electrification option for OGVs from an energy demand perspective, due to the size and power needs of these vessels. Historically, studies on the feasibility of ship hybridization often relied on outdated assumptions when assessing the feasibility of battery technology. These studies typically

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[703] https://doi.org/10.1016/j.renene.2018.11.049
[704] https://www.eenews.net/articles/u-s-shift-on-child-labor-may-scramble-ev-sector/
[705] https://www.science.org/content/article/millions-electric-cars-are-coming-what-happens-all-dead-batteries
[706] The distance between ports of Shanghai and New York by cargo ship is approximately 20,655km / https://www.fluentcargo.com/routes/new-york-us/shanghai-cn
[707] Best available battery assumption of 0.21kWh/kg specific energy / https://doi.org/10.1038/s41560-022-01065-y
[708] https://doi.org/10.1038/s41560-022-01065-y
[709] https://data.bts.gov/stories/s/Container-Vessel-Dwell-Times/pbag-pyes/

used old estimates of battery costs and energy density, which may not have accurately reflected the state of battery technology at the time.[710]

Newer assessments of battery technology in container shipping signal more optimism of the hybridization of container ships. The cost of battery energy storage systems is expected to decrease by about 40% by 2030 compared to 2020 prices.[711] Development of battery technology has also improved, leading to improved energy density. However, applications are still in early stages.[712]

One of the early applications of battery hybrid propulsion was the offshore supply ship *Viking Lady*, designed by Wartsila in 2009. The experimental 92-meter-long and 6,200-DWT ship was built to explore battery and fuel cell technology in shipping. *Viking Lady* included a 442 kWh lithium battery which was used to test how the battery hybrid-electric system could improve fuel efficiency.[713] Fuel consumption was estimated to be reduced by 10-15% with the addition of the hybrid system, leading to 25% reductions in NO_x emissions and 30% reductions in GHG emissions.[714] Additionally, the hybrid system helped reduce maintenance costs through relieving burdens on the engine, including decreasing running hours and reducing low load running.

Subsequent conversions of ships to battery hybrid propulsion occurred in the following years, including the conversion of three platform support vessels by Eidesvik. The vessels were reported to experience fuel savings of 10-17% over the course of a year, leading to emissions reductions by up to 20%. Eidesvik reported that fuel savings vary by mode. The fuel savings for *Viking Energy* were estimated as follows: dynamic positioning: 27%; transit: 7.6%; in port/standby: 21.5%; and total: 17%.[715]

The world's first fully electric cargo ship launched in Guangzhou, China in 2017. The ship is about 70 meters long, has a battery capacity of 2,400 kWh, and tops out at 12.8 km/hour. Charging time takes approximately two hours, resulting in a range of 80km. The ship travels the inland section of the Pearl River.[716]

The world's first fully autonomous electric vessel, *Yara Birkeland* (Figure 22), completed its maiden voyage in Norway. The *Yara Birkeland* was commercially operating in spring of 2022. The ship, 80m-length and 3,200 DWT powered by lithium batteries, has a battery capacity of approximately 7,000 kWh and cargo capacity of 120 TEU. Sensors, including

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[710] https://doi.org/10.1038/s41560-022-01065-y

[711] https://www.pnnl.gov/sites/default/files/media/file/Final%20-%20ESGC%20Cost%20Performance%20Report%2012-11-2020.pdf

[712] https://doi.org/10.3390/en16031122

[713] https://www.wartsila.com/marine/customer-segments/references/offshore/viking-lady

[714] https://doi.org/10.3390/en16031122

[715] https://dynamic-positioning.com/proceedings/dp2018/588_03.1%202018%20DP%20Conference%20Power%20and%20Design%20Aleks%20Karlsen%20and%20Sverre%20Eriksen.pdf

[716] https://www.chinadaily.com.cn/business/2017-11/14/content_34511312.htm

radar and infrared cameras, give the ship information to navigate autonomously. The vessel can be operated remotely if an urgent event requires human intervention.[717]

Figure 22

The *Yara Birkeland* sails in Norwegian waters

Yara Birkeland, the world's first fully-electric, fully-automated cargo ship. Photo: Yara International

Battery: Feasibility overview

A large number of feasibility studies focus on small ships and ferries, showing that battery power can reduce fuel use and costs compared to alternatives.[718,719,720,721,722] If battery costs decline, it is estimated that over 40% of global container ship routes, particularly short-sea routes, could be electrified by 2040.[723] The technical feasibility of battery-system propulsion for OGVs, while less explored, has been assessed in some cases.

A study explored the feasibility of battery propulsion of a 141 m-length RO-RO ship, *Nissos Mykonos*, using lithium-ion batteries with an output of 30,000 kW and a total capacity of 120,000 kWh across all 19 TEU-container battery systems, each container having a total capacity of 6,316 kWh.[724] For a four-hour trip, the containers were estimated to provide about 44% of the trip's energy. The results depend on the assumption that the engine was operating at sustained maximum power. Operating the vessel at maximum power allowed for the ship to take great advantage of the battery power; however, the authors mention that ships of this type typically operate at 75%-77% of the maximum

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[717] https://www.yara.com/news-and-media/media-library/press-kits/yara-birkeland-press-kit/

[718] https://doi.org/10.1109/SPEC.2018.8636010

[719] https://discovery.ucl.ac.uk/id/eprint/1528988/

[720] https://dspace.lib.ntua.gr/xmlui/bitstream/handle/123456789/54066/Markesinis_thesis_2021_e-ferry.pdf?sequence=1

[721] https://repository.tudelft.nl/islandora/object/uuid:cf138038-adc9-41b6-a08f-3f2e9359a3fc

[722] https://doi.org/10.1016/j.energy.2019.116359

[723] https://doi.org/10.1038/s41560-022-01065-y

[724] This capacity is substantially larger than the current state of marine technologies, per the authors' discovery and demonstrated by operational vessels in this section.

power output that an electric power system can generate at normal conditions annually.[725] Additionally, the battery parameters were based on land-based units,[726] which were reportedly chosen based on "maximum power output, total capacity, feasibility of installment, and energy capacity to area ratio." Batteries of this type may not necessarily be able to be used in shipping, due to their lack of suitability for the marine environment and the potential fire hazards presented by the components unique to land-based batteries.

Batteries can undergo "thermal runaway," a rapid and unstoppable increase in temperatures that combust, are difficult to extinguish, and can spontaneously reignite. The European Maritime Safety agency reports that lithium-ion batteries are the main cargo type responsible for fire accidents.[727] Moreover, during this combustion up to 6,000 liters of deadly toxic vapors, such as hydrogen fluoride, hydrogen cyanide, and hydrogen chloride, are released per single kW of battery.[728, 729] Marine batteries are designed to resiliently endure the vibrations and wave thrashing experienced at sea, and the wet and high-salt environment, featuring heavy plate exteriors and stronger internal construction.

All of the current lithium-ion batteries use flammable organic electrolytes, thus in marine applications the construction relies on thick waterproof metal cases arranged in racks and separated by significant air gaps to limit thermal runaway to the smallest number of cells. These design factors cause the fully-installed energy density of marine lithium battery packs to be around half of that for automotive battery packs. Because of the considerable design adjustments of lithium-ion batteries to ensure safety at sea, the future of marine batteries may employ alternative chemistries, such as lithium iron phosphate or lithium-sulfur.[730]

The U.S. Department of Transportation's (DOT) Hazardous Materials Regulations include the regulation of lithium batteries for all modes of transport for commerce, due to their risks to safety (HMR; 49 C.F.R., Parts 171-180).[731] IMO governs the transportation of batteries by sea under the International Maritime Dangerous Goods Code, wherein different lithium-ion batteries are classified as Class 9 hazardous materials.[732] In 2019, IMO introduced Battery Systems Guidance for Installation and Operation within their yacht code. To date, IMO has not yet published additional rules for vessel battery

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[725] https://doi.org/10.3390/asi2040034
[726] https://www.windpowerengineering.com/meet-north-americas-largest-lithium-ion-battery-storage-facility/
[727] https://www.emsa.europa.eu/containership-safety/cargosafe.html
[728] https://safety4sea.com/a-zero-emissions-maritime-industry-needs-better-battery-technology/
[729] https://www.seatrade-maritime.com/casualty/shipping-unprepared-lithium-battery-fires
[730] https://pubs.rsc.org/en/content/articlehtml/2021/ma/d1ma00746g
[731] https://www.phmsa.dot.gov/lithiumbatteries
[732] https://www.imo.org/en/publications/Pages/IMDG%20Code.aspx

propulsion on OGVs.[733] The EMSA and USCG have released non-mandatory safety guidelines for vessel battery systems.[734,735]

Presently, the shipping industry is experiencing the hazards of non-marine batteries at sea when transporting electric vehicles. There were 209 ship fires reported during 2022, the highest number in a decade (13 of the fires took place on car carriers, though the number attributable to electric vehicles is unknown). Fire-extinguishing systems on ships are not designed for these types of fires, thus IMO plans to evaluate new safety measures onboard next year, such as assessing fire-dousing chemicals, large fire blankets, battery piercing fire hose nozzles, etc.[736]

The *Aurora* and *Tycho Brahe* are currently the largest electric RoPax vessels in operation, measuring 111 m-length each, for which their battery system's total installed capacity was 4160 kWh each; the onboard system consists of 640 6.5 kWh lithium-ion batteries.[737,738] Their battery system features a proprietary water-cooling system surrounding the lithium-ion batteries, and aerosol and water sprinkler systems within the containers, to offer safety at sea. They are still equipped with their original diesel engines, but have the capability to run fully electric 3.5 times between their harbor-to-harbor route on a single charge. The vessels charge at each stop, though for intervals of only 5-9 minutes.[739] The *Tycho Brahe* has since been upgraded to 6,400 kWh, without requiring additional space on board the vessel, also doubling the lifespan of the battery pack from 5 to 10 years.[740]

Battery: Emissions

Theoretically, transitioning from conventional engines to fully electric ships could decrease GHG and criteria pollutant emissions. However, it is important to consider the energy sources used for the electricity generation that ultimately powers the vessel, and its impact on life cycle emissions of electric propulsion. The energy sources of the grid recharging the batteries, and the sources of the grid and fuels powering the upstream production processes of these batteries will contribute to the batteries true WtW life cycle analysis. An electrified vessel that recharges from a fossil-fuel-heavy grid may have life cycle emissions that exceed those of conventional fuels, as discussed below.

The WtW life cycle emissions of fully electric RO-RO passenger ships were estimated based on the 2020 energy importation and production status in South Korea. The potential reductions in GWP were approximately 35.7% for the fully electric ship compared

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[733] https://www.imorules.com/GUID-3F95793F-4B36-47EB-8799-4624B3E8EFD1.html
[734] https://www.emsa.europa.eu/electrification/bess.html
[735] https://www.dco.uscg.mil/Portals/9/MSC/PRG/PRG.E2-29.2021.05.20.Lithium-Ion%20Batteries.pdf
[736] https://www.reuters.com/business/autos-transportation/ocean-shippers-playing-catch-up-electric-vehicle-fire-risk-2023-07-27/
[737] https://new.abb.com/news/detail/10434/forsea-formerly-hh-ferries-group-completes-conversion-of-the-worlds-largest-battery-ferries-powered-by-abb
[738] https://electrek.co/2017/08/24/all-electric-ferries-abb/
[739] https://www.deif.com/media/subc3l04/tycho-brahe-uk-lowres.pdf
[740] https://ferryshippingnews.com/forseas-tycho-brahe-has-been-upgraded-with-the-worlds-largest-battery-pack/

to the diesel ship. Greater increases were found in other environmental metrics, highlighting the consequential impacts of maritime emissions occurring from traditional propulsion systems beyond climate warming. Primarily recognized was the harm of nitrogen and sulfur emissions on ecosystems, for which battery propulsion could lead to a 77.6% decrease to acidification potential (e.g. SO_x, NO_x), a 87.8% decrease in eutrophication potential (e.g. NO_x), and a 77.2% decrease to photochemical ozone creation potential (e.g. NO_x, CH_4, CO).[741]

The study throws caution on reliance on electrification to achieve emissions targets. Two identical electrified ships would have entirely different life cycle emissions depending on where they are being charged and operated. Battery applications could not achieve a 50% reduction to GWP under South Korea's current electricity mix (2020). However, battery propulsion could cause more significant reductions to GHG emissions with a cleaner energy mix. For example, in Norway, 98% of electricity comes from renewable sources, while renewables in South Korea only represent 8% of the mix (2022).[742,743] A battery-powered ship sourcing electricity from the Norwegian grid would experience significantly greater emissions benefits than a ship deriving electricity from the South Korean grid.

In 2022, ~54% of California's total energy mix came from zero-GHG and renewable energy sources.[744] The life cycle emissions of batteries produced under this energy mix is unclear. Their study did not highlight an energy mix threshold, for which electric outperform conventional-fueled vessels. To the authors' knowledge no studies have determined this threshold for marine propulsion systems, nor is it directly explored for electric vehicles at this time. It is only reported that battery propulsion becomes more environmentally effective in nations with a higher rate of low- and no-GHG electricity production. Although life cycle emissions vary across nations, the GWP of battery propulsion is decreased in all localities generating electricity using renewable sources like geothermal, hydro, solar, and/or wind power.[745]

The benefits of hybrid and electric propulsion also vary by ship type and activity. According to a study of ship activity around the coast of Norway, offshore support and passenger ships may benefit most from hybrid and electric propulsion, followed by RO-RO ships and container ships. Offshore and passenger ships were observed to spend a lot of time at lower loads, where energy efficiency is lower, leading to increased emissions per kWh and reduced fuel cost savings.

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[741] https://doi.org/10.3390/jmse8080580
[742] https://www.iea.org/reports/norway-2022/executive-summary
[743] https://www.eia.gov/international/analysis/country/KOR
[744]https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2022-total-system-electric-generation
[745] https://doi.org/10.1016/j.jclepro.2022.131756

Incorporating battery propulsion could increase efficiency at lower loads by reducing the burden on the diesel engine, which is inefficient at these loads. Half of the ocean-going offshore ships spent at least 38% of their time at 2%-20% load, 11% of their time at 20%-30% load, and 7% of their time at 30%-40% load.[746] As such, these vessels may benefit from utilizing electric propulsion systems during these stretches of low load operation. Reefers, on the other hand, may benefit the least due to the high speeds they sustain.[747] Technological advancements combined with political, financial, and social reform can help improve the effectiveness of battery propulsion in shipping.[748,749]

Battery-swapping has been found to be an optimal, feasible solution for long-distance battery-powered vessels. Battery-swapping stations (BSSs) built along the navigation route, primarily useful for vessels traveling along coasts or inland, can reduce the number of batteries required onboard in exchange for quick stops to "refuel". Mass battery charging may put undue pressure on local grids, but one solution to this is adopting a pricing structure that fluctuates based on the time of day. The widespread adoption of this time-varying pricing is far from being effectively put into practice. However, under this structure, in addition to battery-swapping to ships, BSS operators (e.g. ports) could lower the operating costs for vessel owners by charging vessels during off-peak hours while simultaneously selling excess electricity back to the grid at a high price to increase revenue.[750]

Start-up company FleetZero has developed a 2,000 kWh lithium iron phosphate battery that fits into a standard TEU shipping container. Moreover, these are built in the U.S. and thus compliant with The Merchant Marine Act of 1920.[751] Their system is tailored for a 3,000-4,000 TEU, taking into account seamless handling of TEU containers by mature infrastructure and crew at commercial scale. They believe their battery swapping scheme can distribute investment and infrastructure costs over a greater number of shipping containers to be competitive with conventional bunker fuels. The *Pacific Joule* was the first hybrid ship piloting this technology, beginning operations in 2023, with aims for additional vessel retrofits in 2025.[752,753]

In the summer of 2023, China's COSCO Shipping Heavy Industry launched *N997*, a 120m-length, 700 TEU inland container ship with a swappable containerized lithium iron phosphate battery system. Each battery is the size of a standard TEU with a capacity of

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[746] Marine diesel engines are optimized for operation at a specific load range, typically 70–100% of their maximum continuous rating / https://doi.org/10.1016/j.trd.2018.09.021

[747] https://doi.org/10.1016/j.trd.2018.09.021

[748] https://doi.org/10.1016/j.apenergy.2017.02.060

[749] https://doi.org/10.3390/jmse9040415

[750] https://doi.org/10.1016/j.oceaneng.2023.115234

[751] Also referred to as The Jones Act (46 USC § 50101); mandates that all goods shipped between U.S. ports must be transported by vessels that are U.S. -flagged, -owned, -crewed, -registered, and -built.

[752] https://fleetzero.com/

[753] https://cleantechnica.com/2022/03/18/fleetzeros-container-ship-battery-swapping-scheme-may-help-electrify-shipping/

1,900 kWh per container,[754] and the vessel holds 36 of these containers onboard. It was designed to traverse a 600 mile route, but will rely on stops to swap, though the frequency is unclear at this time. Each containerized battery is estimated to cost $17-26.5 million.[755] The *N997* will pilot a 'smart management system' that can intelligently adjust energy consumption based on the needs of the ship to plan service speeds according to the arrival time, water flow, battery capacity, and otherwise efficiently consume its electricity across a voyage. Manufacturing of a second comparable vessel *N998* is underway.[756] Insights from pilot operations will reveal the feasibility and scalability of the battery-swapping scheme under real-world scenarios.

Battery: Costs (CAPEX and OPEX)

It has been claimed that utilizing green electricity directly in high-efficiency drive trains would offer the lowest total cost of ownership among low-GHG alternatives, due to low operating costs.[757] Service prices for on shore power across U.S. ports, utilized at berth and to recharge batteries, cost between $0.045-0.133/kWh, not inclusive of additional commissioning, peak demand, maintenance, service and/or facilities charges.[758] To the authors' knowledge, there is a lack of literature examining the comparative costs of recharging a vessel based on energy requirements for a specific voyage, as opposed to the costs associated with fueling with conventional or alternative options.

Under proposed battery-swapping schemes, containerized batteries were estimated to cost $17-26.5 million per TEU. The pilot vessel for this scheme requires 36 of these containers with an unknown distance threshold before recharge.[759] However, under these proposals, the expense of these communally-shared batteries would be distributed across the greater fleet, leveraging economies of scale, and is expected to alleviate the capital expense burden for operators.

Some projections anticipate a 40% reduction in battery energy storage system costs by 2030 compared to 2020 rates, alongside advancements in battery technology expected to enhance energy density.[760,761] The average cost of lithium-ion batteries stands at $151/kWh, predicted to decrease to $100/kWh by 2026. Research indicates that at this price point, the total propulsion expenses of a battery-powered container ship would be

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[754] Some articles are incorrectly reporting the capacity at 50,000 kWh, due to inital translation errors and the novelty of shipping battery technology not raising flags with journalists / https://cleantechnica.com/2023/07/31/and-so-it-begins-1000-kilometer-route-yangtze-container-ship-with-swappable-batteries/

[755] https://www.sustainable-ships.org/stories/2023/cosco-700-teu-full-electric-container-ship

[756] https://maritime-executive.com/article/china-launches-first-700-teu-electric-containership-for-yangtze-service

[757] https://www.forbes.com/sites/michaelbarnard/2023/12/17/how-much-shipping-can-just-use-batteries-for-energy/?sh=325790d73330

[758] https://aapapowers.com/wp-content/uploads/2023/04/Shore-Power-Technology-Assessment-2022-Update.pdf

[759] https://www.sustainable-ships.org/stories/2023/cosco-700-teu-full-electric-container-ship

[760] https://www.pnnl.gov/sites/default/files/media/file/Final%20-%20ESGC%20Cost%20Performance%20Report%2012-11-2020.pdf

[761] https://doi.org/10.3390/en16031122

lower than that of a conventional ICE for distances under 621 miles.[762] If the investment costs of battery propulsion decrease as anticipated, it is projected that over 40% of global container ship routes could transition to electrification by 2040.[763]

Section 8: Technology Readiness

This section discusses the technology readiness of alternative marine fuels in a structured context, with consideration of fuel production, feedstock availability and on-board technology. The following sections also evaluate energy density/range, safety, and regulatory issues for each of the fuels. For fuels with low production capacity or that are in early development, the readiness and decarbonisation potential are inherently uncertain and early-stage fuels should be treated accordingly.

Technologies are broadly categorized in terms of Technology Readiness Level (TRL) in a manner similar to the Fuel Pathway Maturity Map from the Maersk Mc-Kinney Møller Center[764] and a recent technology readiness assessment performed for IMO by Ricardo and DNV.[765] Technology Readiness Levels have been applied across a broad swath of industries, including software development, aerospace, and R&D.[766] Originally developed by NASA in the 1970s, TRLs are also defined in ISO 16290:2013.[767] We employ a simplified scale, shown below, based on the NASA TRLs (right column)[768] and others:

Table 17
Technology Readiness Definitions

	Definition	Maturity	TRL
⬜	Mature technology, commercially deployed at scale, or best available technology.	Mature	9
🟦	Early adopted technology, ready to be deployed at scale, or close to best available technology.	Early Adoption	8
🟧	Technology pilot, but may not be mature or available at scale. Demonstration stage, not yet commercially viable.	Demonstration	6 - 7
🟥	Major technical challenges remain, research and development stage.	Development or early research	1 - 5

We also consider decarbonization potential and price factors alongside technology readiness, as shown below.

○ Low Decarbonization	◎ Moderate Decarbonization	⦿ High Decarbonization
$ Low Cost	$$ Moderate Cost	$$$ High Cost

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[762] https://doi.org/10.1038/s41560-022-01065-y
[763] https://doi.org/10.1038/s41560-022-01065-y
[764] https://www.zerocarbonshipping.com/fuel-pathways/
[765] https://www.imo.org/en/MediaCentre/Pages/WhatsNew-1868.aspx
[766] See, for use examples, https://www.gao.gov/products/gao-20-48g
[767] https://www.iso.org/standard/56064.html
[768] By NASA, see https://esto.nasa.gov/trl/

Table 18

Summary of fuel prices ($/MJ)

Fuel	Fuel Price Low ($/MJ)	Fuel Price High ($/MJ)
MDO	0.021	0.023
LNG	0.019	0.035
HFO	0.011	0.014
H2 (Gray)	0.008	0.023
H2 (Blue)	0.013	0.034
H2 (Green)	0.021	0.050
Methanol (Fossil)	0.014	0.058
Bio-Methanol	0.018	0.058
e-Methanol	0.026	0.107
NH3 (Brown)	0.030	0.032
NH3 (Blue)	0.032	0.043
NH3 (Green)	0.086	0.099
Biofuel (DME)	0.016	0.049
Bio-oil (Woody)	0.016	0.027
FT-Diesel (Bio)	0.024	0.066
FT-Diesel (Advanced)	0.038	0.105
HVO (bio-UCO)	0.020	0.035
FAME	0.026	0.049
Biocrude (HTL)	0.003	0.018

While the costs of hydrogen propulsion systems may be lower than methanol and ammonia costs, they are offset by additional costs for fuel storage and vessel upgrades to accommodate cryogenic systems. A mid-size TEU container ship will generally have a fuel tank around 7,500 - 10,000 m^3 in size, indicating costs around $22.5 - $30 million for LH$_2$ tanks with a range around one-quarter that of conventional fuel tanks. Ammonia costs include both the propulsion and fuel systems, and other than secondary tanks to hold biofuels, and ensuring compatible materials in fueling systems, etc., major vessel modifications needed for biofuels are limited.

Hydrogen

The majority of hydrogen produced today is from fossil sources, so-called brown or gray hydrogen. These have a high carbon intensity, but are mature and commercially proven for supplying hydrogen for industrial purposes. Blue hydrogen uses fossil feedstocks, and relies upon CCUS technology to reduce GHG emissions. CCUS technology has not been widely proven, and commercial use will rely upon improved efficiency and lower costs. Green hydrogen production offers the lowest emissions, but currently represents a very small fraction of global production (~0.1%). Green hydrogen development will require extensive renewable energy resource development, both for dedicated renewables and for low-GHG electrical grids to provide sufficient energy and realize lower costs, which are currently nearly 2.5x conventional fuel prices per unit energy.

Projected hydrogen development is focused in two areas, electrolysis with dedicated renewables or grid electricity (projected to produce 76.2% of hydrogen currently under development) and fossil feedstocks with CCUS (22.6%). The U.S. is launching initiatives like Regional Clean Hydrogen Hubs and the Hydrogen Earth Shot, aimed at producing 1 kg of hydrogen at a cost of $1 in the next decade. These initiatives show that there is increasing need for development of low-GHG hydrogen, both for direct use as an energy carrier, and as a feedstock for other low-GHG fuels including ammonia and methanol. Fuels produced using green hydrogen are often referred to as e-fuels, and together comprise a critical series of pathways to decarbonizing the shipping sector.

While the technology readiness of hydrogen technologies for vessel operations are generally not far beyond small-scale demonstration or pilot projects, low-GHG hydrogen production and development is important for decarbonizing methanol and ammonia production, which exhibit higher degrees of technology readiness.

Table 19

Hydrogen Technology Readiness Levels

	Hydrogen		
	Gray ○ $$	**Blue** ◎ $$$	**Green** ◉ $$$
Fuel Production	96% of global H_2 production is from either brown or gray sources.	Relies upon CCUS efficiency and continues to use fossil feedstocks.	Low emissions H_2 production is currently < 1% of global production.
Vessel Capacity and Range	Cryogenic fuel systems and storage require ~8x space compared to conventional systems. Ocean-going range limited to ~3-4 days.		
Safety	H_2 is highly flammable, though non-toxic if spilled. Precautions necessary around cryogenic materials and systems. Leak detection requires specialized sensors and monitoring.		
Fueling Infrastructure	Small-scale fueling by LH_2 tanker truck is currently available Large-scale pipeline and bunkering barge development is in the very early stages		
Feedstock Availability	Fossil feedstocks are widely available but carry high WtW CO_2e emissions.	Fossil feedstocks are widely available but rely upon CCUS to abate WtW CO_2e emissions.	Development of dedicated or grid renewable energy sources required.
Regulatory Issues	Classification Society and State Certification barriers remain for larger ocean-going vessels.		
On-Board Technology	Fuel cell technology exists in a variety of use cases, but has not been widely deployed at scales necessary for ocean-going vessel propulsion.		

Methanol

Fossil-sourced methanol is widely produced worldwide, while biomass and electrified renewable sources account for less than 1% of total methanol production. As depicted in the following section, methanol derived from fossil sources may increase total life cycle GHG emissions compared to conventional fuels. Methanol, including from renewable sources, is not a carbon-free fuel at combustion. Projections of renewable methanol development anticipate almost 11 million tonnes of annual renewable-sourced methanol capacity to come online by 2027; This would represent ~10% of the current global annual methanol production, which stands at approximately 100 million tonnes.

Table 20

Methanol Technology Readiness Levels

	Methanol		
	Fossil ○ $$	**Bio-MeOH** ◎ $$$	**E- MeOH** ⦿ $$$
Fuel Production	Methanol is widely produced worldwide. Nearly all methanol currently produced is from fossil feedstocks.	Low-CO_2e methanol production currently accounts for < 1% of global production. Efforts are underway to scale production.	
Vessel Capacity and Range	Methanol requires around 2.5x the storage volume for equivalent total energy due to lower volumetric energy density, which offsets cargo volumes, though lost cargo opportunity costs are limited.		
Safety	Low flash point, burns with a clear flame. Fire suppression systems require specialized sensors and monitoring. Methanol is toxic to humans, but spill risk is comparatively low.		
Fueling Infrastructure	Methanol is widely distributed as a chemical feedstock and can utilize current bunkering systems, with appropriate modification. Methanol is currently bunkered in small volumes requiring investment for scaling.		
Feedstock Availability	Fossil feedstocks are widely available but carry high WtW CO_2e emissions.	Bio-methanol feedstocks rely on biomass availability, which is likely to face competition from other sectors.	With rapid scaling of renewable electricity, feedstocks for e-methanol could be readily available.
Regulatory Issues	Classification societies have developed Methanol Ready classifications and methanol has been regulated as hazardous cargo for many years.		
On-Board Technology	There are 164 methanol-fueled vessels built and on order, with another 121 methanol-ready vessels built or on order. Major engine manufacturers are supplying methanol and methanol-ready engines to the market.		

The utilization of methanol as a marine fuel is reasonably well established, evidenced by demonstrated engines and fuel systems, and methanol-ready vessels recently surpassing LNG vessel orders on the alternative fuel orderbook. Methanol does not require cryogenic or cooling tanks or pressurization, unlike some other alternatives (i.e. NH_3 and LH_2).

As regulatory frameworks increasingly prioritize decarbonization and GHG reductions, the scalability and adaptability of methanol production processes, particularly those utilizing renewable feedstocks and energies, will be crucial to achieve these targets. See *Policy Options to Decarbonize Ocean-Going Vessels* for information on the planning and initiatives by various nations, as well as private sector initiatives.

Bio-methanol (bio-MeOH) utilizes biomass gasification, wherein the biomass, having sequestered carbon from the atmosphere during its growth, contributes to reduced life cycle fuel emissions; alternatively, feedstocks such as manure may be used, which in these cases may actually result in net-negative life cycle GHG emissions compared to business-as-usual management practices. Sourcing of sustainable biomass feedstock is constrained by availability limitations, particularly in competition with other sectors, and may also pose negative environmental consequences beyond emissions concerns. E-methanol (e-MeOH) production, however, could theoretically produce large and sustainable amounts of energy, but the technologies are currently less developed. Renewable production of methanol, particularly e-MeOH, may include green H_2 in its generation, thereby connecting the production and life cycle emissions of the two fuels. Reducing the carbon intensity of e-MeOH may also rely on CCUS technologies to source CO_2 emitted from other industrial processes, or may rely on extracting CO_2 directly from the atmosphere.

Ammonia

Ammonia synthesis is currently the largest emitter of CO_2 in the chemical industry, due the high energy intensity of SMR-produced gray ammonia. Ammonia derived from fossil sources may increase life cycle GHG emissions compared to conventional fuels. Therefore, if regulatory policies fail to support adding renewable-sourced ammonia production capacities to fulfill projected demand, dependence on gray ammonia will not help reach climate goals.

Renewable ammonia production accounts for less than 1% of current global output. Reduced GHG ammonia production is dominated by blue ammonia, which uses fossil feedstocks and depends upon CCUS technologies to reduce carbon intensity. CCUS technology has yet to be proven at large commercial scale. The commercial viability of blue production relies on high-efficiency and low-cost CCUS. Green ammonia, which relies on renewable energy sources and H_2, represents less than 0.01% of total global production.

The production of H_2 is a precursor to ammonia production, directly influencing the decarbonization potential of ammonia fuel (i.e. green hydrogen sourcing is required for green ammonia). Projected hydrogen production allocated for ammonia synthesis totals 45.2 million tonnes, which would support production of approximately 250 million tonnes of ammonia; 89.4% of this would use hydrogen from electrolysis to produce green ammonia.

Table 21
Ammonia Technology Readiness Levels

<table>
<tr><th></th><th colspan="3">Ammonia</th></tr>
<tr><th></th><th>Fossil ○ $$</th><th>Blue ◎ $$$</th><th>Green ⦿ $$$</th></tr>
<tr><td>Fuel Production</td><td>Most ammonia is currently produced using fossil feedstocks.</td><td>Relies upon CCUS efficiency and continues to use fossil feedstocks.</td><td>Projections show significant new green ammonia production capacity by 2050. Relies on renewable energy sources.</td></tr>
<tr><td>Vessel Capacity and Range</td><td colspan="3">Ammonia has lower volumetric energy than conventional fuels, requiring around 3x the storage volume for equivalent energy delivery. Ammonia requires corrosion-resistant storage and fuel systems.</td></tr>
<tr><td>Safety</td><td colspan="3">Ammonia requires special handling as it is toxic to humans and aquatic ecosystems, and must be stored in pressurized and/or low temperature (-34°C) systems. Ammonia can be detected by odor.</td></tr>
<tr><td>Fueling Infrastructure</td><td colspan="3">Safe and efficient ammonia bunkering systems are not currently available. Ammonia is corrosive to many existing systems, but ammonia is widely stored and distributed as cargo at hundreds of ports around the world.</td></tr>
<tr><td>Feedstock Availability</td><td>Fossil feedstocks are widely available but carry high WtW CO_2e emissions.</td><td>Fossil feedstocks are widely available but rely upon CCUS to abate WtW CO_2e emissions.</td><td>Requires development of dedicated or grid renewable energy sources.</td></tr>
<tr><td>Regulatory Issues</td><td colspan="3">Ammonia produces high levels of NO_x emissions, which must be controlled to meet MARPOL Tier III NO_x regulations. Ammonia fuels also introduce safety hazards requiring regulation. IMO is developing interim guidelines for using ammonia as marine fuel, but barriers remain.</td></tr>
<tr><td>On-Board Technology</td><td colspan="3">Ammonia may be combusted in ammonia-ready engines or used as an energy carrier and then cracked to produce molecular hydrogen, which is then passed through a fuel cell. Ammonia-ready vessels are on order, but no ocean-going vessels are currently operating using ammonia.</td></tr>
</table>

From a technology-readiness perspective, ammonia faces a set of challenges including safety and toxicity concerns related to combustion on board vessels, limited availability and demonstrated experience with fueling and bunkering, and limited real-world demonstrated experience operating vessels using ammonia. While ammonia-ready vessels are operational, they operate in conventional fuel mode.

Biofuels

Biofuels represent a diverse category of fuels derived from biomass sources, with different sources of feedstocks and methods of production. Established infrastructure and systems can be used for blending and bunkering biofuels in many cases, with additives and appropriate treatment. Biofuels are considered to be “drop-in” fuels as little-to-no modifications are required for existing marine engines and systems. However, they are generally less energy dense than conventional fuels. Challenges to scaling low- or zero-GHG biofuels are expected due to the scarcity of sustainable and appropriate feedstocks.

First-generation biofuels (typically ethanol and biodiesel sourced from food crops) have been generally recognized as unsustainable and unproven to reduce life cycle GHG emissions, while third-generation (sourced from algae and cyanobacteria) and fourth-generation (sourced using genetically-engineered organisms) biofuels are not technologically mature, and their readiness, feasibility and/or GHG savings expected from their use in the marine sector are uncertain in the near term.

Table 22

Biofuels Technology Readiness Levels

	Biofuels					**Bio-oils**	
	DME ◎ **$$**	**FT-Bio** ⊙ **$$$**	**FT-Biogas** ⊙ **$$$**	**HVO** ◎ **$$**	**FAME** ◎ **$$**	**HTL Bio-crude** ⊙ **$**	**Pyrolysis-oil** ⊙ **$**
Fuel Production	Early development.	Early development for gas-to-liquid production, but the FT-process is well understood with hydrocarbon feedstocks.		Current production is <5% of global marine demand.	Commercial production for transport fuels.	Early development.	
Vessel Capacity and Range	Around 21% Lower energy density than conventional fuels. Limited compatibility with conventional fuel engines.	Similar energy density to diesel.			7% lower energy density than diesel.	Up to 22% lower than MDO (lignocellulosic biomass; may be higher than MDO when sourced from microalgae).	Nearly 60% lower than MDO.
Safety	Gas at RTP; Needs to be pressurized.	Similar safety management to conventional fuels.		Non-toxic and stable.	Non-toxic to humans and wildlife. Degrades 2x - 4x faster than diesel.	Similar safety management to conventional fuels.	
Fueling Infrastructure	Low flash point Gas at RTP, so requires pressurized tanks similar to LPG.	Drop-in fuel with characteristics similar to diesel.		Can be used as a drop-in fuel. Stable in cold temperatures. Reduced abrasiveness.	Low cloud point. Corrosive in some fuel systems. May increase microbial fouling but improve lubricity.	Contain higher levels of oxygen and acids. Must be upgraded before blending and use. Prone to engine deposits and carbon residues.	
Feedstock Availability	Relies on second -generation feedstocks (including forest residues) for decarbonization benefits.	Relies on second -generation feedstocks (including municipal and agricultural waste products) for decarbonization benefits.	Relies on second -generation feedstocks (including landfill gasses) for decarbonization benefits.	Relies on second-generation feedstocks (including used cooking oil and waste fats oils and greases) for decarbonization benefits.	Relies on second-generation feedstocks, (including vegetable oils and animal fats),for decarbonization benefits.	Relies on second-generation feedstocks (including woody biomass, manure, and sludge) for decarbonization benefits.	
Regulatory Issues	Biofuels are currently mainly used in blends with conventional fuels, covered under Regulation 18.3 of MARPOL Annex VI. Considerations should be given to NOx and PM emissions, and life cycle GHGs. Additional policy is necessary to address concerns over feedstock fraud and oversight of biofuel supply chains.						
On-Board Technology	Biofuels can be blended with conventional fuels and used in conventional engines with minor modifications. Fuel additives may be necessary for fuel stability and treatment. Current biofuel blends are typically around B20 - B30 (20 - 30% biofuels).						

Second-generation biofuels, made from non-food biomass or organic waste, are not yet fully mature but are recognized to hold the potential for meaningful reductions in GHGs in their application. Each of the biofuels in Table 21 below can be produced with second-generation feedstocks. However, current and future access to many second-generation feedstocks is limited. Furthermore, the challenges in sourcing sustainable second-generation biofuels are further exacerbated by issues like fraud. These challenges highlight the need for strengthened regulations, supply chain management, and certification processes globally to ensure the integrity and sustainability of biofuel trade, aligning with climate goals.

An estimated annual minimum of 10 EJ sustainable biofuel production would be required to decarbonize the present shipping industry. Maritime sector energy demand is projected to reach 10.5 EJ in 2030 and 13 EJ by 2040. Yet the global capacity for sustainable biofuels is only estimated to reach 23 Mtoe, equivalent to less than 1 EJ, by 2026.[769] The total production capacity of biofuels from all feedstocks and pathways is estimated to surpass ~17 EJ in 2030 and could potentially expand to 63 EJ by 2050, exceeding anticipated maritime demand but not exclusively allocated to it; as noted above, the maritime sector faces competition from other sectors (i.e. road and aviation) for biofuels, in particular for high-quality fuels.

Biofuels, particularly FAME (biodiesel) and HVO (renewable diesel) are currently used in vessels in blends up to B20 - B30. Primary technology-readiness issues for biofuels surround their use in higher blends, for greater decarbonization, and production and feedstock availability and volumes. Additionally, biofuels are less energy dense than conventional fuels (some significantly so), so when blended at higher volumes the available energy in the fuel decreases and vessel voyage range decreases.

Electrification and Supplemental Power Systems

Supplemental power systems may provide integral support alongside other fuel and propulsion systems, commonly with fossil fuels, to improve vessel efficiency, reduce fuel consumption, and/or lower GHG emissions. Battery systems may serve as storage to harness the energy power of onboard wind and solar during lull periods and/or may be recharged with shore power, and as such their technological and safety readiness is interlinked with the other systems. Demand for these power systems is uncertain for long distance shipping, but there is growing interest in adopting these technologies, particularly in efforts to follow EEXI standards for vessel efficiency.

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[769] 1 Megatonne of Oil Equivalent = 0.041868 Exajoule / https://www.iea.org/data-and-statistics/data-tools/unit-converter

Table 23

Electrification and Supplemental Power System Technology Readiness Levels

	Supplemental Power Systems			
	Wind ○ $	**Solar ○ $$**	**Battery ○ $$$**	**Shore Power ◎ $$**
Fuel Production	NA	NA	Widespread commercial applications for batteries, though not at scales required for large OGVs.	Local grid
Fuel Price	NA	NA	Local electricity price	Local electricity price
Vessel Capacity and Range	Wind-assist provides around 2 - 22% reduction in energy consumption.	Minimal changes to vessel range, small offsets to auxiliary power.	Batteries can offset up to around 20% of energy consumption, but empirical results are limited.	NA
Safety	Overhead considerations for sky sails and Flettner rotors.	Electrical system management, shock risk.	Thermal runaway risk causes significant fire risk, which can also release large volumes of toxic vapors.	High voltage electrical system loads require specialized training and management.
Fueling Infrastructure	NA	NA	Requires specialized at-berth utility of dedicated system connections.	Requires specialized at-berth utility of dedicated system connections.
Feedstock Availability	NA	NA	NA	NA
Regulatory Issues	Compliance with IMO Safety of Life at Sea (SOLAS) requirements.[770]	Standards apply to the materials, electronics, and placement of the PV system for marine application. Regulation of marine battery systems will apply.	Lithium batteries are regulated by IMO as hazardous materials. No current international regulations on the safety aspects of using onboard battery systems, but EMSA and USCG released non-mandatory safety guidelines.	Regulated by CARB under the At Berth Regulation and in Europe under FuelEU Maritime.
On-Board Technology	Kites may be retrofitted to existing builds; Flettner rotors and fixed sails require dedicated builds.	Passive and active systems can provide supplemental power to vessels, but the power output is limited and system designs do not apply to all vessel types.	Thermal management and safety considerations lead to marine battery applications having densities of approximately half those in automotive battery packs.	Vessel-side electrical system required to handle connecting to the grid and distributing energy to the auxiliary systems.

Decarbonization Potential

The decarbonization potential of alternative fuels and power systems in the marine sector, in terms of percent difference from MDO, are shown in Figure 23 for hydrogen, ammonia, methanol, biofuels, and supplemental power systems. Biofuels assume a B60 blend,[771] which is around 2-3x the current typical blends (B20 - B30) being used. Note that colors are used to denote fuel groups, and do not correspond to the fuel production pathways. Fuels are ordered by percent GHG reduction, considering the range of potential emissions abatement. The figure shows the current baseline fuel, MDO, which makes up the majority of fuel consumed globally, and lines corresponding to 30%, 70% and 100%

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[770] https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx

[771] NOTE: Biofuels assume a B60 blend, i.e. 60% biofuel, 40% conventional fuel. Above B20-B30 blends should be evaluated on a case-by-case basis.

reductions, aligned with the 2023 IMO Greenhouse Gas Strategy net zero goals by 2030, 2040, and 2050, respectively. Positive values depict net increases in WtW CO_2e emissions and negative values depict net emission reductions. The height of bars shows the range in abatement potential depending on the energy pathway for fuel production, which is an important consideration when compared to abatement potential targets. E.g. e-Methanol produced using fossil-intensive methods would not meet 30% decarbonization goals, but when produced using low-GHG renewables it offers strong decarbonization benefits.

Figure 23 also shows supplemental power systems on its right side. The abatement potential of wind, solar, and battery technologies is uncertain (marked with *) due to the limited number of published empirical studies available.

Figure 23 shows that fossil-sourced ammonia and fossil-sourced methanol do not offer any decarbonization potential, and may in fact increase emissions compared to conventional fuels. FAME biofuels have a wide range of abatement potential, depending on the feedstocks and energy sources, but may not offer GHG reductions relative to the conventional fuels baseline (i.e. MDO). FAME, or biodiesel, is currently the most commonly used biofuel in the fleet.[772]

Considering the 30% reduction goal, gray hydrogen is limited in its capacity to meet decarbonization targets. Bio- and e-methanol do meet the targets when produced using renewable energy, as does blue ammonia. When produced using low-GHG energy, those fuels have the potential to meet even 70% reduction targets, but the production pathway is critical or they can fall short.

Figure 23 shows a suite of biofuel blends (assuming B60: Bio Oil, HVO, SVO, DME, bio-FT-Diesel) that have the potential to meet and exceed 30% decarbonization goals. However, unless blends closer to B80 and above are feasible, the decarbonization potential of biofuels is limited to around 50 - 60% compared to conventional fuels. Higher blends (> B30) for certain biofuels will require upgrading fuels and using fuel additives to facilitate compatibility with existing engines, and engine and fuel system modifications may be necessary.

The fuels with potential to achieve greater than 70% WtW GHG reductions include blue hydrogen, green hydrogen and ammonia, FT-Diesel from biogas, and HTL-biocrude. As noted previously, blue ammonia and bio- and e-methanol also have the potential for significant GHG abatement, but only under scenarios where renewable energy sources are available for fuel production. With blue hydrogen and ammonia, fuel production pathways rely on fossil fuel feedstocks and the long-term efficacy of CCUS, which

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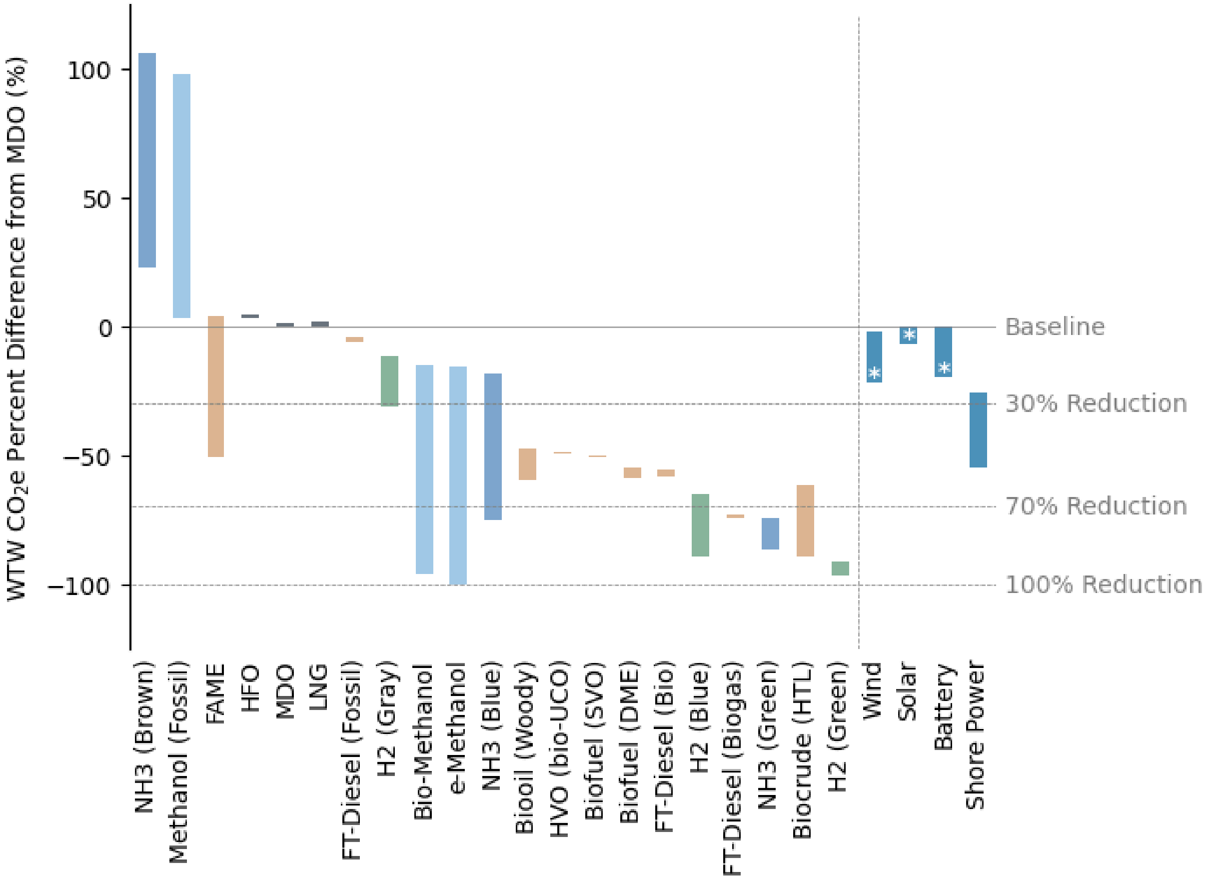
[772] https://www.maersk.com/~/media_sc9/maersk/solutions/transportation-services/eco-delivery/info-sheet-about-bio-fuels-maersk.pdf

remains a relatively nascent industry and not yet at the scale necessary for deep decarbonization.

Figure 23

Decarbonization Potential Compared to MDO



Green hydrogen and ammonia production at scale will require deep decarbonization of the grid and accompanying build-out of dedicated renewable energy sources for production. Current grid mixes range from just over 21% renewables in the U.S. on average,[773] to 40% in Europe,[774] and 49% in California.[775] Green hydrogen and ammonia will be limited in production quantities and in life cycle GHG reductions where the decarbonization of electricity grids and production of dedicated renewable energies lag. Deep decarbonization of energy grids is critical to developing efficient low-GHG fuel production pathways for marine vessels.

Supplemental power systems are shown on the right of Figure 23, including wind assist, solar, battery powered/assist, and shore power. Shore power can reduce at-berth emissions from vessels, aligned with the carbon intensity of shore-side energy sources.

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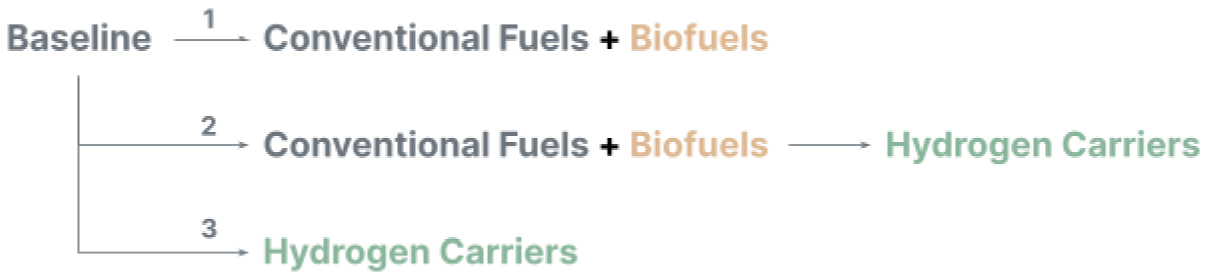
[773] https://www.eia.gov/tools/faqs/faq.php?id=427&t=3
[774] https://www.iea.org/regions/europe
[775] https://www.eia.gov/state/?sid=CA

As local grids trend towards decarbonization, or dedicated renewables proliferate, the at-berth benefits of shore power can extend beyond the 55% reduction in GHGs currently seen in the U.S. While the decarbonization benefits of shore power are limited to at-berth operations, the ability of wind-assist, solar, and battery technologies to produce substantial decarbonization benefits for large OGVs is also limited. While empirical information sources are limited, these technologies are generally estimated to offer 2-20% decarbonization, with some engineering estimates up to 30%.

The decarbonization potential of the fuels shown in Figure 23 indicates the potential for three prime-mover energy pathways to emerge in light of IMO's GHG goals. Under Pathway 1, vessels use a combination of conventional fuels and biofuel blends. This pathway is really an extension of the current baseline (i.e. MDO), with higher uptake of biofuels over time. Under Pathway 2, vessel owners and operators invest in hydrogen-carrier fuel "ready" vessels (e.g. methanol- or ammonia-ready), but initially operate them on a combination of conventional fuels and biofuel blends. A transition occurs once hydrogen-carrier fuel availability and prices become economical in the context of decarbonization goals and standards. Under Pathway 3, vessel owners and operators invest in new-build or retrofit hydrogen-carrier fueled vessels (e.g. methanol-, hydrogen-, or ammonia-fueled) and run those vessels using hydrogen carrier fuels. While different operators may choose to adopt the pathways under varying timelines, Pathway 1 is a near-term timeline under which operators are able to rapidly incorporate decarbonized fuels into their operations. Pathway 2 represents an intermediate timeline where there is investment in the technologies, but deeper decarbonization isn't fully realized until low-GHG molecules are economically available on the market. Pathway 3 is a long-term pathway under which operators invest in alternative fuel vessels and operate primarily on hydrogen carrier fuels.



Energy efficiency measures, supplemental power (i.e. solar and wind), and electrification serve to complement these pathways to lower GHG intensity, but are unlikely to fully replace the prime-mover energy sources due to the high energy demands inherent to maritime operations. Supplementary zero-GHG technologies can be integrated into any of the decarbonization pathways for ocean-going vessels to provide auxiliary power for onboard systems, reduce fuel consumption and emissions, and/or enhance operational efficiency.

While there is a role for supplemental power systems, including wind, battery electrification, and shore power in oceangoing freight transport, these technologies when used alone are not feasible for deep decarbonization of marine transport. Wind systems may provide anywhere from 2-30% energy savings under optimal conditions, but may be incompatible with routing demands and port entry limitations. Battery systems are not technologically ready for large OGVs and require heavy metal mining and refining, with unsolved issues around end-of-use battery recycling. From a WTW perspective, the GHG intensity of battery propulsion or battery-assist is closely linked to the GHG intensity of the electricity source, and would be best applied to renewable grids. Shore power faces similar challenges regarding grid decarbonization, and technical and operational issues.

An integrated approach maximizes the use of renewable energy while ensuring that vessels retain the power, performance, and onboard space required for safe and efficient shipping. Diversifying power or fuel options can provide vessels with resilience and flexibility, aid compliance with regulatory zones like ECAs,[776] and help mitigate risks from price volatility and geopolitical instability.

Decarbonization Pathway 1: Conventional Fuels + Biofuels

Under the Pathway 1, conventionally-fueled vessels begin to blend biofuels into their fuel mixes, incorporating higher percentages of biofuels and achieving corresponding emission reductions. As blends increase in biofuel percentage, those vessel operators will need to upgrade their engine and fuel systems to accommodate biofuels, which may be more acidic or degrade fuel system components. While biofuel blends are increasing, the energy density of the fuel mix may decline, depending on the energy density of the particular biofuels used, meaning vessels will need to adjust operations to accommodate lower operational ranges. Though those adjustments may not be large (0 - 22% lower operational range), they may require significant consideration and planning.

Despite the constraints on biofuel production, which limit its availability for marine vessels, operators are currently incorporating biofuel blends into their operations. IMO regulations treat blends up to B30 (30%) biofuels similarly to conventional fuels. While there is good experience with biodiesel production in Europe, other fuels are either in early development stages or are being produced in limited quantities. Furthermore, the maritime sector faces stiff competition from other sectors for low-GHG transport fuels, further limiting availability and increasing costs.

Energy efficiency measures, electrification, and supplemental power can further reduce carbon intensity under this pathway. Shore power can reduce at-berth emissions by up to 100% with a fully renewable energy grid, though operationally observed reductions in the U.S. are closer to 25 - 60%. Wind sails may be used to reduce energy consumption at sea

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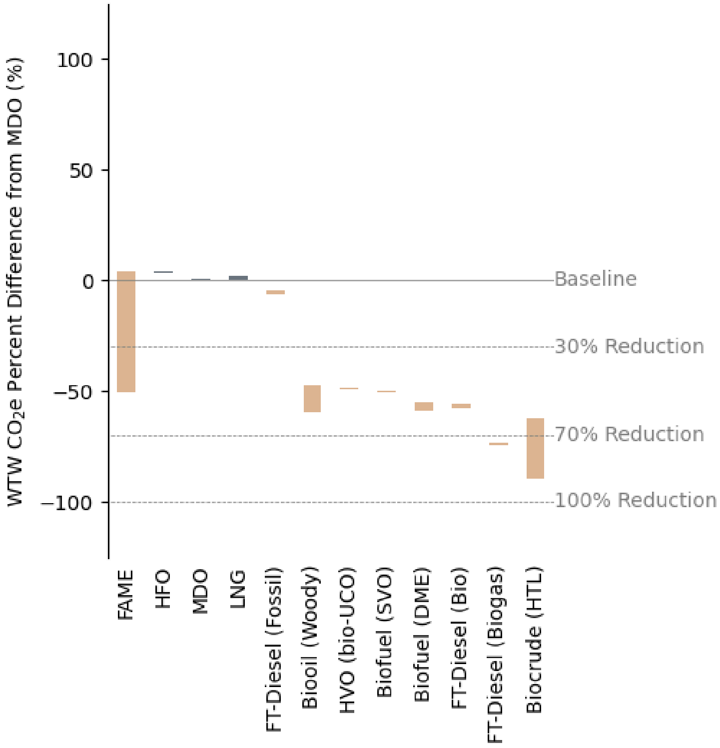
[776] Ammonia combustion can produce NO_x emissions that may exceed NOx ECA limits, necessitating the use of supplementary power or emission abatement technologies to ensure compliance.

by 2 - 20%, depending on prevailing conditions. Depending on fuel and technology availability, biofuels and energy efficiency measures can be immediately adopted for use in OGVs.

From a safety, regulatory, and technology perspective, second-generation biofuels generally do not face many barriers. However, decarbonization with biofuels is ultimately limited unless blends greater than B60 are operationally viable and second-generation feedstocks are available. Feedstock availability is critical for producing biofuels in meaningful volumes for the maritime sector, which sits in direct competition with other transport sectors.

Figure 24

Decarbonization Potential of B60 Biofuel Blends Compared to MDO



Under this pathway shippers can meet near-term decarbonization goals, limited by the percentage of biofuels blended and the decarbonization potential of those fuels. Using B60 fuels as a baseline, this pathway can achieve decarbonization up to around 60% - 80%. In practice, shippers will likely blend biofuels to achieve the most economical blends based on decarbonization standards, but will ultimately be constrained by the decarbonization potential and blending level of the biofuels used.

Considering the IMO's 2023 revised GHG strategy, which strives for 30% decarbonization by 2030, this pathway would require shippers to rapidly incorporate upwards of 84 Mtoe of biofuels into their fuel mix by the end of this decade. Given that global sustainable biofuel production is expected to be around 23 MToe in 2026, and there is competition with other sectors for biofuel, there is a sizable gap in the ability of biofuels alone to satisfy potential demand to meet even near-term decarbonization goals. See *Policy Options to Decarbonize Ocean-Going Vessels* for additional information on policy options related to developing and expanding biofuel production.

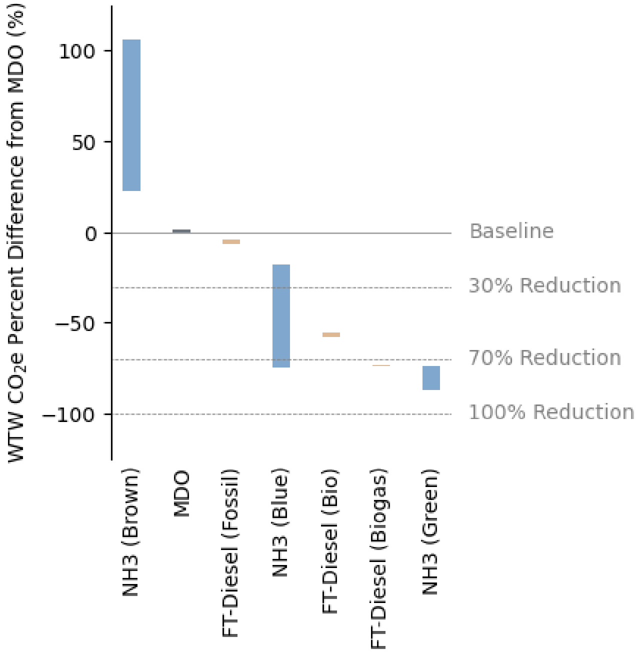
Decarbonization Pathway 2: Conventional Fuels + Biofuels → Hydrogen Carriers

Under Pathway 2 shippers may purchase methanol- or ammonia-ready vessels, but continue to use conventional fuels and blend in biofuels, much like under Pathway 1, until low-GHG hydrogen carriers become widely available, economically viable, and aligned with decarbonization goals. Analysis of planned projects shows that global renewable hydrogen production is expected to grow rapidly in the latter half of this decade, from 0.2 Mt in 2023 to around 20 Mt (~2.4 EJ) in 2030, and subsequently more than doubling to over 40 Mt (~4.9 EJ) by 2050. Using this hydrogen as a feedstock, ammonia and methanol production are expected to follow similar trajectories. Renewable methanol production is expected to grow to around 135 million tons/year (~2.7 EJ) by 2050.

Total energy demand for the maritime sector is estimated to be around 10.5 EJ in 2030, 13 EJ in 2040, and 15.8 EJ in 2050. Comparing production with demand indicates that currently planned low-GHG production of hydrogen carriers, coupled with competition from other sectors, may not fully meet the needs of the maritime sector.

Figure 25

Decarbonization Potential of FT Biofuel Blends and NH_3 Pathways



As low GHG fuels become available, shippers could switch to pathway 3 and implement the shipyard upgrades necessary to convert the methanol- or ammonia-ready vessel to run on a given fuel, taking advantage of lower-GHG emitting hydrogen carriers. While biofuel blends may yield up to around 60 - 80% GHG reductions, low-GHG hydrogen carriers can drive decarbonization further. An example is shown below, where various derivations of FT-diesel may be used to step-down emissions from MDO to just over 70% decarbonization with biogas-derived FT-Diesel. The vessel owner may then opt to switch to green/E-ammonia to further decarbonize as those fuels enter the market at competitive prices.

This pathway provides near-term flexibility in terms of adopting biofuel blends into existing supply chains and marine engines, while also allowing future options for near-zero carbon hydrogen carriers. As with pathways 1 and 3, this pathway faces challenges for decarbonization, limited by biofuel availability and the GHG intensity of hydrogen-carrier production pathways. Decarbonized grids and available renewable feedstocks are critical for cost-competitive decarbonized fuels.

Decarbonization Pathway 3: Hydrogen Carriers

Under Pathway 3 vessel owners and operators invest in vessels and technologies that are either: a) fully capable of running on hydrogen carriers like ammonia, methanol, and LH_2, or b) are “-ready” to run on those fuels with comparatively minor modifications needed to switch over from conventional fuel to those alternatives.

Early adopters under this pathway should be mindful of certain fuel pathways, particularly brown ammonia and methanol, which can actually increase WtW GHG emissions. Fossil-derived hydrogen offers the potential for up to ~32% lower GHG emissions. Coal and natural gas production pathways, while the least cost options, do not enable shippers to reduce carbon by more than ~30%. Furthermore, fossil-derived fuels rely on mining and crude oil extraction and processing, which produce additional deleterious environmental impacts.

As noted under Pathway 2, planned renewable hydrogen production is expected to be around 20 Mt (~2.4 EJ) in 2030 and over 40 Mt (~4.9 EJ) by 2050. Using this hydrogen as a feedstock for low-GHG fuels, ammonia and methanol production are expected to follow similar trajectories, with low-GHG methanol projected to grow to ~2.7EJ by 2050. When combined these estimates fall below projected maritime energy demand in 2040 and 2050, indicating a need for increased effort in producing low-GHG hydrogen carrier fuels to satisfy projected demand.

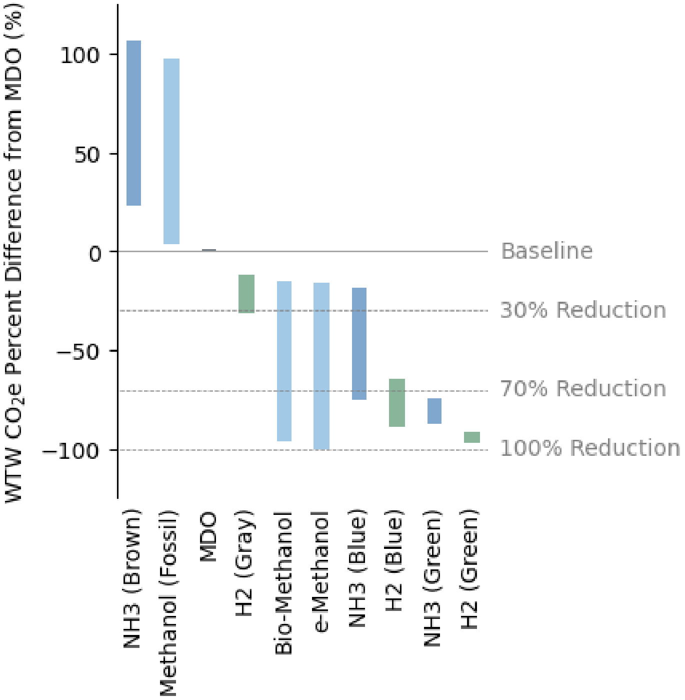
Blue ammonia, hydrogen, and bio- and e-methanol have the potential for decarbonization beyond 70% dependent on energy and feedstock source, while green hydrogen and ammonia have the potential for even deeper reductions. Under this pathway, owners and operators investing in hydrogen, ammonia, or methanol technologies may initially adopt hydrogen carrier fuels with lower decarbonization potential (though not brown ammonia or fossil-methanol, as those increase GHG emissions) due to cost savings and greater fuel availability.

Regardless of the fuel production pathway, methanol molecules are identical (as are ammonia and hydrogen). Fuel systems, storage, and prime movers are unaffected by the upstream carbon intensity of the fuel. Hydrogen, methanol, and ammonia systems can all achieve 90+% reductions relative to MDO. As such, if costs for molecules produced via lower-GHG pathways decline and availability increases, those can be blended with lower GHG versions to achieve desired GHG abatement.

As biofuel decarbonization potential is limited by the blend ratio, one benefit to this approach is that shippers that invest in hydrogen-carrier engine technologies are able to take advantage of the most decarbonized fuels when they come available, without need for engine modifications. Of course, sourcing and uptake of low-GHG fuels relies on competitive pricing, fuel availability, and technology readiness.

Figure 26

Decarbonization Potential of FT Biofuel Blends and Hydrogen Carrier Pathways



From a safety and regulatory standpoint, all three fuels carry non-negligible safety risks, including fire, toxicity, and environmental impacts. And as with other alternative marine fuels, without abundant renewable energy and feedstocks, the costs of low-GHG LH_2, ammonia, and methanol will remain high, and availability will remain low.

Ammonia- and methanol-ready vessels are deployed and operational. Methanol-powered vessels on the orderbook are set to increase from around 26 vessels currently to 138. Liquid hydrogen (LH_2) lags behind in technology readiness. While fuel cells have been applied in other transport modes, challenges remain for implementing fuel cells and hydrogen at the scales needed for large OGVs, and ranges are likely to be limited compared to conventional and other alternative fuels. Furthermore, LH_2 requires cryogenic cooling to -253°C, while methanol may be stored under ambient conditions, and ammonia at -33.3°C. One approach being explored is to use methanol or ammonia as the hydrogen carrier on board the vessel, then pass the chemical through a cracker/reformer to yield molecular hydrogen, which may then be used in a fuel cell.

Among hydrogen, ammonia, and methanol, methanol is the most technologically ready, being widely produced and distributed, providing reasonable energy density, and being used in existing commercial applications. However, the majority of methanol available on global markets today is derived from fossil feedstocks, with limited decarbonization potential. While ammonia is also widely available and used in other sectors, the majority of ammonia available is also derived from fossil feedstocks. Rapid scale-up of low GHG hydrogen carriers is critical to decarbonizing maritime transport. Biofuels can bridge some of the gap toward deep industry decarbonization, but production and second-generation feedstocks are limited. Hydrogen carriers derived from renewable sources are necessary to reduce GHG emissions on a trajectory aligned with IMO goals.

Pathway 3 is a medium- to long-term pathway. There is a need for investment in hydrogen-carrier-ready vessels, which take time to finance and build, and production capacity. While there is demonstrated commercial readiness, low-GHG fuel production also lags significantly behind necessary demand from the shipping sector. Without decarbonized energy grids, production of hydrogen-carrier fuels with the lowest life cycle GHG emissions will be limited to smaller-scale facilities with dedicated renewables. Pathway 3 relies on deep decarbonization of the energy grid to economically produce low-GHG fuels. Without extensive land-based measures and policies to promote clean energy production, low-GHG marine fuel availability will lag behind production levels necessary to meet GHG targets.

Section 9: Conclusion

The decarbonization potential of alternative marine fuels are shown in Figure 27 and Table 24. Ranges in decarbonization potential reflect uncertainty in the literature calculations, based on different energy inputs and feedstocks. Figure 27 shows that, except for fossil-derived methanol and fossil-derived ammonia, alternative fuels do have the potential to lower GHG emissions from marine transport. Brown and gray fuels are included for illustrative purposes, and may provide early potential pathways to decarbonization while lower emission pathways are developed. However, brown and gray fuels should not be considered long-term candidates for decarbonization as they rely on fossil-fuel feedstocks, offer limited abatement potential, and may become stranded assets in the global energy transition.

Table 24

Summary of well-to-wake greenhouse gas emissions from alternative and conventional bunker fuels and percent difference from MDO

Fuel	WtW $kgCO_2/MJ$ (Low)	WtW $kgCO_2/MJ$ (High)	% Diff (Low)	% Diff (High)
MDO	0.092	0.094	NA	NA
H2 (Gray)	0.063	0.083	-32	-12
H2 (Blue)	0.010	0.033	-89	-65
H2 (Green)	0.003	0.008	-97	-92
Methanol (Fossil)	0.095	0.186	3	98
Bio-Methanol	-0.055	0.070	-160	-26
e-Methanol	0.000	0.079	-100	-16
NH3 (Brown)	0.113	0.194	23	106
NH3 (Blue)	0.023	0.077	-75	-18
NH3 (Green)	0.012	0.024	-87	-75
Biofuel (DME)	0.001	0.008	-99	-92
Biofuel (SVO)	0.014	0.014	-85	-85
Bio-oil (Woody)	0.001	0.020	-99	-79
FT-Diesel (Bio)	0.003	0.007	-97	-93
FT-Diesel (Fossil)	0.088	0.088	-4	-6
FT-Diesel (Biogas)	-0.022	-0.022	-124	-123
HVO (bio-UCO)	0.016	0.016	-83	-83
FAME	0.014	0.100	-85	6
Biocrude (HTL)	-0.003	-0.046	-103	-149
LNG	0.094	0.094	2	0
HFO	0.095	0.097	3	3

Hydrogen has the potential to lower GHG emissions by around 92 - 97% compared to MDO, the current conventional bunker fuel, but only through green/E- pathways. Fossil-derived gray hydrogen only reduces GHG emissions by only 12 - 32% and can have significant upstream emissions depending on the feedstocks and energy sources used. Hydrogen as a marine fuel requires special handling, due to the cryogenic nature of the fuel (-253°C), and is most efficiently used in fuel cells rather than combustion engines.

Methanol shows a wide range in carbon intensity, depending on the production pathway and feedstocks used. Fossil-derived methanol may actually increase emissions by 3 - 98%, while bio-methanol and e-methanol each offer significant abatement (26 - 160% reduction and 16 - 100% reduction, respectively). While the end-use prime-mover molecule is practically identical, the production pathway has a large influence on the life cycle (WtW) carbon intensity of methanol. Methanol is a liquid under ambient conditions and does not require special infrastructure, though it does pose safety hazards.

Fossil-derived ammonia is 23 - 106% more carbon- intensive than conventional bunkers, whereas fossil + CCUS[777] (18 - 75% GHG reduction) and e-/green (75 - 87% reduction) production pathways offer significantly lower GHG emissions. Ammonia as a marine fuel requires special handling, due to the toxic nature of the fuel, and requires cooling (-33.1°C) to maintain the fuel in a liquid state.

There are a wide array of biofuels that may be used in the maritime sector. Many of these fuels offer significant emission reductions relative to MDO (Table 24), though it is important to only consider fuels derived from second generation or advanced feedstocks that do not induce significant land use and land cover change effects, or impact food supply. Biofuels are generally seen as drop-in fuels, requiring little-to-no modifications for infrastructure or engines. Biofuels are typically blended with conventional fuels for use in marine engines. The decarbonization potential depends on the biofuel percentage in the blend.

Supplemental power systems, including wind, solar, and batteries can help reduce the carbon intensity of shipping by reducing the effective load on propulsion or auxiliary engines during vessel operations (wind), or providing clean energy when needed (solar, battery). Estimated energy savings from supplemental wind-assist range from 2-30%, though practical observations are generally closer to 5%, and are highly dependent on wind speed, direction, and vessel operational needs.

Supplemental solar power systems are not common on board vessels, and offer limited energy savings. Battery systems, either for supplemental or propulsive power are currently most viable over short distances, and future uptake relies upon improved battery chemistry for the marine environment, improved energy density, and lower costs.

Pathway 3, utilizing hydrogen carriers, has the potential to bring the maritime sector the closest to achieving net zero targets. However, early adopters must consider the life cycle emissions associated with these carriers when derived from fossil feedstocks and production of low-GHG hydrogen carriers must scale. The maritime industry is witnessing

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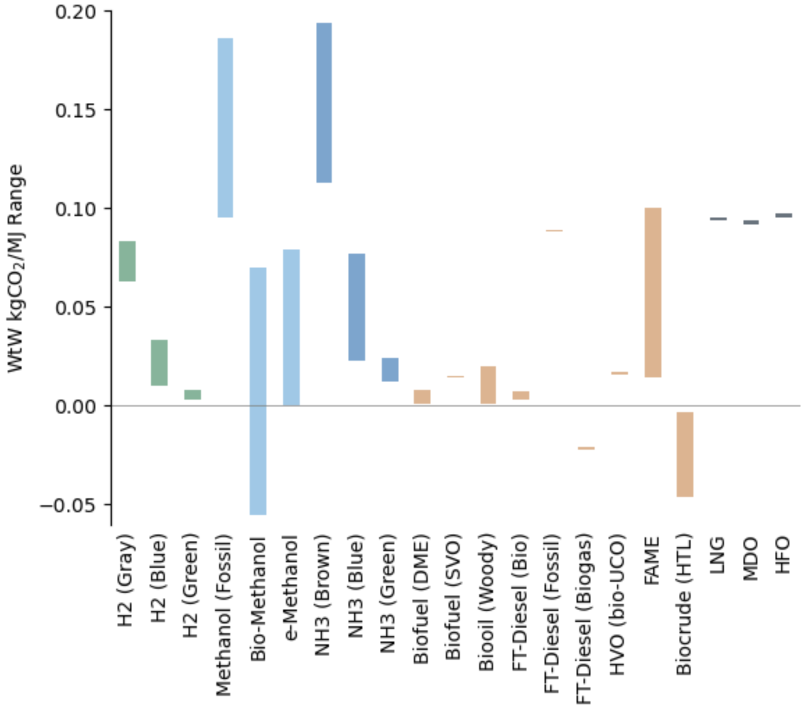
[777] Current, real-world rates sit at approximately 39% CO_2 capture, less than the rates up to 90% assumed for most studies / https://doi.org/10.1016/j.egyr.2023.08.021

a growing popularity of dual fuel engines, and support of power diversification. Until renewable grids and bio-/e- production have reached maturity, vessel operators may seek other efficiency measures in combination with alternative fuels (i.e. supplemental power systems).

Figure 27

Range in well-to-wake greenhouse gas emissions from alternative and conventional bunker fuels



Infrastructure for hydrogen production, storage, and distribution requires substantial investment and efforts to support its widespread adoption, particularly to scale for OGVs. Among hydrogen carriers, methanol and ammonia are likely to be the first applications of hydrogen fuel on OGVs. Methanol, in particular, offers advantages such as relatively straightforward storage and operation at ambient temperatures and well-established infrastructure. Hydrogen carriers, particularly bio- and e- fuels, could be a transitional step towards the broader adoption of zero-GHG hydrogen propulsion in fuel cells. In early applications, hydrogen carriers like methanol and ammonia may be employed with supplemental technologies to improve vessel efficiency and offset fuel costs.

As technology advances and infrastructure matures, carriers can be cracked to utilize hydrogen directly. While hydrogen fuel cells and supplementary power systems show promise for substantial GHG reductions, these are in the early stages of piloting and development, and would benefit from increased public and private support to develop the technical solutions to any challenges. This underscores the need for continued regulatory support, investment, and innovation to scale these power sources effectively and align with decarbonization targets.

There are a range of fuels presented within this report representing the highest potential for decarbonization within the maritime sector. Given the unique technical and operational aspects of both OGVs and the shipping industry, there will most likely remain a range of zero- and low-GHG fuels into and past 2040 to meet climate and health goals within California and globally. This will most likely involve developing new infrastructure, protocols, and standards compatible with this next generation of marine fuels, similar to previous energy transitions in history. Significant economic, employment, and health benefits are possible within the maritime energy transition representing an important opportunity and need for critical policy support and continued investment.