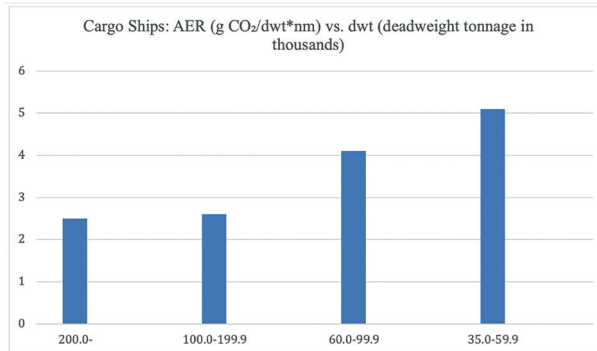
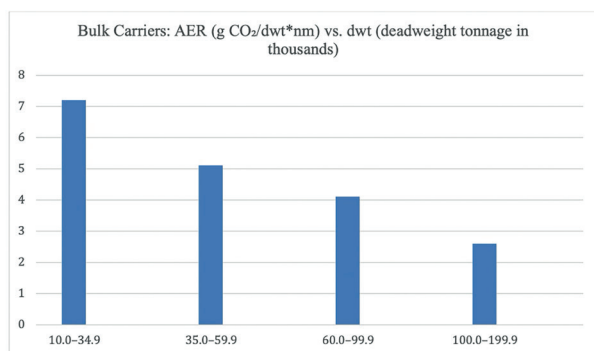




# ALTERNATIVE MARINE FUELS: A COMPREHENSIVE REVIEW OF PATHWAYS, CHALLENGES, AND PROSPECTS FOR DECARBONIZING SHIPPING

## Introduction

The shipping industry accounts for approximately 80% of global commerce, producing around one billion tonnes of carbon dioxide per year [1, 2]. This high level of emissions is largely due to the scale of global trade and the widespread use of traditional marine fuels such as heavy fuel oil (HFO) and marine gas oil (MGO), which are renowned to be highly carbon intensive. While efficient for transporting mass commerce, large diesel engines burn huge quantities of these fuels, resulting in significant carbon dioxide emissions. As illustrated Figures 1 and 2, bulk carriers and container ships account for among the highest carbon dioxide emissions within the maritime sector, reflecting their size, cargo capacity, and extensive fuel consumption.



Figures 1 & 2 Carbon Emission Intensities: AER (Annual Efficiency Ratio) vs. dwt for Bulk Carriers and Cargo Ships, respectively [4].

Consequently, the International Maritime Organization (IMO) strives to reach net-zero emissions by 2050. In addition to carbon emission concerns, the IMO has enforced a global sulfur cap of 0.50% by mass. Compared to the limit of 3.50%, this represents an approximate 85.7% reduction in allowable sulfur content of marine fuels, aimed at reducing sulfur oxide emissions. Further, in emission control areas (ECAs), fuels must contain no more than 0.10% sulfur by weight [3]. In response to these environmental regulations, shipowners are being pushed to transition from conventional fuels toward low and zero-carbon alternatives. Over the past two years, significant advancements have been made in marine fuels: options that were previously hypothetical, such as liquefied natural gas (LNG), methanol, hydrogen, ammonia, and biofuel/green variants, are being exposed to more experimentation, innovation, and even commercial usage. However, environmentally friendlier alternatives are still immature, as they often come with lower energy density, higher production costs, and limited global infrastructure.

## Liquefied Natural Gas

LNG is primarily composed of methane, with small amounts of ethane, propane, and traces of other hydrocarbons. It takes a liquid state after being cooled to about -162 °C; this process makes it much denser, enabling storage convenience and efficient transportation. It is seen as a transition fuel for the maritime industry because it produces almost zero sulfur oxides, reduces nitrogen oxides by ~85%, and cuts carbon emissions by ~25% [5]. Generally, LNG burns cleaner compared to HFO, paving the pathway to net-zero emissions. However, there are significant downsides to the current state of LNG technology. Aside from expensive infrastructure and lifecycle emissions, methane slip is a major flaw. Methane slip refers to the unburned methane that escapes from the ship's engine during combustion or fuel leakage, entering the atmosphere. This occurs because portions of methane are not completely oxidized to carbon dioxide and water.

Following the policies such as the IMO's sulfur cap in 2020 under MARPOL Annex VI, LNG has emerged as one of the earliest and most prominent sources of alternative fuels to HFO and MGO. This immediate, unprecedented change in policy directly contributed to the adoption of alternative fuels, such as LNG and dual-fuel systems that can operate on both LNG and conventional marine fuels. Moreover, LNG is seen as a 'band-aid' or transition fuel while truly zero-carbon alternatives are developed. Although still fossil-fuel based, it burns much cleaner than conventional fuels and is viable for large-scale deployment, serving as a 'bridge' to renewable fuels.

As of 2025, a total of 1,369 LNG dual-fuel vessels is in operation or on order globally, supported by nearly 200 ports equipped with LNG bunkering facilities [7]. This supports LNG's increasing prevalence and status as a popular transitory fuel; to deal with mentioned downsides, initiatives have been taken to advance LNG technology. For instance, MAN Energy Solutions introduced a new future-proof, cost efficient, and methanol-compatible auxiliary engine to reduce emissions. The MAN 33/44DF CD incorporates features aimed at lowering greenhouse gas emissions for LNG container ships and carriers. Based on controlled and field tests, the engine reduces methane slip by 85% compared to typical marine fuel standards [8]. Features include engine calibration, operating strategies, and advanced oxidation catalysts such as the IMOKAT II, which is a sulfur-resistant, precious metal-free catalyst for four-stroke engines. Further, this catalyst specifically aims to reduce 70% in methane slip at 100% load [9]. Figure 3 shows an image of the engine:

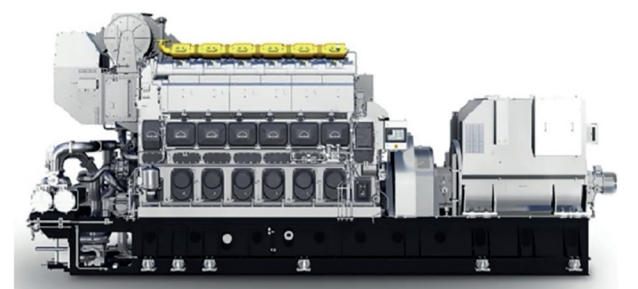


Figure 3: An image of the MAN Energy Solutions 35/44DF CD Engine [10].

Alongside other engine prototypes, the MAN 35/44DF CD passed the Type Approval Test in April 2025 at the STX Headquarters in South Korea, with expected upcoming commercial usage within 2025 [7]. Similarly, Technology group Wärtsilä has introduced the Wärtsilä 46TS-DF dual-fuel engine that operates



on LNG. The Wärtsilä 46TS-DF is equipped with 'NextDF Technology', an enhancement in combustion that significantly reduces methane slip. Based on controlled tests during engine development, the engine can limit methane emissions to below 1.4% across all load points, capable of reaching 1.1% across a wide operating range. These numbers are almost a third of the 3.1% maximum methane threshold enforced by the IMO and FuelEU Maritime for Otto-cycle four-stroke dual-fuel engines.

The system incorporates in-cylinder pressure sensors to monitor each occurrence of combustion, allowing feedback that adjusts injection timing and the mixture of air/fuel to reduce pockets of unburned methane, or methane slip. NextDF engines also operate with a higher air-fuel ratio, lowering peak combustion temperatures that helps reduce nitrogen oxide as well [11]. Overall, NextDF's combustion control leads to optimizations in engine performance and reduced nitrogen oxide and carbon dioxide emissions. In fact, the first installation of the Wärtsilä 46TS-DF is planned for the MSC World Asia cruise ship, which is expected to enter operation in 2026 [6]. Figure 4 shows an image of the engine:

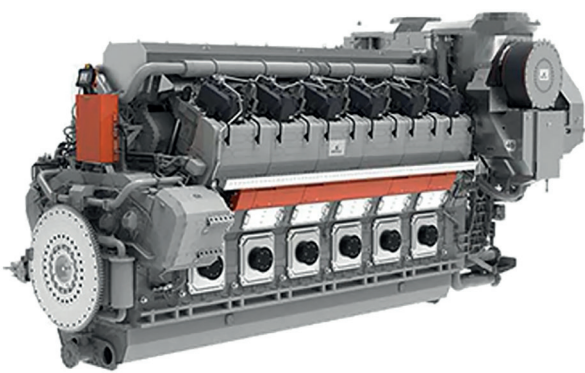


Figure 4: An image of the Wärtsilä 46TS-DF dual-fuel engine [6].

The rapid advancements in LNG-tailored engine technologies, aimed to lower both greenhouse gas emissions and methane slip, and active the deployment in commercial marine operations demonstrate the sector's committed transition towards cleaner propulsion solutions.

In addition to innovative emission-reducing LNG dual-engines, the fuel itself has been revolutionized. Mentioned earlier, LNG's role as a 'bridge' fuel to renewable energy is increasingly prevalent with widespread adaptations, especially following the carbon emission restrictions implemented by the European Emissions Trading System (EU ETS) and the FuelEU Maritime

regulation. Bio-LNG is continuing to gain momentum as LNG infrastructure continues to expand. It is made by anaerobic digestion of organic material, such as agricultural waste, food waste, and sewage sludge, making it renewable and sustainable. Moreover, the production of bio-LNG is deemed "carbon-neutral" and is chemically identical to regular LNG and is therefore compatible with LNG engines and infrastructure. The need for minimal reductions essentially makes LNG a "drop-in alternative" and is a huge advancement for the shipping industry considering its increased commercial use.

Subsequently, the First Bio-LNG Plant in the Netherlands has

*LNG is primarily composed of methane, with small amounts of ethane, propane, and traces of other hydrocarbons.*

been in operation since late 2024, particularly focused on maritime applications. Located in Wilp, Gelderland, the facility was a collaboration project between Nordsol, Attero, and Titan Clean Fuels, recognized as FirstBio2Shipping. An estimated 2,400 tons of bio-LNG from biogas are produced annually and then distributed to bunkers by customers such as Titan. Still, this is a relatively small number compared to global marine fuel demand, ranging in millions of tons. Additionally, distribution is geographically limited due to a lack of infrastructure in ports, such as specialized cryogenic tanks, pipelines, and safety precautions. Vessels functioning on bio-LNG require larger tanks as well due to their less energy density compared to heavy fuel oil and marine gas oil. The annual greenhouse gas emissions from the production of bio-LNG at this site were reduced by 92% compared to MGO and HFO. This is only claimed to be achievable under compliance with Article 5 and Annex III of Regulation (EU) 2023/1805. Article 5 sets strict sustainability criteria and greenhouse gas saving requirements for renewable fuels, including sourcing feedstock responsibly and minimizing lifecycle emissions. Annex III ensures that these criteria are verified and certified. By meeting these requirements, the FirstBio2Shipping plant demonstrates that bio-LNG can scale sustainably for maritime applications, offering a practical alternative to conventional fuels while aligning with EU decarbonization goals [12]. Ultimately, recent advancements in LNG-fuel technology including dual-fuel engines and the reduction of methane slip marks tangible progress towards decarbonization—not only are carbon emissions trending down but supports that alternative fuels can be integrated into shipping operations.

#### Methanol

Methanol has been recognized as a viable alternative shipping fuel since 2016. Not only is it recognized for being more environmentally friendly with lower emissions of sulfur oxides, nitrogen oxides, and particulate matter, in addition to the synthesis of bio-methanol from decomposing matter, it proves as a cost-effective solution. Now, a major trade off in the usage of methanol is its significantly lower price, being 38.6% cheaper per metric ton compared to diesel; however, annual fuel costs increase by 28.16% due to methanol being less energy dense, requiring a 28% reduction in ship speed to keep consistent cost of fuel [13]. Practices like reducing ship speed or "slow steaming" can counteract the higher annual fuel costs by reducing fuel consumption, but this comes at the expense of fewer trips and additional operational and miscellaneous costs [13]. Nevertheless, if methanol propulsion systems become a primary source of fuel, there are significant economic benefits in terms of investment for infrastructure compared to LNG due to factors such as specialized equipment, such as cryogenic storages and pumps, and extensive safety systems.

These factors, especially the proposed environmental benefits, have prompted advancements in new ship designs and bunkering infrastructure. Specifically, in July of 2023, Maersk, one of the world's largest container shipping companies, and Hong Lam Marine Pte Ltd., a leading operator of coastal vessels in Southeast Asia, successfully refueled a Maersk container vessel in the first-ever ship-containership methanol bunkering procedure. Further, this procedure was completed with bio-

methanol. Bio-methanol, also referred to as green methanol, is produced from biomass (agricultural waste, biogas) or renewable resources instead of fossil fuels. Thus, the key difference from conventional methanol is that bio-methanol is carbon-neutral or low-carbon depending on the method of production.

The ship was refueled with an estimated 300 metric tons of bio-methanol, delivered by Hong Lam's MT Agility tanker. This new vehicle was also successfully refueled by bio-methanol stored at Vopak Terminals; however, no public data regarding performance and emissions data was released [14]. Following this, container shipper company X-Press Feeders carried out its inaugural bio-methanol at the port of Singapore in 2024, follows the company's reception of fourteen dual-fuel methanol-ready vehicles during May. This aligns with the company's goals of using more methanol to reduce carbon emissions by 20% before 2030, and by 100% by 2050. These recent accomplishments not only demonstrate successful pilot operations but also represent the step towards operational scaling of methanol-fueled shipping; to conduct large-scale bunkering shows the advancements of methanol fueling logistics and port compatibility [15]. In conjunction with the newly developed engines for LNG, methanol's increasing prevalence is being demonstrated by new dual-propulsion engines catered to methanol are being released.

#### Hydrogen

Although studied for roughly half a millennium, hydrogen has only been developed and scaled up for maritime applications in recent years. Viewed as one of the most likely fuels to be used in the future, hydrogen, especially 'green hydrogen,' perfectly aligns with future goals of the maritime industry and policy-enacting organizations such as the IMO. As context, green hydrogen is produced by electrolysis of water using renewable electricity (wind or solar power), producing oxygen as the only byproduct. Compared to hydrogen, which is usually produced from the partial combustion of methane, green hydrogen serves as a carbon-free alternative. Additionally, with the combination of hydrogen fuel cells, hydrogen can be a fuel source that generates no emissions (shown below) with byproducts of only heat, water, and electricity [16]. As marine fuel, green hydrogen supports carbon-neutral fuel cells and propulsion systems; however, like all other non-conventional fuels, challenges arise with insufficient storage systems and infrastructure. Shown in Figure 5 is a diagram of a hydrogen fuel cell.

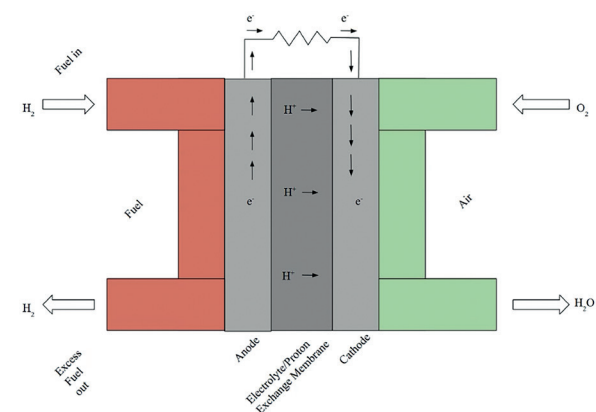


Figure 5: An adapted image of a schematic diagram of a hydrogen fuel cell [17].

Concluding in early 2024, a five-year collaboration between Bay Area Air Quality Management District and SWITCH Maritime produced Sea Change, the first U.S. hydrogen fuel cell-powered passenger ferry. This pioneering vessel demonstrates the viability of zero-emission technology for maritime applications, such as freight transportation and government operations. Thomas Hall, spokesman of the ferry service, commented on its first passenger cruise. He claimed that the ship performed as described and drew excitement from the community. A drawback he mentioned was the lack of fueling providers which only provided gray hydrogen (hydrogen produced from natural gas, like methane), not renewable green hydrogen [18]. After demonstrations of passenger service and regulatory approval (Certificate of Inspection) from the U.S. Coast Guard, the project began commercial passenger service on July 19, 2024, in the Francisco Bay Area [1]. Ultimately, this project sets a powerful precedent for the future of marine fuels. Sea Change has proved the commercial feasibility of a recently developed fuel and validates the possibility of hydrogen bunkers through its operation and refueling. Figure 6 is an image of Sea Change.

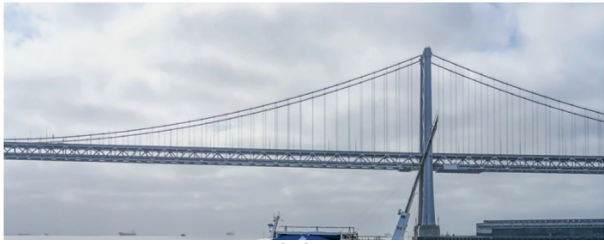


Figure 6: An image of Sea Change [18].

In 2024, Japan's Yanmar Power Technology delivered their GH240FC maritime hydrogen cell system to HANARIA, a passenger vessel. The ship is an example of Japanese maritime innovation as it holds the status of being the first hybrid passenger ship. The fuel system features "a proprietary lithium-ion battery system... and an integrated management system that controls all onboard power." It also includes two modes of operation: a combination of hydrogen cells with lithium-ion batteries to produce zero emissions, and a biodiesel generator. However, because hydrogen requires large storage volumes and there is a lack of infrastructure for fueling, HANARIA can only conduct short to medium ferry operations. Yanmar's team received an award in Japan for "best marine engineering of 2024," and, likewise, HANARIA was awarded with "ship of the year 2024" by the Japan Society of Naval Architects and Ocean Engineers. The ship has been operational since April 2024 [20].

Demonstrated by these projects, modern marine technology is increasingly focused on integrating hydrogen propulsion into commercial and public maritime transport, marking the shift from small-scale demonstrations. With the employment of hydrogen fuel cells, hydrogen can be a major player towards reaching net-zero emissions, but is faced with insufficient storage capacity, low energy density, and limited bunkering infrastructure. Moreover, hydrogen's low volumetric energy density makes it impractical for high-fuel demand vessels like cargo ships and tankers, as needed for larger storage [21]. The industry is confronting these challenges by using cryogenic tanks; this stores the hydrogen at extremely low temperatures (-253°C) to increase density, though this needs significant energy, specialized insulation, and more precautions. Solid-state storage materials chemically bind hydrogen for more compact and safer containment but are still in development [21]. Therefore, an alternative approach uses ammonia as a hydrogen carrier. Ammonia, compared to hydrogen, is more volumetrically dense and stable, making it more suitable for transport. The ammonia onboard can be cracked back into hydrogen using catalysts. However, this conversion process is still inefficient because of substantial heat requirements [22]. Beyond storage technology, a lack of adequate infrastructure further restricts hydrogen's immediate viability, as hydrogen bunkering facilities are scarce and under development.

**Ammonia**

Ammonia is another promising candidate for the zero-emission future of marine technology, although more nascent in development than newer fuels such as hydrogen. Both hydrogen and ammonia are carbon-free molecules that can be produced in a "green" manner by using renewable energy and electrolysis instead of fossil fuels. Furthermore, in comparison to hydrogen, ammonia has a particular advantage of being 'easier to handle' compared to hydrogen. Ammonia can be stored at -33 °C, while hydrogen needs cryogenic (-253 °C) or high-pressure conditions for storage [22], [23]. Also, due to ammonia being one of the most traded chemicals in the world as fertilizer products, there are well-established global storage tanks, pipelines, and port terminals.

Despite its promising theoretical advantages, ammonia faces several hurdles that have delayed its development and usage as a fuel, including its toxicity, combustion challenges (slow and difficult to ignite/burn, ammonia slip), nitrogen oxide emissions, and insufficient development in the scaling of producing green ammonia. Despite the many challenges and intimidation factors for using ammonia, significant advancements have been made, specifically in the innovation of engines, creation of functioning vessels, and the overall step towards ammonia as a possible fuel.

At a land-based testing facility in Perth, Australia, a mining company named Fortescue successfully converted two four-stroke engines to function on a dual-fuel system consisting of ammonia and diesel. This retrofitted engine was installed in a vessel called the Green Pioneer, demonstrating the adaptability of alternative and even synergistic fuel sources within existing engine systems. The ship is seen as a symbol for marine-

engineering ammonia, as the vessel has been presented as a model for several meetings for the UN Framework Convention. Post-October 2023, the Green Pioneer completed the world's first ammonia bunkering trial in Singapore. Ammonia was loaded from Vopak's existing infrastructure, suggesting that completely new systems may not be needed.

The trial involved using the retrofitted four-stroke engines as proxies for actual ammonia-fueled engines under development. A highlighted result was combustion, considering the compound's poor burning efficiency and emissions. The post-combustion of nitrogen oxide met local air quality levels, but diesel/pilot fuel (used to help ignite ammonia) and nitrous oxide still need to be reduced [24]. In contrast, traditional diesel engines achieve high combustion efficiency, with known nitrogen oxide emissions that are controlled using selective catalytic reduction or exhaust gas recirculation. Further, diesel engines do emit carbon dioxide, but do not require pilot fuels for ignition, and their energy density permits longer travel. The Green Pioneer showcases the potential of ammonia as a fuel source but is still immature to be widely implemented.

Ammonia-focused energy provider Amogy's marine vessel, the NH<sub>3</sub> Kraken, completed its first voyage whilst being completely carbon-free and ammonia-powered. Originally a tugboat constructed in 1957, the NH<sub>3</sub> Kraken was retrofitted with an ammonia-to-electrical power system and sailed on the Hudson River. This specialized design breaks down liquid green ammonia into hydrogen and nitrogen, with hydrogen channeled into a fuel cell to create carbon-free power. Amogy's missions and projects aim to change the fuel setting to be more carbon-free, especially considering the widespread use and abundance of ammonia [25]. Although the functioning of the vessel serves as a step towards ammonia as an alternative fuel, there are still existing obstacles: energy density, storage challenges, engine efficiency, and, mentioned earlier, nitrogen oxide emissions.

The previously mentioned technology group, Wärtsilä, has officially partnered with Norwegian shipowner Eidevisk to convert Viking Energy, a platform supply vessel, to run on ammonia by the first half of 2026. Introduced in November 2023, Wärtsilä's ammonia solution enables up to 90% reduction in greenhouse gas emissions compared to diesel engines based on controlled lab testing. However, nitrogen oxide emissions remain a concern, requiring selective catalytic reduction to be cleaner [26, 27]. The engine is based on low-pressure Otto-cycle dual-fuel technology originally developed for LNG, making it compatible with current, existing modern engines. Wärtsilä claims current decarbonization methods can reduce shipping emissions up to 27%, but greener fuels like ammonia are needed to eliminate that remaining 73% [28].

Ultimately, the experimentation and advancements with ammonia are continuing to gain credibility—although there are many unanswered issues; advancements prove ammonia's potential to be an alternative marine fuel. While LNG has already gained traction commercially, it is evident that emerging zero-emission-capable fuels such as methanol, hydrogen, and ammonia are gaining popularity. Table 2 provides a contextual overview regarding vessels on order and in operation.

Table 2: Numbers on operational and on-order alternative fuel vessels, as of 2024 [29].

Type of Alternative Fuel	Operational or Built	On Order
Methanol	34	244
Hydrogen	14	29
Ammonia	3	26

**Conclusion**

The rapid pace of advancements in LNG, methanol, hydrogen, and ammonia over the past two years proves how the maritime industry is already taking immediate action in reimagining a greener era of transportation. LNG continues to serve as a transitional fuel with improved methane slip reduction, while methanol has reached commercial viability through successful large-scale bunkering operations such as Maersk's trial in 2023. Bio-methanol is also being largely produced, hinting at initiative to invest into alternative fuel infrastructure. Likewise, hydrogen and ammonia have moved beyond laboratory testing, with vessels like Amogy's Green Pioneer functioning carbon-free propulsion and the HANARIA commercially utilizing hydrogen fuel cells. Despite these advancements, overarching challenges remain, including limited global infrastructure, lower energy

density, combustion inefficiency, and persistent nitrogen oxide emissions (particularly in ammonia-based technology). Addressing these obstacles requires engineering innovations, such as refined dual-fuel systems, enhanced selective catalytic reduction, and ammonia-cracking technology to improve combustion efficiency and flexibility in fuel.

Ultimately, the progress accomplished within the past two years heavily emphasizes the possibility of greener marine fuel alternatives. As new vessels are launched, ports expand bunkering systems, and fuel is further cleaned. The maritime sector looks ahead to an emerging era of a zero-emission standard.

**Works Cited:**

[1] T. Furusaki and M. Asmussen, "The role of maritime fuel projects in decarbonizing shipping," World Economic Forum, Apr. 18, 2024. Available: The role of maritime fuel projects in decarbonizing shipping | World Economic Forum.

[2] International Energy Agency (IEA), "International shipping," IEA, 2022. Available: International shipping - IEA.

[3] International Maritime Organization, "IMO2020 fuel oil sulphur limit – cleaner air, healthier planet," IMO, 28 Jan. 2021. Available: <https://www.imo.org/en/mediacentre/pressbriefings/pages/02-imo-2020.aspx>.

[4] J. Boekhoff, "Understand your shipping emissions," CarbonChain, Nov. 1, 2022. Available: Understand your shipping emissions.

[5] SEAM, "The Promising Fuel Options of the Maritime Energy Transition," SEAM Insights, May 7, 2024. Available: The Promising Fuel Options of the Maritime Energy Transition - SEAM

[6] Wärtsilä, "Wärtsilä expands methane slip reduction capabilities by introducing NextDF technology for third engine," Press Release, Apr. 30, 2025. Available: Wärtsilä expands methane slip reduction capabilities by introducing NextDF technology for third engine.

[7] SEA-LNG, The LNG Pathway: Mid-Year Market Review, July 2025. Available: 18318\_SEA-LNG\_2025\_Mid-Year\_Review\_v3.pdf.

[8] "MAN Energy introduces auxiliary engine aimed at reducing emissions," World Oil, 12 June 2023. Available: MAN Energy introduces auxiliary engine aimed at reducing emissions.

[9] MAN Energy Solutions, "New Project Aims to Significantly Reduce Four-Stroke Methane Slip," MAN Energy Solutions, 20 Nov. 2023. Available: New Project Aims to Significantly Reduce Four-Stroke Methane Slip

[10] MAN Energy Solutions, "MAN L35/44DF CD GenSet Passes Type Approval Test," Press Release, 19 May 2025. Available: MAN L35/44DF CD GenSet Passes Type Approval Test.

[11] Wärtsilä, "How Innovative NextDF Technology Is an Easy Way to Reduce Methane Emissions," Wärtsilä Insights, 18 Feb. 2025. Available: How innovative NextDF technology is an easy way to reduce methane emissions

[12] J. Berger, "Bio-LNG for Seagoing Vessels – Direct CO<sub>2</sub> Reduction without Retrofit," Berger Maritiem, Jun. 22, 2025. Available: Bio-LNG in 2025: Direct Emissions Reduction for LNG-Powered Vessels.

[13] D. Parris, "Methanol, a plugin marine fuel for greenhouse gas reduction," Energies, vol. 17, no. 3, p. 605, 2024. Available: Methanol, a Plugin Marine Fuel for Green House Gas Reduction—A Review.

[14] Reuters, "Maersk's methanol ship makes maiden refuelling in Rotterdam," Reuters, Aug. 29, 2023. Available: Maersk's methanol ship makes maiden refuelling in Rotterdam | Reuters.

[15] Reuters, "X-Press Feeders completes its first bio-methanol bunkering at Singapore," Reuters, May 27, 2024. Available: X-Press Feeders completes its first bio-methanol bunkering at Singapore | Reuters.

[16] U.S. Department of Energy, "Fuel Cell Basics," Office of Energy Efficiency & Renewable Energy. Available: Fuel Cell Basics | Department of Energy.

[17] A. Rossi, "Electrolyzer and Hydrogen Fuel Cell Safety," Electrolyzer, Green Energy, Mar. 14, 2023. Available: Electrolyzer and Hydrogen Fuel Cell Safety | TotalShield

[18] C. Conley, "Next-Gen Marine Fuels Power Progress, Yet Challenges Remain," WorkBoat, 14 July 2025. Available: www.

workboat.com/next-gen-marine-fuels-power-progress--yet-challenges-remain

[19] L. E. Klebanoff, MV Sea Change: Fuel Cell, Emissions, and Hydrogen Fueling Performance, Sandia National Laboratories, Tech. Rep. SAND2024-11463, Sept. 2024. Available: [Sea-Change-DOE-Report.pdf](#).

[20] Yanmar Holdings Co., Ltd., "Passenger Ship HANARIA Equipped with Yanmar's Maritime Hydrogen Fuel Cell System Wins Marine Engineering of the Year 2024," Yanmar News, 23 July 2025. Available: [Passenger Ship HANARIA Equipped with Yanmar's Maritime Hydrogen Fuel Cell System Wins Marine Engineering of the Year 2024 | 2025 | News | Marine Commercial | YANMAR](#).

[21] MAN Energy Solutions, "New Project Aims to Significantly Reduce Four-Stroke Methane Slip," MAN Energy Solutions, 20 Nov. 2023. Available: [New Project Aims to Significantly Reduce Four-Stroke Methane Slip](#)

[22] J. H. Jacobsen, "Ammonia: a cracking opportunity for hydrogen," Topsoe Blog, Dec. 07, 2024. Available: [Ammonia: a cracking opportunity for hydrogen](#).

[23] U.S. Department of Transportation Maritime Administration, "Exploring Liquid Hydrogen Tank Technology for Zero-Emission Fuel Cell Vessels," 26 Mar. 2024. Available: [Exploring Liquid Hydrogen Tank Technology for Zero-Emission Fuel Cell Vessels.pdf](#)

[24] U.S. Department of Energy, "Fuel Cell Basics," Office of Energy Efficiency & Renewable Energy. Available: [Fuel Cell Basics | Department of Energy](#).

[25] Amogy, "Amogy Sails World's First Carbon-Free Ammonia

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Powered Maritime Vessel," Sep. 23, 2024. Available: [Amogy Sails World's First Carbon-Free Ammonia Powered Maritime Vessel - Amogy](#).

[26] Wärtsilä Corporation, "Landmark deal between Wärtsilä and Eidesvik Offshore pioneers growing demand for ammonia in shipping," Wärtsilä Corporation, Press Release, 26 Aug. 2024. Available: [Landmark deal between Wärtsilä and Eidesvik Offshore pioneers growing demand for ammonia in shipping](#).

[27] Yanmar Marine International, "Yanmar Unveils Advanced Selective Catalytic Reduction (SCR) System Achieving 90% NO<sub>x</sub> Emission Reduction for 6LY400-440," 2024. Available: [YANMAR Marine International introduces the SCR system for 6LY Series](#).

[28] Wärtsilä, "Extensive testing of Wärtsilä's 4-stroke ammonia engine demonstrates GHG emission reductions by up to 90 percent," Wärtsilä Corporation, May 27, 2025. Available: [Extensive testing of Wärtsilä's 4-stroke ammonia engine demonstrates GHG emission reductions by up to 90 percent](#).

[29] "Alternative Fuels Update," Britannia P&I, 31 Oct. 2024. Available: [britannapandi.com/2024/10/alternative-fuels-update/](https://britannapandi.com/2024/10/alternative-fuels-update/).

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