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Can Maritime Hydrogen Overcome the Headwinds?

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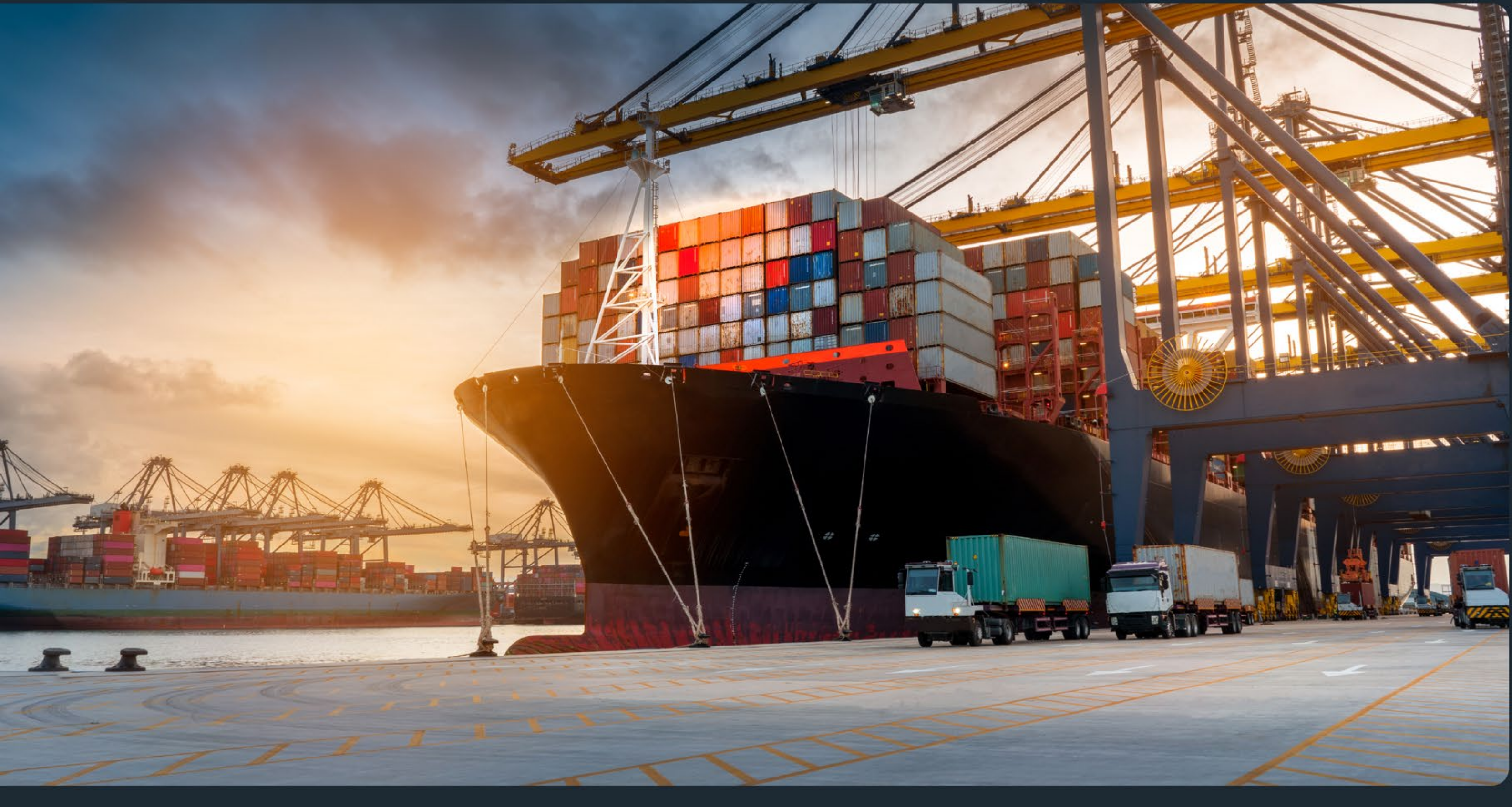

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Key Findings

Fossil fuels currently power more than 99% of global shipping, and the sector produces more than 700 million Mt of CO_2 annually.

Stakeholders are increasingly considering fossil fuel substitutes such as hydrogen.

Hydrogen, despite some potential uses, currently faces cost, infrastructure, and technological barriers to widespread maritime adoption.

A large-scale buildout of dirty hydrogen capacity risks undermining the sector's (and planet's) decarbonization goals.

Executive Summary

Maritime shipping is vital to the global economy, facilitating 80% of trade and enabling trillions of dollars in annual economic activity.[1] It is also responsible for more than 700 million tonnes (Mt) of carbon dioxide (CO_2) a year—a larger carbon footprint, if taken alone, than all but about six of the world's countries.[2,3] And with its emissions forecast to continue growing under business-as-usual, the maritime sector's misalignment with the energy transition is coming into ever-starker relief.[4]

Recognizing the need for action, the International Maritime Organization (IMO) has committed to achieving net-zero emissions by 2050.[5] Alternative energy sources, particularly hydrogen and its derivatives, have attracted attention for their potential to contribute to this goal. However, widespread adoption requires overcoming substantial economic, technological, and operational barriers—and a poorly-planned scaleup of maritime hydrogen could risk undermining net-zero goals in the long run. In this report, IEEFA summarizes the opportunities and hurdles facing hydrogen in shipping.

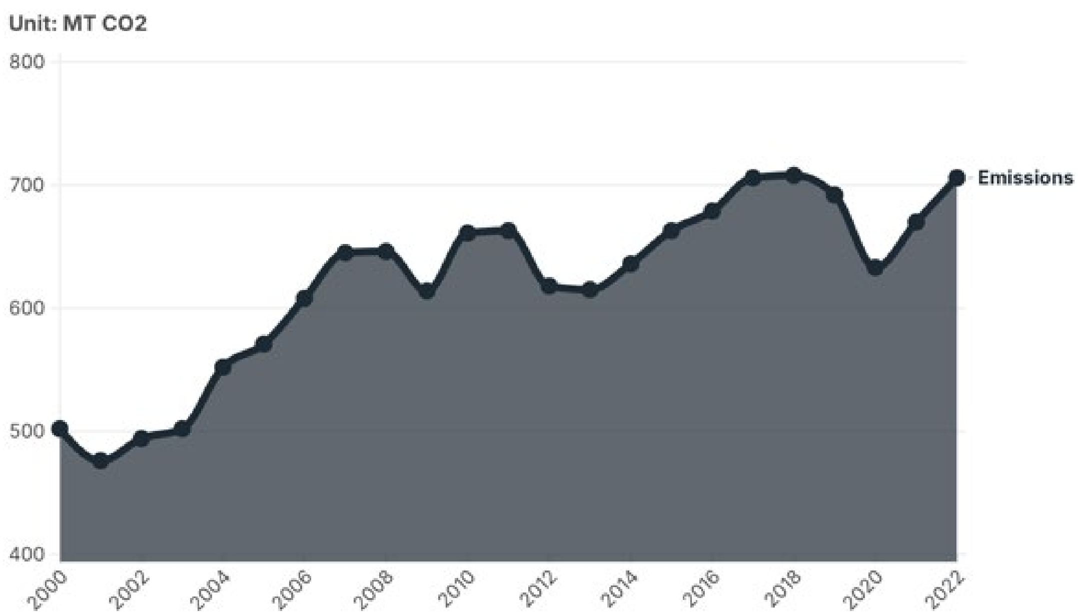

Figure 1: Historical Emissions From International Shipping

Source: International Energy Agency

[1] UNCTAD. Review of Maritime Transport. 2024. Estimates of the total size of the "blue economy" vary. The ICS, for example, puts it at $14 trillion: International Chamber of Shipping. Shipping and world trade: driving prosperity. Accessed January 21, 2024.
[2] International Energy Agency. International Shipping. Accessed January 21, 2024.
[3] European Commission. CO2 emissions of all world countries. 2022.
[4] International Maritime Organization. Fourth IMO Greenhouse Gas Study. 2020.
[5] IMO. IMO's work to cut GHG emissions from ships. Accessed January 27, 2024.

The Sustainable Shipping Landscape

As regulations, technologies, and markets evolve, a range of lower-carbon approaches are emerging across the maritime sector, and it is important to note that fuel stock substitution is only one part of a much broader discourse.

Many regulatory efforts to date have focused on vessel efficiency and usage patterns. Vessel speed reduction (VSR) programs, for example, have shown evidence of significantly lowering fuel consumption and associated pollutant production within designated port zones. For example, the California Air Resources Board reported that reducing vessel speeds to 12 knots within 24 miles of the Port of Los Angeles achieved a 37% reduction in CO_2 emissions and a 49% reduction in diesel particulate matter (PM) and sulfur oxides (SO_x). Initiatives such as the New York-New Jersey Port Authority's Clean Vessel Incentive Program have encouraged vessel efficiency improvements.[6] Meanwhile, as mandatory vessel efficiency reporting standards take effect, market players are increasingly exploring ways to lower emissions while improving competitiveness in an evolving market.[7]

Electrification is also attracting attention. The uptake of batteries in maritime settings has historically been limited by lower energy densities and short lifespans. But as battery costs fall and performance improves (driven in large part by demand from the consumer electronics and lately, automobile industries), the scope of maritime use-cases has expanded. Battery Energy Storage Systems (BESS) are increasingly being integrated into maritime vessels, largely in hybrid configurations to increase efficiency and reduce environmental impacts (especially while docked or during dynamic positioning).[8] Because they can increase operational performance without requiring costly infrastructural buildup, hybrid electrification has attracted significant industry and political support.[9] Meanwhile, all-electric propulsion shows emerging promise for short-sea shipping routes, with several battery-powered short-sea vessels already in commercial operation. These ships operate with no exhaust emissions and can be recharged using renewable energy sources.[10]

Nature can also play a role in driving vessel efficiency: Lloyd's Register has identified Wind-Assisted Propulsion Systems (WAPS), where sails or other wind capture devices are used to harvest kinetic energy, as nearing a "tipping point."[11] WAPS can deliver fuel savings of 4.5% to 9% and as much as 25% with retrofitting, with even greater potential for purpose-designed new builds. Market penetration will hinge on ability to overcome adoption challenges, including operational reliability across diverse conditions.[12]

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[6] Port Authority NY-NJ. Clean Vessel Incentive Program. Accessed January 24, 2024.
[7] Opsealog. How Ship Fuel Efficiency Impacts the Maritime Industry. March 29, 2023.
[8] DNV. Batteries on board: offshore vessels setting the course. November 17, 2018.
[9] *Ibid*.
[10] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Understanding the potential of battery-powered vessels for deep-sea shipping. September 4, 2024.
[11] Lloyd's Register. Wind-assisted ship propulsion nears tipping point for rapid adoption. August 20, 2024.
[12] DNV. WAPS – Wind Assisted Propulsion Systems. Accessed January 22, 2024.

But where does fuel stock fit into the picture? Though the promise of low-carbon fuel replacement should not be used to divert attention or capital from other promising regulatory and technological pathways, it is nonetheless emerging as an important part of the conversation. The rest of this report aims to evaluate the hurdles and opportunities facing the nascent green shipping fuel sector.

The Fuel Source Crux

Fossil fuels currently power more than 99% of global shipping,[13] and the maritime sector consumes some 325 million metric tons of fossil fuels annually[14]— accounting for an estimated 5% of total global oil demand.[15] As of 2021, some 51% (109 million metric tons per year) of shipping's bunker fuel demand was serviced by variants of heavy fuel oil (HFO), a remnant from the distillation and cracking stage of refining. About 30% was light fuel oil (LFO), another distillate. diesel/gas oil (MDO/MGO) rounded out the conventional fuels with 12%.[16] These fuels are known both for their high energy densities, and their high levels of pollutants produced at combustion, since the industry's fuel consumption is a significant source not just of CO_2, but also of nitrogen oxides (NO_x), SO_x, PM, and more.[17]

Having been marketed as a cleaner-burning energy source, recent years have seen the rise of liquefied natural gas (LNG) as a bunker fuel (almost 6% of sector demand, as of the latest data).[18] But while it is true that LNG produces less CO_2 and of some other air pollutants at point of combustion, its overall value chain tells another story. From extraction to transport, nearly all points of the fuel's lifecycle result in leakages of methane, a greenhouse gas more than 80 times as potent as CO_2 on a 20-year basis.[19] When the whole lifecycle is taken into account (a so-called "well-to-wake" analysis), LNG hardly demonstrates viability as a sustainable maritime fuel. The risks are heightened by commercial vessels' long lifespans (topping 20 years), increasing sectoral inertia and reducing the space for short-term fossil bridge fuels.[20] One World Bank study, for example, finds that wider LNG adoption would be unlikely to deliver significant CO_2 reductions, and could even contribute to a net increase.[21] Another analysis finds "no climate benefit from using LNG, regardless of the engine technology."[22]

In light of the sector's transition misalignment, stakeholders are increasingly turning attention to fossil fuel substitutes. This report focuses on one set of proposed approaches: hydrogen and its

[13] International Energy Agency. International Shipping. Accessed January 21, 2024.
[14] S&P Global. Shipowners need to enhance energy efficiency by 55%-60% by 2030: UMAS. April 5, 2024.
[15] C&EN. The shipping industry looks for green fuels. February 27, 2022.
[16] International Maritime Organization. Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS. September 10, 2022. See annex on p. 8.
[17] Marine Insight. What is Nitrogen Oxides or NOx air pollution from Ships? April 1, 2019.
[18] International Maritime Organization. Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS, *op. cit.*
[19] RMI. Reality Check: US Natural Gas Is Not a "Cleaner" Alternative Fuel. February 27, 2024; IEA. Methane Tracker 2021. 2021.
[20] Taiga Shimotsuura. Environmental consequences in lifecycle changes of container shipping vessels. Journal of Environmental Management. 2024.
[21] World Bank. Expectation management: LNG as a bunker fuel for shipping. August 3, 2021.
[22] ICCT. The Climate Implications of using LNG as a Marine Fuel. January 28, 2020.

derivatives. (Other pathways such as biofuels have also been proposed; we leave these outside the scope of this particular report.[23])

Hydrogen has been promoted based on a premise that its combustion yields only water vapor and energy, though this does not consider the presence of air during combustion. By volume, the atmosphere is 78% nitrogen (N_2) and 21% oxygen (O_2).[24] In the typical process of hydrogen combustion, the hydrogen gas (H_2) reacts with air to produce water (H_2O) and nitrogen. But various intermediate reactions and subsequent reactions can occur, especially given the high temperature of hydrogen combustion, resulting in emissions of nitrous oxide (N_2O), a powerful greenhouse gas, and other oxides of nitrogen that pose environmental health risks.[25]

The issue of fugitive emissions must also be considered. Hydrogen leakage is poorly understood and notoriously hard to measure, yet it can hinder the breakdown of greenhouse gases in the atmosphere and contribute to global warming.[26] One recent study estimates that hydrogen could have 11 times the warming potential of CO_2 on a 100-year basis, and could be 33 times worse on a 20-year basis.[27]

On the basis of CO_2 alone, however, hydrogen can in principle deliver significant footprint reductions over fossil fuels—or not, depending on its origin. This last point is the fundamental hurdle for the nascent maritime hydrogen industry. Currently, more than 95% of hydrogen is produced from fossil fuels—so-called "black," "brown," and "gray" hydrogen—with lifecycle emissions that often exceed those of the fossil fuels they replace.[28] Efforts to promote "blue" hydrogen—produced from fossil fuels with carbon capture—have also faced scrutiny. Research, including reports by IEEFA, highlights that the carbon savings of blue hydrogen are often overstated, with issues like methane leakage and low capture efficiencies undermining its supposed benefits.[29]

The shortcomings of fossil-based hydrogen extend to its derivatives. Research suggests that methanol from renewable-produced hydrogen, for example, could reduce greenhouse gas emissions by an order of magnitude, while blue methanol offers only minor improvements at best, far from enough to meet sectoral goals.[30] Also, increased fossil infrastructure designed to generate blue hydrogen risks generating new fossil fuel demand, undermining decarbonization in the long run.[31] To

[23] See: Department of Energy. Biofuels Can Power the Biggest Ships: Five Things to Know About Expanding Their Use. August 8, 2024.
[24] Engineering Toolbox. Air – Composition and molecular weight. Accessed January 27, 2025. The remaining 1% is comprised of water, argon, carbon dioxide, and trace gases.
[25] L. Jung, *et al.* Numerical investigation and simulation of hydrogen blending into natural gas combustion. *Energies* 17(15):3819. August 2, 2024, p. 3. Nitrogen oxides can irritate airways in the human respiratory system, contribute to acid rain and combine with volatile organic compounds to form tropospheric ozone (photochemical smog). Environmental Protection Agency. Basic information about NO_2. Last updated July 16, 2024.
[26] Maria Sand et al. A multi-model assessment of the Global Warming Potential of hydrogen. *Communications Earth & Environment*. 2023.
[27] Nicola Warwick et al. Atmospheric implications of increased Hydrogen use. April 2022.
[28] Robert Howarth and Mark Jacobson. How green is blue hydrogen? *Energy Science & Engineering*. August 12, 2021, see Fig. 1.
[29] IEEFA. Blue hydrogen: Not clean, not low carbon, not a solution. September 12, 2023. Also see: Howarth and Jacobson, *op. cit.*
[30] ICCT. A Step Forward for "Green Methanol." September 1, 2021. The source notes that its blue hydrogen estimates could be an undercount given assumptions about methane leakage rate, among other factors.
[31] Jan Rosenow and Richard Lowes. Will blue hydrogen lock us into fossil fuels forever? One Earth. November 19, 2021.

the extent that hydrogen is deployed in marine transportation, global production must pivot toward green hydrogen, which is derived from renewable-powered electrolysis and water.

For sustainable fuels to make a real difference in the shipping sector, they need to be as low-emissions as possible. LNG is not viable as a broad-sector bridge fuel, and fossil hydrogen does not appear to be a promising path for deep decarbonization in the industry. Adoption of green hydrogen, generated from clean-energy electrolysis, would demonstrate progress on a well-to-wake carbon emissions basis. But as discussed below, it will need to close significant cost gaps, must address infrastructure challenges, and will need significantly more regulatory guidance before it can be viable at scale for maritime markets.

Technologies Overview

A key technical challenge for hydrogen fuel is its relatively lower volumetric energy density compared to fossil fuels. As a result, maritime uses revolve a variety of more energy-dense forms and derivatives instead of elemental gaseous hydrogen. Each has unique uses, benefits, and drawbacks.

Compressed Hydrogen

Storing hydrogen as compressed gas (CH_2) at high pressures (150–700 bar) is one approach to increase its volumetric energy density—as much as 1,800 MJ/m³ at 200 bar and 4,820 MJ/m³ at 700 bar. It can also be stored as a liquid at cryogenic temperatures (around -253°C). Compression allows for transportation via pipelines or tube trailers, stored in high-pressure tanks made of steel, aluminum, carbon fiber, or polymers.

Challenges

Compressed hydrogen adoption faces several challenges, including:

- **Energy density limitations:** Even in compressed form, hydrogen has only about one-third the energy density of LNG. Due to storage volume constraints, this limits its use to smaller-scale applications, such as short-haul vessels. The lower energy density necessitates operational changes, including limited range and dedicated routes. Bunkering remains a challenge, especially for liquid hydrogen, since port turnaround times restrict refueling opportunities. Container swaps for compressed hydrogen storage show promise but require detailed logistical frameworks.[32]

[32] IVL. HOPE - Hydrogen fuel cells solutions in Nordic shipping. June 2023, p. 3.

- **Leakage:** When hydrogen isn't produced near to where it's used, hydrogen losses during compression and transport add up quickly. Thorough lifecycle assessments are needed to ensure that hydrogen usage does not compromise environmental progress.[33]
- **Safety risks:** Hydrogen is highly flammable and burns invisibly at 2,000°C.
- **Cryogenic and high-pressure requirements:** Storing hydrogen as a liquid requires maintaining -253°C temperatures. Use as a compressed gas requires high-pressure storage.

Potential Opportunities

Currently, hydrogen fuel cells are primarily used for auxiliary systems on larger vessels, reducing emissions during port operations. Future advancements aim to scale these systems for main propulsion. Short-sea and inland vessels, with lower power and range requirements, are early candidates for hydrogen adoption. The Nordic region's HOPE project has highlighted hydrogen's potential in reducing emissions across shipping segments.[34] For RoPax ferries (segment that transports passengers and goods), the project finds that hydrogen fuel cells could significantly cut emissions of CO_2, NO_x, and particulate matter.[35]

Regulations and standards for hydrogen as a marine fuel are under development. Proton-exchange membrane fuel cells (PEMFCs) and ICEs are being tested at megawatt scales, with results indicating progress but underscoring the need for further innovation.[36]

Ammonia

Ammonia (NH_3), derived from hydrogen and atmospheric nitrogen via the Haber Process, has emerged as a promising hydrogen-based fuel for long-distance maritime trade. Today, almost all ammonia is synthesized from natural gas or coal.[37] However, green ammonia created from renewable hydrogen has begun to attract attention from the industry, policymakers, and regulators.[38]

Challenges

Despite its promise, ammonia presents several operational and environmental challenges:

- **Toxicity, Corrosiveness, and Performance:** Even at low concentrations, ammonia is hazardous, requiring stringent safety measures to protect crews and prevent spills that could harm marine ecosystems. Ammonia emits a strong odor at low concentrations and has low

[33] Paul Martin et al. A review of challenges with using the natural gas system for hydrogen. *Energy Science and Engineering*. August 18, 2024.
[34] *Ibid*.
[35] *Ibid*.
[36] *Ibid*.
[37] Marta Hatzell. The Colors of Ammonia. ACS Energy Letters. June 14, 2024.
[38] Regarding regulatory attention, recent IMO guidance has opened the door to more methanol use, but uncertainties remain. See: Chemical Market Analytics. Ammonia as a marine fuel: The state of play heading into 2025. January 13, 2025.

flammability, complicating engine design. Limited pilot fuels can facilitate its use in two-stroke engines, but four-stroke engines may require more than 10% hydrocarbon-based pilot fuel.[39]

- **Energy Density Limitations:** Ammonia's energy density is about half that of LNG and a third of conventional fuel oil, necessitating larger onboard storage or more frequent bunkering stops.
- **Combustion Emissions:** Without further pollution controls, tailpipe emissions from maritime ammonia (including N_2O, NO_x, and particulate matter-inducing unburnt ammonia) have significant air-quality effects.[40] This could be particularly problematic in port cities and those near shipping routes.
- **Regulatory Uncertainty:** Regulators are only just beginning to adapt to ammonia usage as a bunker fuel. Recent IMO guidelines have sought to clarify best practices, but standards remain in flux.[41]

Potential Opportunities

Green ammonia produced using renewable energy would offer several key benefits:

- **Established Infrastructure:** Ammonia is widely traded and already transported globally with robust safety protocols, being commonly used in fertilizers, refrigerants, and selective catalytic reduction (SCR) systems.
- **Transportability:** Ammonia can be stored at relatively mild temperatures and pressures compared to hydrogen, and is far less flammable than methanol, making it easier to bunker.
- **Engine Development:** Two-stroke engines designed for ammonia have reached prototype stage,[42] while solid oxide fuel cells (SOFC) capable of running directly on ammonia offer the promise of high efficiency, reduced vibration, and sharply reduced combustion emissions.[43]

Methanol

Methanol (CH_3OH) is a promising alternative fuel for shipping, widely used in petrochemical, industrial, and pharmaceutical sectors. Traditionally synthesized from natural gas and coal, methanol can also be produced using carbon dioxide, green hydrogen, and renewable electricity making it a viable option for decarbonization.[44]

Challenges

- **Safety Concerns**: Methanol's low flashpoint (12°C), near-invisible flames, and toxicity require robust onboard safety mechanisms.[45]

[39] BV M&O. Alternative Fuels Outlook for Shipping. October 4, 2022, p. 69, section 7.5.
[40] MIT. Study finds health risks in switching ships from diesel to ammonia fuel. July 11, 2024.
[41] Chemical Market Analytics. Ammonia as a marine fuel: The state of play heading into 2025. January 13, 2025.
[42] Marine Insight. MAN Starts Full-Scale Testing Of World's 1st Ammonia-Powered Two-Stroke Engine. December 5, 2022.
[43] BV M&O, *op. cit.*
[44] There also exist synthesis pathways through biomass. DOE NETL. Syngas Conversion to Methanol. Accessed January 22, 2024.
[45] Methanol Institute. Marine Methanol. May 2023, p. 12.

- **Feedstock Constraints:** A shortage of sustainable hydrogen and reliance on CO_2 feedstock have created bottlenecks for low-carbon methanol synthesis. To be categorized as "green," CO_2 must come from non-fossil sources.[46] Production from direct air capture (DAC) or bioenergy with carbon capture and storage (BECCS) is constrained by high cost, scalability challenges, and environmental uncertainty.[47]
- **Regulatory Uncertainty:** As with ammonia, the regulatory landscape for methane fuel remains in flux.

Potential Opportunities

- **Existing Infrastructure:** With a global trade volume exceeding 10 million tons annually, methanol benefits from an established transportation and storage network. More than 120 ports worldwide are equipped for methanol handling.[48]
- **Commercial Availability**: Methanol engines are already on the market, facilitating near-term adoption.[49]
- **Energy Density:** Methanol's energy density outpaces both compressed hydrogen and ammonia (though it is still less than traditional fossil fuels).[50]
- **Storage Simplicity:** Methanol is liquid at standard temperature and pressure, meaning that it does not require cryogenic or high-pressure storage.[51]
- **Environmental Impacts:** Methanol is miscible in water, reducing environmental consequences of a fuel spill.[52]

[46] *Ibid*.
[47] On the state of DAC, see: RMI. Reality Check: This Decade Is Make-or-Break for Direct Air Capture. October 17, 2023. For a critique of the climate impacts of BECCS, see: NRDC. The BECCS Hoax. October 16, 2024.
[48] Methanol Institute, *op. cit.*, p. 9.
[49] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. E-Methanol. Accessed January 22, 2024.
[50] IRENA. A Pathway to Decarbonizing the Shipping Sector by 2050. 2021, p. 42.
[51] IRENA, *op. cit.*, p. 59.
[52] Yusuf Bicer and Ibrahim Dincer. Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: A comparative evaluation. *International Journal of Hydrogen Energy*. March 2018, pp. 4583-4596. See also: Methanol Institute, *op. cit.*, p. 42.

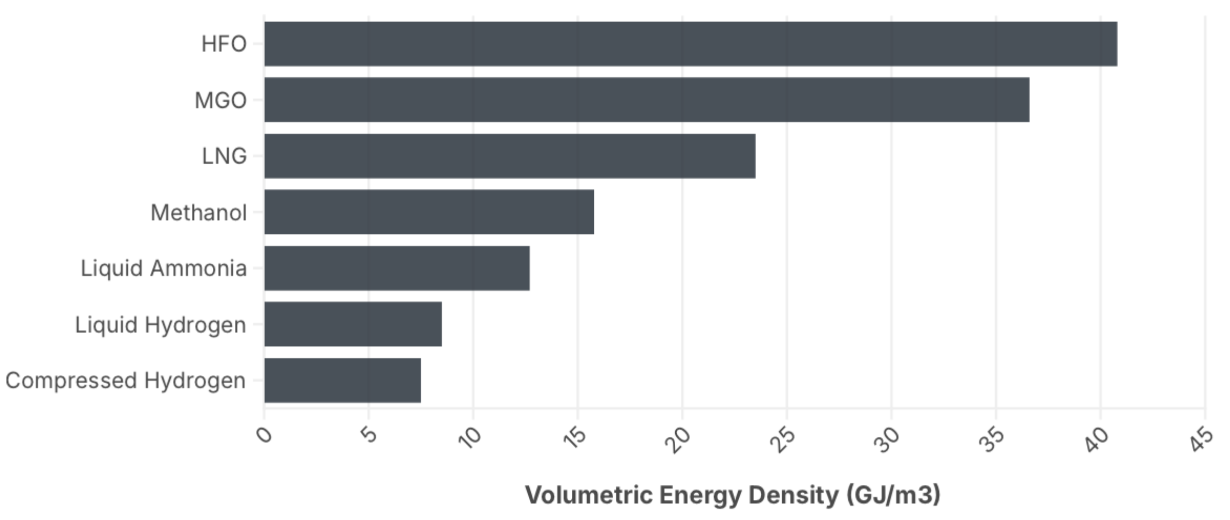

Figure 2: Energy Density by Fuel

Source: IRENA (2019) and Kim et al. (2020)

Market Outlook

Maritime Hydrogen Would Require Significant Infrastructure Buildout

Before hydrogen-based fuels could demonstrate broad commercial viability for shipping, significant infrastructural hurdles must be addressed. Effective production, storage and transport pathways would be essential for hydrogen to become a viable and scalable green energy source in the maritime and broader industrial sectors.

On the production side, a maritime hydrogen economy would have significant electricity needs. Renewables generated some 17 exajoules (EJ) in 2023;[53] replacing the 10 to 12 EJ needed to power the shipping sector would require a substantial share of output. Given the 50% efficiency of e-fuel production, the industry's energy needs could reach 20 to 24 EJ annually.[54] Current hydrogen synthesis capacity is also limited; in 2023, about 97 Mt of hydrogen were produced around the word, almost all using fossil fuels.[55] Green hydrogen capacity would need to scale up dramatically before it could meet the needs of the maritime sector. As the International Energy Agency warned in a recent report, "current hydrogen plans and implementation don't match."[56]

[53] Energy Institute. Statistical Review of World Energy. 2024, p. 56.
[54] BV M&O, *op. cit.*, p. 3.
[55] IEA. Global Hydrogen Review. 2024, p. 60.
[56] See internal citations: IEEFA. Hydrogen Gas Does Not Belong In Your Home. January 2025, p. 15

The transportation of hydrogen from production to port would have its own infrastructural hurdles. Although industry voices often pitch hydrogen as backwards-compatible with LNG pipelines, the scientific literature sounds some notes of caution. "Hydrogen has fundamentally different physical and chemical properties to natural gas," one recent study warned, and thus "the ability to move large amounts of hydrogen using existing pipelines is limited."[57] Though some ports already possess methanol and ammonia infrastructure for petrochemical trade, modernizing ports to support the demand of hydrogen fuels as bunker fuels would require attention.

The danger of carbon lock-in caused by technical, economic, and institutional factors causing carbon-intensive technological systems to persist over time—lurks at many stages of the hydrogen supply chain.[58] This is especially true if hydrogen infrastructure buildout continues to outpace the availability of low-carbon hydrogen. Where infrastructural deployment occurs, more robust action will be needed to ensure that the expansion of the hydrogen economy does not merely spur new fossil fuel demand or interfere with the transition to renewable energy.[59]

A robust hydrogen and hydrogen fuel infrastructure will require standardization, technical capacity building, and cross-sector interoperability. Uniform technical standards and safety certifications are paramount for the safe and efficient deployment of hydrogen across industrial clusters and large-scale applications. Safety remains a core concern for green hydrogen projects. Rigorous certifications and standardization at the project design stage are vital to ensure risk mitigation and operational reliability. Enhancing safety measures, proper audits and certifications will require close collaboration between government and industry.

Economic and Market Factors Will Affect the Rate of Adoption of Hydrogen-Based Fuels in the Maritime Industry

Market dynamics heavily influence hydrogen adoption, with key challenges including high production costs, substantial capital requirements, limited green hydrogen availability, and price gaps with fossil fuels. Despite these hurdles, hydrogen-based fuels, particularly methanol, are showing some preliminary signs of traction. Currently, 29 methanol-capable ships are operational, with more than 200 vessels—almost 10% of ordered new builds—under contract.[60] Additionally, retrofitting older vessels for dual-use engines is creating momentum. BloombergNEF has noted that the demand for methane-ready vessels may already be suppressing sales of LNG-powered ships.[61]

Outlooks for low-carbon shipping fuels vary widely based on political and economic assumptions. Without new policy interventions, BNEF projects that the shipping sector will reach peak oil demand

[57] Martin, *op. cit.*
[58] Peter Erickson et al. Assessing Carbon Lock-In. *Environmental Research Letters*. August 2015.
[59] Rosenow and Lowes, *op. cit.*
[60] S&P Global. Methanol at pole position for Jan alternative fuel ship orders: DNV. February 2, 2024. Also see: BNEF. 2024 Marine Fuel Outlook (proprietary). 2024, p. 3
[61] *Ibid.*

by 2025, with methanol and ammonia collectively accounting for 10% of marine fuels by 2050.[62] However, under a 1.5°C climate pathway with stricter emissions policies, IRENA estimates that these fuels could dominate some 60% of the energy mix by mid-century.[63] The IEA puts hydrogen fuels at about two-thirds of 2050 shipping demand in a net-zero pathway.[64] As RMI notes, "future green methanol and ammonia supply dynamics are not predetermined but will be shaped by the real-world action taken by stakeholders over the coming years."[65]

The cost of hydrogen-based fuels is a critical factor in determining their uptake. Green hydrogen currently remains significantly more expensive than its fossil-derived counterpart. BloombergNEF estimates the current cost of green hydrogen at $4.50 to $12 per kilogram, compared to $0.98 to $2.93 for gray hydrogen and $1.80 to $4.70 per kilogram for blue. There is also significant regional variability, with many Asian economies seeing significantly higher costs—a key challenge for adoption in a global industry.[66] Policy initiatives like the U.S. Inflation Reduction Act's hydrogen credits and the EU Hydrogen Bank provide some incentives to the nascent market. But while future price projections vary, it may take time before green hydrogen is broadly and commercially viable in the maritime sector.[67]

Along with limited green hydrogen supply, the need for carbon dioxide feedstock is also a significant constraint for green methanol. While IRENA predicts ammonia may outpace methanol by 2050 due to these challenges, BloombergNEF's baseline case is relatively more bullish about methanol's longer-term prospects.[68]

Methanol and ammonia compete with other critical applications—methanol as a key input in household products and ammonia for fertilizers that underpin global food security. However, the transportation of green hydrogen and its derivatives could represent a growth area if demand picks up in other sectors of the global economy, such as heavy industry. Conversely, decarbonization could pose a challenge for international shipping, since almost 40% of the sector's current tonnage consists of fossil fuels and petrochemicals.[69] One recent study warns that more than $100 billion dollars in fossil-carrying fleet value could be stranded by 2030 in a net-zero pathway.[70]

Meanwhile, the broader maritime industry faces its own challenges. The container market is expected to experience excess capacity by 2025, which could suppress secondhand vessel prices.[71] New build prices, in turn, will depend on activity in other shipping sectors. Geopolitical tensions,

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[62] *Ibid.*
[63] IRENA, *op. cit.*, p. 80.
[64] IEA. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. 2023, p. 94.
[65] Global Maritime Forum et al. Oceans of Opportunity. April 2024, p. 18.
[66] BNEF Blog. Green Hydrogen to Undercut Gray Sibling by End of Decade. August 9, 2023.
[67] HydrogenInsight. Green hydrogen will be far more expensive than previously thought up to 2050: BloombergNEF. December 23, 2024.
[68] IRENA, *op. cit.*, p. 80; BNEF. 2024 Marine Fuel Outlook (proprietary). 2024, p. 1.
[69] Quartz. Forty percent of all shipping cargo consists of fossil fuels. January 14, 2022.
[70] Kühne Foundation and UCL Energy Institute. Fossil fuel carrying ship and the risk of stranded assets in the transition to a low-carbon economy. May 2024.
[71] BIMCO. Container Shipping Market Overview & Outlook. June 2024, p. 3.

including trade disputes among the EU, U.S., and China, could further affect cargo volumes and specific markets, such as reefer freight.

In summary, preliminary demand already exists for hydrogen-based maritime fuels. Methanol is already establishing a foothold, with ammonia positioned for future growth. Yet, the path to widespread adoption is fraught. High production costs, infrastructure limitations, and competition for renewable resources remain significant barriers. For green shipping to fulfill its potential, coordinated policy action, strategic investments, and technological innovation will be essential. In addition, as described below, further action to develop regulatory standards for safety and environmental protection is needed.

More Regulatory Progress Is Needed on Safety Standards and Emission Targets

The Paris Agreement (which the U.S. has withdrawn from) was adopted in 2015 and serves as a cornerstone for global climate action. Its goal is to limit the rise in global temperatures to well below 2°C above pre-industrial levels, with an ambition to cap it at 1.5°C.[72] While progress has been made in aligning the maritime sector with these goals, much remains to be done to incentivize green fuel production, internalize the external costs of fossil fuel use, and prevent fossil fuel infrastructure lock-in.

International Maritime Organization (IMO)

The IMO has led institutional efforts to decarbonize maritime shipping. Its current climate-related rules largely focus on energy efficiency reporting and disclosure; these alone are not expected to significantly reduce emissions.[73] Its 2023 Strategy on Reduction of GHG emissions, however, represents a significant step up in ambition:

- **Key Goals**: Aims to reduce shipping emissions by 30% by 2030, 80% by 2040, and achieve net-zero by 2050.[74]
- **Zero-/Near-Zero Fuels:** Seeks to derive 5% to 10% of energy used in shipping from zero-/near-zero emission sources by 2030.[75]

These targets are not yet legally binding. Discussions are ongoing about formal mechanisms, such as a GHG fuel standard and a carbon levy, that could operationalize the IMO's net-commitments; success will depend on overcoming resistance from certain member states. It will also depend on instrument design. The ICCT and Climate Action Tracker, for example, have warned that a poorly-

[72] BV M&O, *op. cit.*, p. 7.
[73] BNEF. 2024 Marine Fuel Outlook, *op. cit.*, p. 9. Also see: ICCT. Potential CO2 Reductions Under the Energy Efficiency Existing Ship Index. November 2, 2020.
[74] IMO. IMO Strategy on Reduction of GHG Emissions from Ships. 2023.
[75] *Ibid.*

designed GHG standard risks entrenching LNG and undermining decarbonization in the long run.[76] BloombergNEF warns that achieving net zero by 2050 is unlikely without stricter regulations, such as a global carbon tax.[77] If the IMO is able to build on its present momentum, however, it could meaningfully reshape markets in the coming years.

European Union

The EU has implemented some of the most stringent regulations for maritime emissions:

- **FuelEU Maritime Regulation**: Establishes phased reductions in greenhouse gas intensity, targeting an 80% decrease by 2050.[78]
- **Cap-and-Trade Expansion:** Extends the EU Emissions Trading System (ETS) to cover maritime emissions. EU-regulated ships represent 18% of global fuel consumption, giving these measures substantial market influence.[79]

Despite these steps, BloombergNEF notes that EU regulations' technology-neutral policies may incentivize LNG use through at least the 2030s.[80] This could delay progress toward truly green energy in the maritime industry.

United States

The U.S. has historically avoided direct regulation of carbon emissions from shipping. Some legislative initiatives have sought to change this, such as the proposed Clean Shipping Act and the International Maritime Pollution Accountability Act (both introduced in 2023), which would create emissions intensity reductions and a carbon border adjustment mechanism. The bills, while facing political hurdles, could signal future directions of travel.[81]

Corporate Commitments

Voluntary commitments from major corporations are also driving demand for zero-carbon maritime fuels. Maersk, for example, reported in 2021 that more than half of its largest customers have emissions reduction goals for their supply chains.[82] Companies like Amazon, Unilever, and Nestle have pledged to use only zero-carbon-powered ocean freight services by 2040.[83]

[76] ICCT. Without More Action, LNG Could Pull International Shipping Off its Decarbonization Course. January 10, 2024. Also see: Climate Action Tracker. International Shipping. October 12, 2021.
[77] ICCT. IMO's Newly Revised GHG Strategy. July 7, 2023.
[78] European Commission. Decarbonizing Maritime Transport — FuelEU Maritime. Accessed January 22, 2024.
[79] BNEF. Scaling Up Hydrogen: The Case for Low-Carbon Methanol (proprietary). June 18, 2024, p. 16. Also see: ICCT. Comparing the Future Demand For, Supply of, and Life-Cycle Emissions from Bio, Synthetic, and Fossil LNG Marine Fuels in the European Union. September 2022.
[80] BNEF. 2024 Marine Fuel Outlook, *op. cit.*, p. 1.
[81] Office of Senator Alex Padilla. Padilla, Whitehouse Introduce Bills to Reduce Ocean Shipping Emissions. June 8, 2023.
[82] BNEF. Scaling Up Hydrogen, *op. cit.*, p. 16.
[83] CoZEV. Leading Cargo Owners Stand Together for Maritime Decarbonization. May 2024.

Conclusion

The maritime sector stands at a pivotal moment as the urgency to combat climate change grows. This report highlights both the opportunities and challenges associated with hydrogen and its derivatives. Amidst strengthening regulatory ambition and growing buyer interest in hydrogen-based alternative fuels, it finds a growing appetite for change in a critical industry.

However, these fuels will confront some significant hurdles as they seek to scale up at the necessary pace:

- **High Costs:** The economic feasibility of green hydrogen depends on reducing production costs and increasing infrastructure investments, while cheaper, higher-carbon forms of hydrogen risk undermining decarbonization goals.
- **Infrastructure Needs:** A green shipping sector requires substantial investment in vessels, fueling systems, and port infrastructure.
- **Policy and Guidance Gaps:** Robust regulatory frameworks are needed to incentivize adoption, avoid carbon lock-in, and ensure the transition is truly sustainable. There is immense peril in a poorly-managed scaleup. ***Not all hydrogen is created equal, and a large-scale buildout of dirty hydrogen capacity risks undermining the sector's (and planet's) decarbonization goals.***

Collaboration among regulators, industry stakeholders, and market actors is essential to navigate these risks effectively.

Hydrogen-based fuels are not a panacea, but they are beginning to play a role in maritime markets. In the meantime, other non-combustion measures are gaining significant attention and likely will also play significant roles in reducing maritime vessel emissions. As various low-carbon approaches continue to emerge and develop, it is important to remember that the industry's path is neither inevitable nor pre-determined; economics, technology, and policy all will continue to inform the maritime sector's energy transition.

About IEEFA

The Institute for Energy Economics and Financial Analysis (IEEFA) examines issues related to energy markets, trends and policies. The Institute's mission is to accelerate the transition to a diverse, sustainable and profitable energy economy. www.ieefa.org

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