White Paper

Ammonia as a Clean Energy Solution for Maritime Use

Published October 2023

Commissioned by Amogy

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Table of Contents

Introduction

Maritime shipping accounts for 90% of international trade by volume and approximately 3% of global carbon emissions. The imperative that all sectors of the global economy significantly reduce greenhouse gas (GHG) emissions has become increasingly apparent in recent years. In the shipping industry, ship owners, operators, charterers, and technology providers are aware of this necessity and are finding more support from other stakeholders, including infrastructure operators, bankers, insurers, and cargo owners. Complementing these efforts are a range of maritime-focused emissions targets and incentive schemes introduced by national governments.

A wide range of alternative fuels and decarbonization solutions are available to the maritime sector, each with various advantages and drawbacks. Ammonia has emerged as arguably the shipping industry's leading medium- and long-term fuel replacement. It offers benefits across a broad range of vessel classes, from short-sea freight and roll-on/roll-off passenger (ROPAX) operations to oceangoing container vessels, but more work is needed to unlock its full potential. In particular, production incentives must be coupled with sector-specific policy measures such as carbon pricing or support for the installation of zero carbon power and propulsion systems. Another key priority is developing and enforcing harmonized standards for ammonia use across the maritime value chain.

This paper assesses ammonia's potential for decarbonizing maritime applications, covering its performance compared with alternative fuel options and the policies and industry initiatives required to drive uptake throughout the sector.

Progress Demonstrated by Pilot Projects and Trials

Shipping industry stakeholders are exploring the use of clean fuels in various marine vessel types, including bulk carriers, ferries, freighters, tankers, and container ships. The industry is implementing a range of pilot and demonstration projects to test ammonia engines and power systems in different vessel classes. Examples include the following:

- Amogy is retrofitting a 1957 tugboat that currently runs on diesel generators and electric motors. A 1 MW zero-emission ammonia-to-power system will power the vessel in the next few months. The project follows Amogy's launch of the world's first ammonia-powered, zero emissions semitruck. A retrofitted 2018 Freightliner Cascadia was powered by Amogy's ammonia-to-power technology and had a total of 900 kWh of stored net electric energy. This is approximately the same energy storage capacity as the Tesla Semi but required only 300 gallons (1.15 m^3) of fuel storage. Before retrofitting the 900 kW truck, Amogy successfully demonstrated its first ammonia-powered 5 kW drone in July 2021 and 100 kW tractor in May 2022.[1]
- Backed by European Union (EU) funding, the ShipFC project, a consortium of 14 European companies, aims to equip the *Viking Energy*, an offshore supply vessel, with a 2 MW direct ammonia fuel cell system intended to run on clean fuel for up to 3,000 hours annually.[2]
- In 2022, the Chinese shipyard New Times Shipbuilding constructed the world's first ammonia-ready vessel, the *Kriti Future*.[3] The 274-meter vessel has met the American Bureau of Shipping's Ammonia Fuel Ready Level 1 and Liquefied Natural Gas (LNG) Fuel Ready Level 1 standards and will be equipped with a dual-fuel ammonia engine at a later date.
- In the southeastern US, a study conducted at the Port of Savannah, the nation's largest single container terminal, will provide an analysis of the supply chain for green ammonia ship-to-ship bunkering[4] in the region.[5] The project will study green ammonia's safety, availability, and readiness as an alternative shipping fuel. Its end goal is to develop the country's first ammonia ship-to-ship bunkering base.
- In April 2023, the Global Centre for Maritime Decarbonisation (GCMD) completed a 9-month safety study entitled "Safety and Operational Guidelines for Piloting Ammonia Bunkering in Singapore." The study aimed to define a set of safety guidelines for ammonia bunkering trials at two sites. DNV consulted with 22 study partners and received feedback from more than 130 industry and consultation alignment panel members. Overall, more than 400 risks were assessed during the study and were found to be low or feasible to mitigate, or both.[6]

[1] Amogy, "Amogy Presents World's First Ammonia-Powered, Zero-Emission Semi Truck," January 17, 2023, **https://amogy.co/amogy-presents-worlds-first-ammonia-powered-zero-emission-semi-truck/**.

[2] Maritime CleanTech, "ShipFC - Green Ammonia Energy System," accessed September 23, 2023, **https://maritimecleantech.no/project/shipfc-green-ammonia-energy-system/**.

[3] Marine Insight, "World's First Ammonia Ready Vessel 'Kriti Future' Delivered," February 4, 2022, **https://www.marineinsight.com/shipping-news/worlds-first-ammonia-ready-vessel-kriti-future-delivered/.**

[4] Bunkering refers to the process of supplying bunker (i.e., marine fuel oil, marine diesel oil, or marine gas oil) to vessels for their own use.

[5] Jasmina Ovcina Mandra, "Maritime Industry Giants to Explore Ammonia as Green Fuel for U.S. East Coast," Offshore Energy, April 4, 2023, **https://www.offshore-energy.biz/maritime-industry-giants-to-explore-ammonia-as-green-fuel-for-u-s-east-coast/**.

[6] Nikos Späth, "GCMD Completes Study and Readies Stakeholders for First Ship-to-Ship Pilot to Transfer Ammonia in Singapore," DNV, April 27, 2023, **https://www.dnv.com/news/gcmd-completes-study-and-readies-stakeholders-for-first-ship-to-ship-pilot-to-transfer-ammonia-in-singapore-242876**.

- Color Line, Norway's largest ROPAX cruise liner company, has launched a pilot project in Japan backed by a 16-party consortium to investigate whether direct ammonia fuel cells can power shipboard systems safely.[7]
- Finnish engineering technology company Wärtsilä has partnered with Norwegian offshore supply vessel company Eidesvik Offshore to retrofit a supply vessel with an ammonia combustion engine. The conversion project is aimed to be completed in 2025 and will allow the ship to use a fuel blend of up to 70% ammonia.[8]
- With the goal of decarbonizing the offshore energy sector, Amogy, Skansi Offshore, and SEAM signed a memorandum of understanding to study ammonia applications. The first project will retrofit one of Skansi's existing vessels to include an ammonia-to-power system.[9]
- The Green Shipping Programme has launched a new pilot project supported by a consortium consisting of Fred. Olsen Seawind, Hafslund, and Ørsted.[10] The project will study how green ammonia can be used to fuel installation and anchor handling vessels in the floating offshore wind sector.
- In Norway, Yara Marine Technologies and Azane Fuel Solutions, an ammonia bunkering technology company, launched a pilot project in summer of 2021 to develop bunker terminals to supply ships with zero carbon ammonia as a marine fuel.[11]

Ammonia's Significant Decarbonization Potential for Multiple Vessel Classes

Emissions from marine fuel consumption can be sorted into two categories. Well-to-tank emissions derive from fuel production, extraction, delivery, and other upstream processes. Tank-to-wake emissions are those released during energy conversion processes that occur on the vessel, including combustion or cracking. Collectively, these emissions are referred to as well-to-wake emissions and cover the full lifecycle emissions associated with different marine fuel options.

Ammonia in tank-to-wake emissions does not emit CO_2 when consumed as a fuel since it does not contain carbon. However, the combustion of ammonia does release some nitrous oxide (NOx), which acts as a potent GHG. Unlike combustion, Amogy's technology uses a thermo-catalytic cracking process to release the hydrogen contained in ammonia, which is then fed into a fuel cell.

Current ammonia production processes for well-to-tank emissions are carbon intensive due to the use of fossil fuel feedstocks and energy inputs. Reductions in lifecycle emissions from ammonia fuel

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[7] Qian Zhu, "Developments in Ammonia Fuel Use to Decarbonise Emission Heavy Sectors," International Centre for Sustainable Carbon, March 7, 2022, **https://www.sustainable-carbon.org/blogs/developments-in-ammonia-fuel-use-to-decarbonise-emission-heavy-sectors/**.

[8] Maria Gallucci, "The Race Is On to Build the World's First Ammonia-Powered Ship, Canary Media, November 10, 2022, **https://www.canarymedia.com/articles/sea-transport/the-race-is-on-to-build-the-worlds-first-ammonia-powered-ship**.

[9] Amogy, "Amogy, Skansi and SEAM Sign MoU to Explore Ammonia as Fuel for Offshore Supply Vessels," May 19, 2023, **https://amogy.co/amogy-skansi-and-seam-sign-mou-to-explore-ammonia-as-fuel-for-offshore-supply-vessels/**.

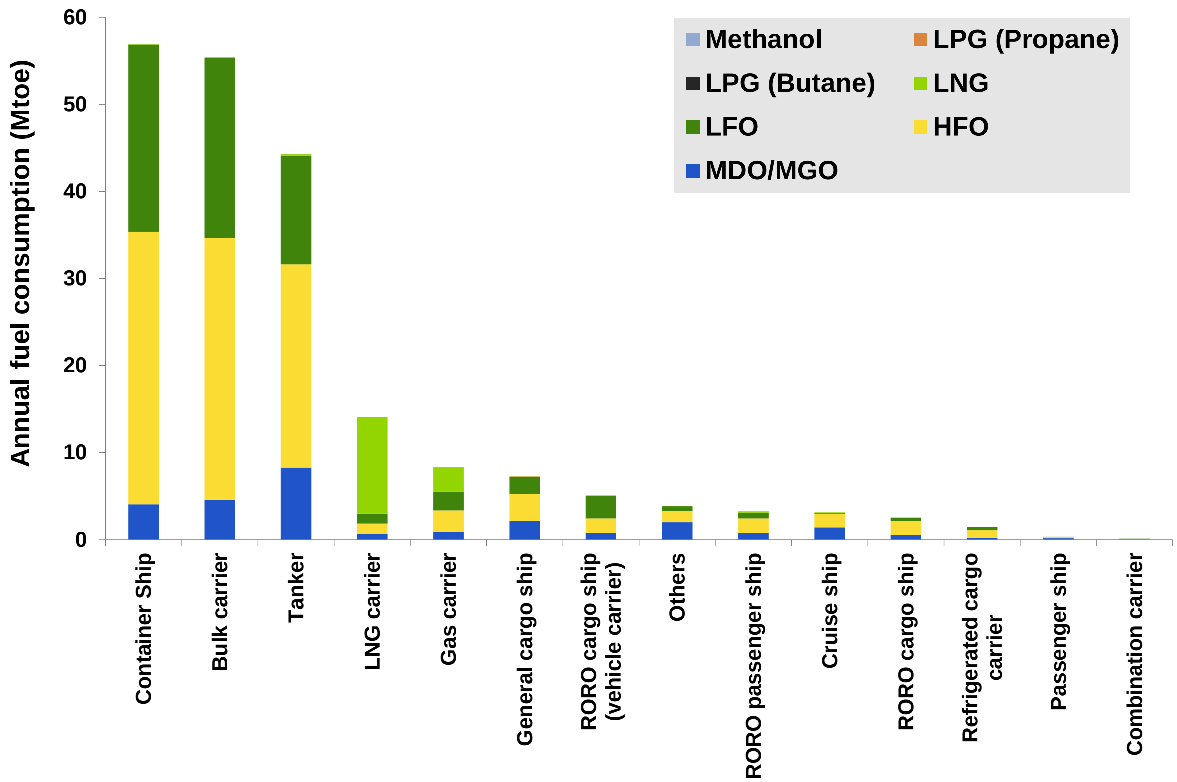
[10] Adrijana Buljan, "New Pilot Project Looking to Decarbonise Floating Wind by Using Green Ammonia-Fuelled Vessels," Offshore WIND, June 28, 2023, **https://www.offshorewind.biz/2023/06/28/new-pilot-project-looking-to-decarbonise-floating-wind-by-using-green-ammonia-fuelled-vessels/**.

[11] Victoria Klesty, "Yara to Set Up Scandinavian Green Ammonia Shipping Fuel Network," Reuters, April 1, 2022, **https://www.reuters.com/business/sustainable-business/yara-set-up-scandinavian-green-ammonia-shipping-fuel-network-2022-04-01/**.

consumption therefore require that ammonia be produced in facilities equipped with carbon capture technologies or by using green hydrogen derived from renewable electricity. These low carbon pathways are expected to drive growth for a substantial share of ammonia production and can also be used to decarbonize existing plants. Industry observers expect that more than 9 million tons per year of low carbon ammonia production capacity could be added by 2025.

Figure 1 shows the current breakdown of conventional marine fuel demand segmented by fuel type and vessel class. Heavy fuel oil (HFO) remains the primary fuel option for larger vessel classes. Because of HFO's high sulfur content, vessels must either be equipped with scrubbers to reduce sulfur oxide emissions, or use fuel that has undergone additional processing steps to limit sulfur content. Light fuel oil (LFO), marine diesel oil (MDO), and marine gas oil (MGO) satisfy most of the remaining marine fuel demand. Ammonia can be used to reduce carbon intensity for each of the vessel classes in Figure 1, with the highest emissions reduction potential in the container, bulk carrier, and tanker segments.

Figure 1 Current Marine Fuel Demand in Vessel Classes for Ships of 5,000 Gross Tonnage and Above



Note: Mtoe = million tons of oil equivalent
(Source: Guidehouse Insights, data from International Maritime Organization)

Ammonia can deliver noteworthy improvements to air quality in ports and aboard vessels, especially if consumed in a cracker. Conventional marine fuels produce a range of harmful substances when combusted, including sulfur dioxide, carbon monoxide, particulate matter, and heavy metals. A 2022 report[12] that reviewed 32 studies assessing the health burden of shipping-sourced air pollution concluded

[12] Natalie Mueller, "Sea Transport: The Forgotten Air Pollution," ISGlobal, February 17, 2023, **https://www.isglobal.org/en/healthisglobal/-/custom-blog-portlet/transporte-maritimo-la-contaminacion-olvidada/6008088/0**.

that maritime transport is a source of air pollution and a health risk for port communities, which are exposed to the highest concentrations of the air pollution caused by shipping. The study found that approximately 265,000 premature deaths were projected globally for 2020 due to increases in international trade, maritime transport volumes, and associated emissions levels.

Another study on the health benefits of fuel substitution found that marine fuels with low or zero sulfur content, including ammonia, can "reduce ship-related premature mortality and morbidity by 34 and 54% respectively, representing a ~2.6% global reduction in PM2.5 cardiovascular and lung cancer deaths and a ~3.6% global reduction in childhood asthma."[13]

Benefits of Ammonia Compared with Other Alternative Fuels

The following subsections detail the leading alternative fuel options available to the maritime sector. Each description includes the solution's specific advantages and drawbacks..

Hydrogen

Hydrogen is a zero carbon fuel with very low lifecycle emissions when produced using renewable electricity. However, compressed hydrogen's low volumetric energy density is only suitable for use on short-sea vessels. It is also costly and challenging to handle and store in compressed or liquid form, as liquid hydrogen is stored at around -250°C, and compressed hydrogen is stored at >350 bar. These drawbacks explain why hydrogen is more likely to be converted to ammonia prior to use on most vessels. Nevertheless, in certain applications, direct hydrogen's use offers benefits, such as on high speed vessels with weight restrictions.

E-Methanol

E-methanol is produced by combining green hydrogen and captured CO_2. Unlike green ammonia, renewable methanol releases GHG emissions and other pollutants such as CO_2, sulfur oxide, and particulate matter. In addition, given that the production of e-methanol requires green hydrogen and large quantities of CO_2 that are currently limited, supplying a significant amount of e-methanol for commercial use would be challenging. Another barrier to using e-methanol is that it is more expensive to produce than conventional marine fuel, costing $1,200/metric ton. According to the maritime research consultancy Drewry, the switch to e-methanol would raise bunker costs by 340%.

Other E-Fuels

Other e-fuels that can be used to decarbonize the shipping sector include e-diesel and e-LNG. Each of these fuels needs green hydrogen and captured CO_2 as feedstocks, with the CO_2 inputs preferably sourced from the atmosphere using direct air capture or biological processes to deliver optimal reductions in lifecycle emissions. These scarce and expensive feedstocks impose additional costs and a high likelihood of supply constraints. The principal advantage of drop-in e-fuels such as e-diesel is that they are already compatible with existing engines and bunkering infrastructure.

Marine Biofuels

Biofuels are liquid fuels produced using food waste, dedicated energy crops, and other forms of biomass. Achievable lifecycle emissions reductions from biofuels are largely determined by the feedstock source.

[13] Mikhail Sofiev et al, "Cleaner Fuels for Ships Provide Public Health Benefits with Climate Tradeoffs," *Nature Communications* 9, no. 406 (2018), **https://doi.org/10.1038/s41467-017-02774-9**.

The highest emissions reductions are obtained from waste feedstocks, which are available in limited quantities. Other feedstock sources result in limited emissions reductions or even net-positive emissions impacts, depending on land use change, emissions from agricultural operations and fuel processing, and other relevant factors.

Biodiesel is the most common form of biofuel currently used in the maritime sector. Each of the three biodiesel production pathways detailed below uses a different feedstock material: fatty acid methyl ester (FAME), biomass to liquid (BTL), and hydrotreated vegetable oil (HVO).

- **FAME:** Also known as biodiesel oil, FAME is produced through transesterification. Triglycerides from vegetable oils or animal fats are converted to methyl esters in the presence of a catalyst. FAME is often used as a blending component with marine diesel, such as MGO, and is the industry's most widely available type of biodiesel. Compared with MGO and MDO, FAME has a lower average carbon footprint at just 38-48 grams of CO_2 equivalent per megajoule (gCO_2e/MJ), versus 85-87 gCO_2e/MJ for MGO/MDO.[14]
- **BTL:** Currently at lower levels of commercial and technological readiness, BTL pathways enable liquid fuels to be produced from solid biomass using a range of thermochemical processes. BTL's end product has a composition similar to conventional diesel's and can be used in existing diesel engines.
- **HVO:** A renewable paraffinic fuel produced from fats or vegetable oils, HVO can be introduced in diesel engines without additional modifications. HVO is produced by hydrocracking and hydrotreating vegetable oils. Depending on the feedstock, HVO can reduce carbon emissions by up to 90% in the marine and industrial sectors.[15]

The advantages of biofuels include high commercial readiness for some production pathways and compatibility with existing engines and bunkering infrastructure (especially when blended into conventional marine fuels). Disadvantages include sustainability concerns for common feedstocks as well as limited scalability potential. According to projections by the International Energy Agency (IEA), ammonia and hydrogen will meet more than 80% of the shipping sector's fuel needs by 2070, while biofuels are projected to meet less than 20%.[16]

Policy Outlook

The International Maritime Organization (IMO) has made considerable progress in advancing the global agenda for shipping decarbonization. In addition, a growing range of industry-backed consortia have developed shipping decarbonization strategies and targets. This progress indicates support for decarbonization across all stages of the value chain; ship owners, operators, charterers, and technology providers are aware of the need to decarbonize and are finding increasing support from other stakeholders such as infrastructure operators and cargo owners. Unlike other transportation segments, the approach to maritime decarbonization must be characterized by open dialogue at a global level. The

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[14] Hulda Winnes et al., *Biofuels for Low Carbon Shipping*, Triple F, August 2019, **https://docplayer.se/170867386-Biofuels-for-low-carbon-shipping-triple-f-reportnumber-c-august-2019.html**.

[15] Daniel Tillack, "Using Biofuel to Reduce Fossil CO2 Emissions by up to 90%," Volvo Penta, October 26, 2022, **https://www.volvopenta.com/about-us/news-page/2022/oct/using-biofuel-to-reduce-fossil-co2-emissions-by-up-to-90/**.

[16] IEA, "Technology Needs in Long-Distance Transport," in *Energy Technology Perspectives 2020*, revised February 2021, **https://www.iea.org/reports/energy-technology-perspectives-2020/technology-needs-in-long-distance-transport**.

adoption of previous international regulations, most notably the 0.5% sulfur cap that the IMO introduced in 2020, also offers a strong precedent for international cooperation on shipping emissions.

However, significant levels of investment are needed to fully decarbonize the maritime shipping sector. According to research conducted by the Global Maritime Forum, out of the total investment needed to decarbonize international shipping—using clean ammonia as the primary and lowest cost zero carbon fuel—43% will be dedicated to ammonia storage, synthesis, and distribution.[17] A further 44% of investment needs are focused on hydrogen production. In cumulative dollar terms, the research estimates that the investment requirements will amount to between $1 trillion and $1.4 trillion from 2030 to 2050. Unlocking investment at this scale requires strong support from national and regional governments. The following subsections summarize recent policy progress at the international level as well as important regional and industry-backed initiatives.

International Policy Context

The IMO has strengthened its GHG reduction strategy following the 80th session of the Marine Environment Protection Committee in July 2023. While it will ultimately fall to national governments to transpose and enforce IMO targets, the revised strategy now stipulates a minimum well-to-wake emissions reduction of 20% by 2030 and 70% by 2040, relative to a 2008 baseline. By 2030, zero or near-zero carbon technologies and fuels are targeted to account for a minimum of 5% of marine energy consumption. The end goal of net-zero operations is targeted to be achieved close to 2050.

International policy developments have also been driven by direct collaboration among national governments. The Clydebank Declaration, which was introduced at the 26th United Nations Climate Change Conference (COP26) in 2022 and signed by 24 national governments, targets the establishment of at least six green shipping corridors by the middle of this decade. These will be routes on which low carbon fuels and propulsion technologies are adopted more quickly, with supporting infrastructure at participating ports. In 2023, COP27 saw the launch of the Green Shipping Challenge, which solicited more than 40 major announcements from ports and shipping companies covering issues such as innovations for ships, expansion of low emissions or zero emissions fuels, and measures to promote the uptake of next-generation vessels.[18]

Including those proposed under the Clydebank Declaration, at least 10 green shipping corridors have been announced, covering lanes from Australia to Asia, corridors between Europe and Asia, transatlantic and transpacific routes, and even local initiatives such as the St. Lawrence Seaway in North America. Many corridors are at a pre-feasibility stage. However, a proposed Australia-Asia bulk carrier lane focused on iron ore traffic is among a handful of routes that have already moved on to implementation and advanced planning stages. An Asia-US automotive carrier route that would run from Shanghai to Los Angeles was also identified for its rapid decarbonization potential.[19]

Mission Innovation is another global effort that lists the decarbonization of the shipping sector among its seven core missions. The action-oriented platform is backed by two dozen countries and includes public-private alliances to bring governments, investors, innovators, and industry together. Led by Denmark,

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[17] Randall Krantz, Kasper Søgaard, and Tristan Smith, "The Scale of Investment Needed to Decarbonize International Shipping," Global Maritime Forum, January 20, 2020, **https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping**.

[18] U.S. Department of State, "Launch of the Green Shipping Challenge at COP27," November 7, 2022, **https://www.state.gov/launch-of-the-green-shipping-challenge-at-cop27/**.

[19] Getting to Zero Coalition, *The Next Wave: Green Corridors*, 2021, **https://www.globalmaritimeforum.org/content/2021/11/The-Next-Wave-Green-Corridors.pdf**.

Norway, and the US, Mission Innovation’s zero emissions shipping initiative aims to demonstrate commercially viable zero emissions ships by 2030.

Industry Initiatives

The IMO’s targets are supported by the Getting to Zero Coalition, a group of shipowners and other key industry stakeholders who argue that a 5% zero carbon fuel update is needed by 2030 to achieve the emissions reductions established in the Paris Agreement. Another key industry initiative, Cargo Owners for Zero Emission Vessels, is working with carriers to decarbonize their routes fully by 2040. Moreover, the three leading container lines—Mediterranean Shipping Company, Mærsk, and CMA CGM—have all set targets for net-zero operations by mid-century or earlier. Together these companies control close to half of global shipping container TEU[20] capacity.

Policy in North America

In the US, current policies are focused on research and innovation in areas such as sustainable fuel production, electric propulsion systems, shoreside power facilities, exhaust treatment, and carbon capture. The Inflation Reduction Act (IRA) also allocates funding for ports to develop climate action plans and acquire zero emissions equipment. The IRA is complemented by the Port Infrastructure Development Program, which offers grant assistance for port and terminal infrastructure improvements.

The US published its Ocean Climate Action Plan (OCAP)[21] in 2023 to address ocean-based climate actions necessary to meet three goals: creating a carbon-neutral future, accelerating nature-based solutions to protect and support coastal and ocean systems, and enhancing community resilience to ocean change. The OCAP provides a framework for near-term initiatives in support of these goals implemented through several agencies, including the U.S. Department of Energy (DOE), the U.S. Department of Transportation (DOT), the DOT Maritime Administration, and the U.S. Committee on the Marine Transport System.

These bodies have responsibility for the five green maritime shipping OCAP actions, which cover a broad set of challenges that include advancing the US commitment to zero emissions shipping by 2050, accelerating green shipping corridor development, providing incentives for zero emissions marine fuels, and constructing a net-zero GHG US-flagged commercial fleet. The greening of US ports by modernizing and decarbonizing infrastructure also falls into the OCAP’s remit. Further, the *U.S. National Blueprint for Transportation Decarbonization*[22] includes specific recommendations and priority action areas to decarbonize the maritime sector.

Policy in Europe

Since 2018, vessels over 5,000 tons gross that load or unload at ports within the European Economic Area have been required to monitor CO_2 emissions under the Monitoring, Reporting, and Verification (MRV) Maritime Regulation. As of January 2024, the MRV will be extended to include measurement of NOx and methane emissions. In addition, from 2024, ships entering EU ports will fall under the extended

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[20] A TEU, or twenty-foot equivalent unit, is an exact unit of measurement used to determine cargo capacity for container ships and terminals.

[21] Ocean Policy Committee, *Ocean Climate Action Plan*, March 2023, **https://www.noaa.gov/sites/default/files/2023-03/Ocean-Climate-Action-Plan_Final.pdf**.

[22] DOE et al., *The U.S. National Blueprint for Transportation Decarbonization*, January 2023, **https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf**.

EU Emissions Trading System (ETS), which will place economic penalties on the use of more carbon-intensive fuels.

As part of the EU's Fit for 55 package, intended to deliver a 55% reduction in economy-wide GHG emissions by 2030, the FuelEU Maritime initiative has been introduced to boost uptake of renewable and low carbon fuels in the maritime segment. The initiative will oblige vessels docking at EU ports to meet minimum carbon intensity reduction thresholds, including a 6% reduction by 2030 and an 80% reduction by 2050. While at berth, vessels will also be required to connect to an onshore power supply or generate power onboard using a zero emissions power generation solution.

While Norway is not a member of the EU, the country aims to reduce maritime emissions by 50% by 2030, which is more ambitious than the IMO target. Additionally, in August 2023, Enova SF, a state enterprise owned by the Norwegian Ministry of Climate and Environment, announced it is planning two new support programs for hydrogen and ammonia in vessels, with the goal of establishing the first profitable value chains for hydrogen and ammonia at sea by stimulating demand. The two programs will be implemented as a competitive bidding framework with maximum aid reaching up to 80% of approved additional costs for the projects.

The maritime industry is a key contributor to the Norwegian economy. The country ranks 7th in terms of flagged vessels and 11th in terms of global tonnage, and remains one of the few high cost European countries to boast a sizable shipbuilding industry. Significant innovation hubs such as the Sustainable Energy Catapult Center have grown with support from the Norwegian government, which has identified advances in ocean industries as being of primary economic importance to the country. Amogy is now using the Catapult Center to test its 200 kW ammonia-to-power platform, which will be a building block to produce multi-megawatts in Amogy's technology-powered ships.

Policy in Asia Pacific

The Asia Pacific region possesses significant advantages for adopting ammonia as a maritime fuel. For instance, Singapore is the largest bunkering port and China is the largest ammonia producer in the world. These two countries, along with Japan and South Korea, are among the top 10 ship-owning countries globally.

Southeast Asia has emerged as a global leader in the development of ammonia bunkering activities. In 2021, Singapore's Maritime and Port Authority (MPA) and industry partners formed the GCMD. The GCMD's research has concluded that the risks inherent in undertaking a pilot ammonia bunkering project are either low or manageable. The MPA has committed to methanol bunkering trials in the short term, with an ammonia bunkering pilot scheduled for 2027, according to an expression of interest[23] released in 2022. The project also aims to generate a minimum of 50 MW of electricity from imported low or zero carbon ammonia for an operational period of up to 25 years.

Elsewhere in Asia Pacific, Japan and South Korea have policies focusing on using ammonia as a fuel. Japan sees fuel ammonia as a key technology for achieving carbon neutrality by 2050, and the country's Road Map for Fuel Ammonia aims to establish an international fuel ammonia supply chain. South Korea's First National Plan for the Development and Popularisation of Green Ships (2021-2030), which was

[23] Energy Market Authority and MPA Singapore, "Call for Expression of Interest to Develop Low or Zero-Carbon Power Generation and Bunkering Solutions," December 5, 2022, **https://www.mpa.gov.sg/media-centre/details/joint-media-release-call-for-expression-of-interest-to-develop-low-or-zero-carbon-power-generation-and-bunkering-solutions**.

released in 2020, aims to explore advanced emissions-free technologies and sets targets to reduce shipping emissions by 70% by 2030 and convert 15% of the country's ships to green ships.

Green Shipping Corridors

While ammonia offers clear and unique benefits to shipping, it suffers from many of the barriers that face other emerging technologies. Overcoming them will require a combination of technological innovation, strong policy support, and collaboration among stakeholders to establish effective regulatory guidelines.

The emergence of green shipping corridors, many of which are centered on US ports, has been a key driver for the development of ammonia as a marine fuel. Ammonia is referenced as a leading fuel option for the Hamburg-Halifax Atlantic corridor. The Port of Los Angeles has also announced green shipping corridors with Nagoya, Tokyo, and Shanghai. Other traffic-dense Pacific corridors remain at earlier stages of development. In Georgia, the Port of Savannah intends to develop supply chain infrastructure to support the bunkering of ammonia-powered ultra large container ships.

In Asia Pacific, the Australia-Asia Iron Ore Green Corridor could see ammonia-fueled vessels enter service on the route as early as 2028. Another proposed route will run from Singapore to Rotterdam. However, as with North America and Europe, policy interventions to reduce the cost difference between clean ammonia and conventional fuels are essential to unlock investments in zero carbon propulsion technologies and vessels.

Conclusions

The technical groundwork necessary for the widespread adoption of ammonia as a shipping fuel is rapidly being established. Proof-of-concept and demonstration work continues, and while the proposed timelines for some green shipping corridors may seem ambitious, this ambition is matched by determination across the entire value chain.

Policy support remains of critical importance. Widespread adoption of low carbon fuels requires reductions in the additional costs imposed on carriers. At present this cannot be left solely to market mechanisms, and a combination of policy measures will likely be required. For instance, production incentives (such as the tax credits offered under the IRA) can reduce the cost of clean ammonia supplies for vessel operators. Likewise, carbon pricing schemes such as the EU ETS raise the costs associated with continued use of fossil fuels. An appropriate balance of incentives and emissions control measures is likely to be the most efficient and effective approach to unlocking alternative fuel demand. Policy support should also target reductions in the retrofit costs associated with alternative power systems and propulsion technologies to stimulate adoption.

On the regulatory side, the international nature of the shipping sector necessitates a collaborative and cross-jurisdictional approach. Harmonized standards applied to storage, handling, and hazard mitigation measures will simplify both training requirements and operational complexity. The properties of ammonia may be well understood, but its use as a marine fuel remains immature. A cooperative approach to regulation will facilitate its wider adoption as a clean, scalable, and easily obtainable zero carbon fuel.

Acronym and Abbreviation List

BTL ... Biomass to Liquid

CO_2 ... Carbon Dioxide

COP ... Conference of the Parties

DOE ... U.S. Department of Energy

DOT ... U.S. Department of Transportation

ETS ... Emissions Trading System

EU ... European Union

FAME ... Fatty Acid Methyl Ester

GCMD ... Global Centre for Maritime Decarbonisation

gCO_2e/MJ ... Grams of CO_2 Equivalent per Megajoule

GHG ... Greenhouse Gas

HFO ... Heavy Fuel Oil

HVO ... Hydrotreated Vegetable Oil

IEA ... International Energy Agency

IMO ... International Maritime Organization

IRA ... Inflation Reduction Act

kW ... Kilowatt

kWh ... Kilowatt-Hour

LFO ... Light Fuel Oil

LNG ... Liquefied Natural Gas

LPG ... Liquid Petroleum Gas

m^3 ... Cubic Meters

MDO ... Marine Diesel Oil

MGO ... Marine Gas Oil

MPA ... Maritime and Port Authority

MRV ....Monitoring, Reporting, and Verification

Mtoe .... Million Tonnes of Oil Equivalent

MW .... Megawatt

NOx .... Nitrous Oxide

OCAP .... Ocean Climate Action Plan

PM .... Particulate Matter

ROPAX .... Roll-On/Roll-Off Passenger

RORO..........Roll-On/Roll-Off

TEU ....Twenty-Foot Equivalent Unit

US .... United States

Scope of Study

Guidehouse Insights has prepared this white paper, commissioned by Amogy, to explain how ammonia can contribute to emissions reductions in the shipping industry. It explores ammonia's advantages compared with other marine fuels and summarizes the current policy landscape affecting maritime decarbonization.

Sources and Methodology

Guidehouse Insights' industry analysts use a variety of research sources in preparing research reports and white papers. The key component of Guidehouse Insights' analysis is primary research gained from phone and in-person interviews with industry leaders including executives, engineers, and marketing professionals. Analysts are diligent in ensuring that they speak with representatives from every part of the value chain, including but not limited to technology companies, utilities and other service providers, industry associations, government agencies, and the investment community.

Additional analysis includes secondary research conducted by Guidehouse Insights' analysts and its staff of research assistants. Where applicable, all secondary research sources are appropriately cited within this report.

These primary and secondary research sources, combined with the analyst's industry expertise, are synthesized into the qualitative and quantitative analysis presented in Guidehouse Insights' reports. Great care is taken in making sure that all analysis is well supported by facts, but where the facts are unknown and assumptions must be made, analysts document their assumptions and are prepared to explain their methodology, both within the body of a report and in direct conversations with clients.

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Published October 2023