White Paper

Ammonia as an Essential Energy Carrier for the Energy Transition

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Commissioned by Amogy

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Table of Contents

Introduction

The transportation sector will need to replace its current mix of fossil energy sources with alternative fuels and technologies to ensure compliance with global climate targets. While the passenger vehicle segment can be extensively battery-electrified, maritime applications present a more complex range of challenges. Lengthy travel times, high power output demands, and tradeoffs with cargo storage space necessitate energy-dense fuels for most vessel classes. Some of the options currently being explored include hydrogen, methanol, marine biofuels, and ammonia.

Ammonia has been used for over a century as a key chemical input for synthetic fertilizer production. However, it could also provide a more energy-dense alternative to liquid hydrogen or battery electrification for the shipping industry. Additionally, when compared with many biomass-derived fuels, ammonia offers greater potential for scalability and lifecycle emissions reduction. Adoption will be assisted by progress in clean ammonia production pathways and by technological advances in ammonia-fueled power systems.

This white paper has been commissioned by Amogy, an ammonia-to-power technology provider. It explains how ammonia can be produced at very low carbon intensities, why it is increasingly viewed as the key zero carbon energy carrier needed to unlock net-zero, and how it compares with alternative marine fuels. The report also provides an overview of specific applications for ammonia-to-power systems within the maritime sector and beyond.

Ammonia as an Energy Carrier and Alternative Fuel

Today, most of the 200 million tons of ammonia consumed each year is produced using natural gas. In a typical ammonia plant, a steam methane reformer is used to produce hydrogen from natural gas. This hydrogen is combined with atmospheric nitrogen via the Haber-Bosch process, which occurs at elevated temperatures and pressures. The use of unabated fossil fuel feedstocks and energy inputs means that the process is highly carbon intensive.

However, most new ammonia plants currently under development will employ one of two low carbon production pathways. Under the blue ammonia pathway, plants are equipped with carbon capture and storage (CCS) systems to capture the CO_2 released during the conversion of natural gas to hydrogen. Under the green ammonia pathway, renewable electricity is used to produce the hydrogen, resulting in nearly zero CO_2 emissions. Energy inputs used for nitrogen capture and process heat can also be obtained from low emissions sources. Clean ammonia production technologies can be integrated into existing plants as well, providing a viable path to decarbonizing the existing ammonia production capacity.

Clean ammonia produced with CCS or renewable energy will help decarbonize existing applications in the fertilizer and chemical industries, as well as enable ammonia to replace carbon-intensive energy sources in other hard-to-abate sectors.

Ammonia Will Be a Key Long-Distance Energy Carrier

Underlying the growth in clean ammonia production is an emerging consensus that ammonia will be the most economic option for transporting hydrogen over long distances.[1, 2] The chemical is a key enabler for the dozens of gigawatts of green hydrogen production capacity currently under development in remote, renewable energy-rich locations such as Australia, Saudi Arabia, Namibia, and Chile. According to project data compiled by Guidehouse Insights,[3] the majority of developers intend to convert hydrogen into green ammonia before shipping it to international markets.

More than 5 million tons per year of clean ammonia production capacity are currently under development in the US.

Blue ammonia is also an attractive option for reducing emissions from existing production sites and for decarbonizing fossil fuel exports. Since fossil fuel-producing regions tend to have high geological potential for permanent carbon storage, converting natural gas to blue ammonia prior to export simplifies the value chain required for CCS. ADNOC, QatarEnergy, and other leading fossil fuel producers are currently developing large-scale blue ammonia projects on this basis.

In the US, strong progress is being made on clean ammonia production. According to International Energy Agency project data, more than 5 million tons per year of clean ammonia production capacity are currently under development, including major projects in Louisiana and Texas. Ammonia projects are also prominently featured in many of the hydrogen hub proposals currently seeking federal funding from the Department of Energy.

Ammonia Can Be Used as a Fuel in Shipping and Other Sectors

Ammonia can also be used directly as a fuel in hard-to-abate sectors. It is a key contender within the shipping industry, which currently consumes 300 million tons of fossil-based fuels each year and accounts for approximately 3% of anthropogenic CO_2 emissions.

Ammonia can potentially be combusted in specialized marine engines alongside a pilot fuel (typically diesel, but potentially also hydrogen). Alternatively, a fuel processor such as a cracker (also referred to as a reformer) can be used to decompose ammonia into hydrogen and nitrogen molecules, with the hydrogen fed into a fuel cell to provide electricity for propulsion or onboard power consumption. Ammonia-to-power technologies can also be used to generate electricity in other sectors, such as

[1] International Renewable Energy Agency (IRENA), *Global Hydrogen Trade to Meet the 1.5°C Climate Goal. Part II: Technology Review of Hydrogen Carriers* (Abu Dhabi: IRENA, 2022), **https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf**.

[2] Charles Johnson et al., "Shipping the Sunshine: An Open-Source Model for Costing Renewable Hydrogen Transport from Australia," *International Journal of Hydrogen Energy* 47, no. 47 (2022): 20362-77, **https://www.sciencedirect.com/science/article/pii/S0360319922017281**.

[3] Guidehouse Insights, *Hydrogen Electrolyzer Tracker 1Q23*, **https://guidehouseinsights.com/reports/hydrogen-electrolyzer-tracker-1q23**.

stationary power generation for critical infrastructure sites, off-grid or remote locations, and port-side applications.

Ammonia Is Already an Internationally Traded Commodity

The ammonia industry transports and stores 18 million tons of internationally traded ammonia each year. More than 200 gas carriers capable of shipping ammonia and liquid petroleum gas are currently in operation around the world,[4] and 150-200 ports are equipped with terminals for unloading and storing traded ammonia.[5]

A similarly well-developed distribution infrastructure is available at the national level. The US alone has more than 3,000 miles of pipelines capable of transporting around 2 million tons of ammonia over a 12-month period. The country is also home to approximately 10,000 ammonia storage sites, predominantly located in the rural Midwest.[6]

150-200 ports are equipped with terminals for unloading and storing traded ammonia globally.

Additional opportunities exist for converting existing fossil fuel infrastructure to transport ammonia. For instance, several organizations are currently exploring the possibility of converting liquefied natural gas receiving terminals to offtake liquid ammonia.

Ammonia Can Decarbonize a Significant Share of Marine Fuel Demand

Several low or zero carbon fuels have been proposed to decarbonize the shipping industry. To assess which of these options provides the greatest decarbonization potential, Guidehouse Insights has evaluated them along five metrics: scalability, anticipated fuel costs, capital expenditure requirements, greenhouse gas (GHG) savings potential, and volumetric energy density. Figure 1 summarizes the outcomes of this analysis.

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[4] Pacific Northwest National Laboratory, "Ammonia as Maritime Fuel," May 7, 2021, **https://www.energy.gov/sites/default/files/2021-08/9-nh3-maritime-fuel.pdf**.

[5] Alfa Laval, Hafnia, Haldor Topsøe, Vestas, and Siemens Gamesa, *Ammonfuel: An Industrial View of Ammonia as a Marine Fuel* (2020), **https://www.topsoe.com/hubfs/DOWNLOADS/DOWNLOADS%20-%20White%20papers/Ammonfuel%20Report%20Version%2009.9%20August%203_update.pdf**.

[6] Guidehouse Insights, *Leveraging Ammonia as a Hydrogen Carrier and Decarbonization Tool*, 1Q 2023, **https://guidehouseinsights.com/reports/leveraging-ammonia-as-a-hydrogen-carrier-and-decarbonization-tool**.

Figure 1 Evaluation of Alternative Marine Fuels and Propulsion Options

Fuel or Propulsion Option	Scalability Assessment	2030 Fuel Cost Range (USD/toe)	Capital Cost Assessment	GHG Savings* (%)	Volumetric Energy Density (MJ/l)
Green Ammonia	Excellent	1,100-2,000	Good	90-100	12.7
Bio-Methanol	Poor	790-1,740	Good	50-65	16
Marine Biodiesel	Poor	690-1,950	Excellent	40-70	33.3
E-Methanol	Good	1,780-3,290	Good	50-100	16
Synthetic MDO	Good	2,090-4,150	Excellent	50-100	36.6
Liquid Green Hydrogen	Good	1,910-2,870	Poor	90-100	8.5
Battery Electrification	Poor	500-890	Very Poor	90-100	1.6

Best overall option when assessed across the full range of evaluation criteria (Green Ammonia)

Near term options with limited GHG saving and scalability potential (Bio-Methanol, Marine Biodiesel)

Development constrained by the availability of biogenic CO2 and DAC (E-Methanol, Synthetic MDO)

Only suitable for short-sea shipping due to energy density constraints (Liquid Green Hydrogen, Battery Electrification)

* GHG savings are strongly determined by feedstock choice and electricity sourcing considerations. Values included here are intended to provide an indicative range.

(Source: Guidehouse Insights)

Maritime Applications for Ammonia-to-Power Systems

Currently 94% of shipping sector fuel consumption is supplied by petroleum-based liquid fuels, primarily very low and ultralow sulfur fuel oil, marine gas oil, and marine diesel oil (MDO).[7] The remaining proportion of marine fuel consumption is largely supplied by liquefied natural gas. Since the average life expectancy of a vessel is typically 25-30 years, achieving decarbonization targets set by the International Maritime Organization (IMO) will require near-term adoption of new fuels and propulsion technologies to assure a gradual transition and head off high retrofit costs in future years.

In July 2023, IMO member states voted to adopt a revised GHG reduction strategy at the 80th meeting of the Marine Environment Protection Committee. The new strategy includes a commitment to ensure the uptake of alternative zero and near-zero GHG fuels by 2030. It also sets the target of reaching net-zero emissions “close to 2050,” replacing the IMO’s previous target of a 50% reduction in GHG emissions by 2050.

Achieving decarbonization targets set by the IMO will require near-term adoption of new fuels and propulsion technologies.

The following sections explore some key applications for ammonia-to-power systems in the shipping industry. Early deployments are likely to occur on smaller vessels that operate within ports or near to shore. As the technology matures and increasing volumes of ammonia are made available for marine applications, adoption is expected to be extended to larger oceangoing vessels.

[7] Guidehouse Insights, *Hydrogen and Power-to-X Fuels in Shipping and Aviation*, 3Q 2022, **https://guidehouseinsights.com/reports/hydrogen-and-power-to-x-fuels-in-shipping-and-aviation**.

Offshore Support Vessels

Offshore support vessels (OSVs) are used to carry supplies, equipment, and crew to offshore energy installations. Historically, the offshore sector has been dominated by the oil & gas industry. However, recent years have witnessed strong investment in offshore wind projects, especially in Northern Europe and China. The US Gulf Coast is also expected to become a key location for offshore wind projects. According to Guidehouse Insights' *Global Wind and Solar Energy Database*, total global installed offshore wind capacity is projected to rise from approximately 85 GW in 2023 to more than 330 GW by 2030.[8]

Increasing construction and maintenance demands from the offshore wind sector will contribute to strong growth in the global OSV fleet. Since OSV fuel consumption increases the lifecycle emissions associated with offshore renewable energy projects, decarbonizing maintenance vessels is a key concern. Globally, approximately 740 OSVs are currently equipped with hybrid diesel-electric propulsion systems that can be retrofitted with ammonia-to-power systems at relatively low expense.

Long-term, the offshore wind industry may also offer some important sector coupling opportunities for ammonia. Various companies, including Siemens Energy, Vattenfall, and Lhyfe, are currently developing offshore electrolysis concepts to reduce transmission costs associated with offshore wind projects. Offshore ammonia synthesis is also being considered to enable vessels to refuel while still at sea.

In April 2023, Amogy signed a memorandum of understanding with Singapore-based Marco Polo Marine to install its ammonia-to-power system on vessels used to service offshore wind projects throughout the Asia Pacific region.

Tugboats

Tugboats are used to assist with maneuvering barges, cargo ships, and other vessels around ports and inland waterways. This task requires relatively powerful engines and large propellors, making tugboats some of the most emissions-intensive commercial harbor craft. In the US, approximately 6,500 tugboats are used to tow the 12,000 barges that transport about 14% of intercity freight.[9]

Ammonia-to-power technologies can be used to replace diesel propulsion systems in these vessels. Amogy has already begun retrofitting a diesel genset-powered tugboat with ammonia-to-power technology and expects the vessel to become operational by the end of 2023. The vessel will be powered by green ammonia.

[8] Guidehouse Insights, Global Wind and Solar Energy Database (2023), **https://guidehouseinsights.com/subscription-services/global-wind-and-solar-energy-database**.

[9] Blue Sky Maritime Coalition, *Collaboration for Accelerating Emission Reductions across Maritime Transportation Systems* (2023), **https://www.bluesky-maritime.org/_files/ugd/8ed502_6533ad26bc5140a2b84f95558a6147ae.pdf**.

Oceangoing Vessels

Ammonia-to-power systems can complement combustion engines to provide a range of important services to the oceangoing vessel segment.

The majority of marine fuel demand comes from large oceangoing vessels such as tankers, bulk carriers, and container ships. As of 2022, over 100,000 large oceangoing vessels were in operation globally.[10]

Marine fuel consumption on oceangoing vessels is the shipping industry's central decarbonization challenge. Commitments from manufacturers and shipowners underscore the key role that ammonia is expected to play. Engine manufacturers MAN Energy Solutions and Wärtsilä are both developing ammonia-compatible dual-fuel combustion engines due for commercial release by 2025-2026 at the earliest. By late 2022, 130 ammonia-ready vessels were already on order, according to shipping service provider Clarksons.[11]

Ammonia-to-power systems can complement combustion engines to provide a range of important services to the oceangoing vessel segment, especially in the port environment where air quality considerations are paramount. These services include auxiliary power for maneuvering in port and onboard electricity generation. Hydrogen from ammonia cracking can also be used as a pilot fuel in dual-fuel ammonia engines.

The efficiency benefits of fuel cell technologies mean that ammonia-to-power systems may be used to replace higher shares of primary propulsion demand over the long term. Optimizing the efficiency of onboard energy conversions will be a priority for shipowners interested in mitigating the additional costs imposed by alternative fuel adoption. Fuel cells also deliver emissions reductions compared with combustion-based systems.

Other Applications for Ammonia-to-Power Systems

Ammonia-to-power technology is also well suited to a range of stationary power generation applications. Some of the most attractive near-term opportunities will be in locations that already have access to ammonia supplies, as well as regions where ammonia will be imported as an energy carrier. These locations include ports, industrial sites, and agricultural facilities.

In ports, ammonia-to-power systems can be used for shoreside power. Also referred to as cold ironing, shoreside power is the practice of supplying electricity to berthed vessels as an alternative to using onboard diesel gensets. Adopting fuel cell technologies for shoreside power can greatly reduce CAPEX requirements for new grid connections and infrastructure. Ammonia-to-power systems could also be used to provide clean power to gantry cranes, drayage trucks, and other material-handling equipment.

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[10] Gary Dixon, "Deliveries Slow but World Fleet Tops 100,000 Ships for First Time," TradeWinds, February 15, 2021, **https://www.tradewindsnews.com/tankers/deliveries-slow-but-world-fleet-tops-100-000-ships-for-first-time/2-1-962728**.

[11] Jasmina Ovcina Mandra, "Clarksons: There Are 130 Ammonia-Ready and 6 Hydrogen-Ready Vessels on Order," Offshore Energy, October 18, 2022, **https://www.offshore-energy.biz/clarksons-there-are-130-ammonia-ready-and-6-hydrogen-ready-vessels-on-order/**.

Facilities that have strict round-the-clock power requirements such as mining operations, data centers, remote microgrids, and military sites, could use ammonia-to-power technologies to provide resiliency to their operations. Also, since ammonia is easier to transport and store than liquid or compressed hydrogen, ammonia crackers provide a compelling value-add for fuel cell power generation in remote areas.

Case Study: Amogy's Ammonia-to-Power Technology

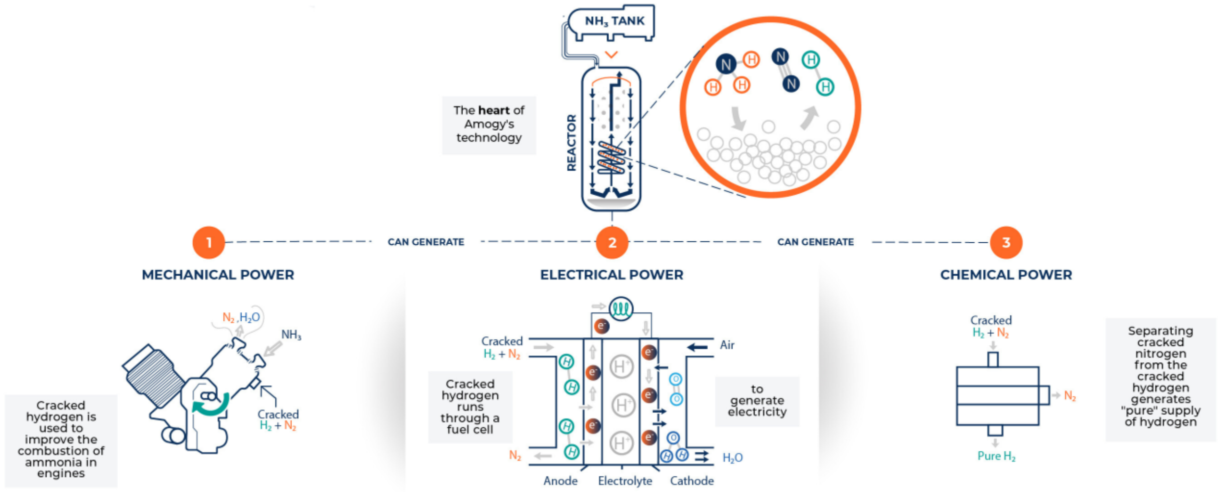
Founded in 2020, Amogy has developed an ammonia-to-power technology that can be used to decarbonize the maritime, power generation, and other industries by combining the performance advantages of hydrogen with the storability and energy density characteristics of liquid ammonia.

The reactor system is equipped with a high activity catalyst, which allows the ammonia-cracking reaction to take place at low operating temperatures and high efficiency levels. The company couples the reactor with a proton exchange membrane fuel cell as part of a compact, modular, and integrated power system known as a "powerpack."

Amogy successfully demonstrated the world's first ammonia-powered drone flight at a 5 kW scale in July 2021. This was followed by the demonstration of a 100 kW tractor in May 2022. The company unveiled the world's first ammonia-powered semitruck in early 2023, scaling its technology to 300 kW. Amogy now plans to achieve a 1 MW tugboat demonstration by the end of 2023. Between 2024 and 2025, the company will integrate its technology into an ammonia tank barge as the first commercial maritime deployment. The powerpack will use boil-off gas from the liquid ammonia to generate electricity used to maintain tank pressures. By the end of 2024, Amogy intends to offer commercial modular powerpacks with a capacity of 400 kW that can achieve larger power scales of a few megawatts by installing several powerpacks in parallel.

Figure 2 shows Amogy's position in the emerging ammonia fuel supply chain. Further information on Amogy can be found on the **company's website**.

Figure 2 Amogy's Technology Unlocks Ammonia's Potential as a Hydrogen Carrier



(Source: Amogy)

Key Takeaways

Ammonia shows considerable promise as a clean fuel suitable for use in the shipping industry, distributed energy generation, and various hard-to-abate applications. Adoption in coming years will be driven by increasing volumes of clean ammonia production and ongoing reductions in the cost of clean ammonia delivered to end users. Technological innovations in vessel and propulsion system design will also be critical.

However, scaling the clean ammonia value chain to decarbonize priority sectors in line with global climate ambitions will require significant investments from private players, extensive collaboration among market participants, and a supportive policy and regulatory environment. Guidehouse Insights offers the following key takeaways to ammonia and maritime industry stakeholders.

- **Policymakers should provide clear incentives to clean ammonia producers.** Incentives for clean ammonia production will be a key investment driver during the early phases of market development. Developers have responded positively to both the volume of public funds committed under the Inflation Reduction Act in the US, and the simplicity of fixed-premium Production Tax Credits and Investment Tax Credits as a subsidy mechanism for blue and green hydrogen. These forms of support will significantly lower production costs for clean ammonia projects. The European Union (EU) has a more complex regime of incentives but will offer targeted support for green ammonia imports under a revised version of its European Hydrogen Bank auction mechanism.
- **Carbon taxes will be key to ammonia uptake in the shipping sector.** Production-based incentives may need to be complemented by additional demand-side measures. In the EU, the Emissions Trading System (ETS) will be expanded to include emissions produced by international vessels that dock at EU ports. Expansion of the ETS will be complemented by the FuelEU initiative, which sets minimum quotas for the uptake of fuels produced using renewable

hydrogen. The quotas will start at 2% in 2025 and rise to 80% by 2050.

- **Shipowners currently lack investment support for zero carbon propulsion systems and technologies.** While production incentives and carbon taxes can help deliver cost parity for alternative fuel options, shipowners will still incur additional costs for installing fuel cells, ammonia crackers, and other zero carbon power and propulsion technologies. To assist with market formation, policymakers should consider additional incentives focused on reducing the cost of new onboard technologies for zero carbon vessels.
- **Target setting and early adoption should be key priorities for shipowners.** For shipowners, establishing ambitious company-level emissions reduction targets, including intermediate ambitions and end goals, will send a clear signal to stakeholders in the ammonia sector that there is a ready market for adoption. These targets can help accelerate necessary investments in ammonia production, bunkering and port infrastructure, and technology R&D. When investing in fleet renewals, vessel asset life, retrofit considerations, and the declining cost outlook for zero carbon fuels should be key considerations.
- **Ammonia technology providers need to generate public awareness while resolving safety concerns.** Despite decades of safe transport in vessels, ammonia handling remains a concern for some stakeholders. Industry members should work with regulators to accelerate the adoption of safety guidelines for ammonia use as a fuel, drawing on existing rules for ammonia handling on vessels where appropriate. In parallel, ammonia technology providers should focus on demonstrating safe use of ammonia as a fuel through collaborations, trials, and pilot projects.
- **Governments should implement and codify the recent IMO recommendations for net-zero maritime vessels by 2050.** Achieving the IMO's targets will require action from member state governments. National policy frameworks for decarbonizing the shipping sector should be revised to support the IMO's current timeline for zero carbon fuel adoption.

Acronym and Abbreviation List

ADNOC .... Abu Dhabi National Oil Company

CAPEX .... Capital Expenditure

CCS .... Carbon Capture and Storage

CO_2 .... Carbon Dioxide

ETS .... Emissions Trading System

EU .... European Union

GHG .... Greenhouse Gas

GW .... Gigawatt

IMO .... International Maritime Organization

kW .... Kilowatt

MDO .... Marine Diesel Oil

MJ/L .... Megajoule per Liter

MW .... Megawatt

OSV .... Offshore Support Vessel

R&D .... Research and Development

toe .... Ton of Oil Equivalent

US .... United States

Scope of Study

Guidehouse Insights has prepared this white paper, commissioned by Amogy, to provide an overview of the role that ammonia is expected to play as a zero carbon energy carrier and marine fuel. It explains how ammonia can be produced at very low carbon intensities, why it will be used to transport energy over very long distances, and how it compares with competing fuels. The report also provides insights into specific applications for ammonia-to-power systems in the maritime industry and other sectors.

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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