Guidehouse INSIGHTS

White Paper

Ammonia as a Fuel to Decarbonize Transportation

The Inception of a New Fuel in Established Markets Amid the Energy Transition

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Introduction

As countries around the world aim to reach net-zero emissions by mid-century, the success of global decarbonization efforts depends upon technological developments in the transportation industry. Together, passenger and freight transportation account for more than one-third of global CO_2 emissions from end-use sectors.[1] Progress on emissions reductions to date has been concentrated mainly on the electrification of the passenger vehicle segment. EVs accounted for almost 9% of new global car sales in 2021, with most growth occurring in North America, Europe, and China. However, other forms of transportation—especially long-haul trucking, locomotives, aviation, and shipping—have proven much more difficult to decarbonize. Technologies such as hydrogen and high performance batteries show significant promise but remain at the pre-commercial stage.

Ammonia is attracting increasing attention as an enabler of emissions reductions in the hard-to-abate transportation sectors. Produced by combining hydrogen with atmospheric nitrogen, ammonia has been used by various industries for more than a century, primarily as a chemical precursor to nitrogen fertilizers. However, ammonia also possesses a relatively high volumetric energy density compared with hydrogen and existing battery chemistries, which makes it an attractive energy carrier.

Technological advances in recent years have presented new opportunities for using ammonia within the transportation sector. These include more efficient methods of cracking ammonia to generate hydrogen for use in fuel cells or combustion engines; propulsion systems optimized for the direct use of ammonia; or combined approaches that can include blending ammonia or hydrogen with conventional fuels. For instance, Brooklyn-based startup Amogy has developed a compact, high efficiency reactor that cracks ammonia in situ and uses the hydrogen to generate power through a fuel cell. The design leverages the superior physical characteristics of liquid ammonia to carry the performance advantages of hydrogen far from the supply source and does so at lower operating temperatures and higher efficiency levels than alternative designs.

Technology such as Amogy's is already well on its way toward commerciality and could soon be seen in shipping and ground transportation, as well as stationary power generation applications. This report explores the different applications for ammonia as an affordable, readily accessible, and storable zero-carbon fuel within the transportation sector and beyond. This paper also explores drivers that support further adoption of ammonia use, barriers that could impede its growth, and recommendations for key stakeholders to consider.

[1] International Energy Agency, "Transport: Improving the Sustainability of Passenger and Freight Transport," **https://www.iea.org/topics/transport**.

Ammonia as a Transport Fuel and Hydrogen Carrier

Building off a longtime presence in the agriculture sector as a fertilizer, ammonia production, transport and usage already has the technological maturity, existing infrastructure, and familiarity of the public to expand into new industries, such as fuel and energy storage. The COVID-19 pandemic spotlighted the world's need for a seamless supply chain, which critically depends on the efficient transportation of goods and commodities from ship to truck to warehouse. The pandemic also underlined the importance of seamless digital transportation of information (i.e., internet traffic), which consumes vast amounts of energy and has high reliability requirements. As a transportation fuel and a hydrogen vector, ammonia can play a key role in reducing emissions and improving resiliency in both regards.

Table 1 Characteristics of Ammonia as a Transportation Fuel

Characteristic	Description
Boiling point	Although ammonia is a gas at ambient temperatures, it can be stored as a liquid at -34°C. This reduces the cost, complexity, and space requirements for storage compared with liquid hydrogen and liquefied natural gas (LNG), which have boiling points of -253°C and -162°C, respectively. A higher boiling point also limits the energy inputs needed to achieve liquefaction temperatures. At an ambient temperature, ammonia can also be stored as a liquid with a mild pressure of ~8 bar.
Volumetric energy density	The volumetric energy density of liquid ammonia is 12.7 MJ/L, which is higher than for liquid hydrogen at 8.5 MJ/L and compressed hydrogen at 4.7 MJ/L (at a pressure of 69 MPa in ambient temperature conditions), but lower than for diesel or gasoline. Over an equivalent distance, fueling a vehicle solely using ammonia would require approximately three times the internal tank volume needed for conventional diesel fuel but three times less than the volume required for compressed hydrogen.
Carbon intensity of production	Ammonia can be produced without any carbon emissions providing that the electrolyzer and ammonia plant are supplied with electricity solely from renewable energy sources.
Method of use	When passed through a cracker, ammonia provides a hydrogen source for fuel cells or hydrogen combustion propulsion systems. Ammonia can also be combusted directly within compatible internal combustion engines (ICEs) in combination with an ignition fuel. ICE propulsion systems can also use ammonia crackers to produce hydrogen as a pilot fuel.
Emissions	Ammonia does not produce any CO_2 emissions but combustion will result in some nitrous oxide emissions. These can be eliminated through engine design adjustments, tweaking the proportion of ignition fuel, and adopting selective catalytic reduction (SCR) systems. Ammonia crackers combined with fuel cells do not produce any carbon or nitrogen-based greenhouse gases (GHGs).

(Source: Guidehouse Insights)

Shipping

The shipping industry accounts for approximately 3% of global CO_2 emissions. The sector is largely dependent upon oil-derived fuels such as heavy fuel oil (HFO), very low sulfur fuel oil, and marine gas oil (MGO) to meet its energy needs. Together these fuels represent approximately 221 million tons of oil demand per annum. Liquefied natural gas (LNG) accounts for a smaller proportion of shipping fuel demand, with 2.3 million tons of the fuel consumed in 2021. The only low carbon fuels deployed beyond pilot project scale are marine biofuels, which make up less than 0.1% of the sector's fuel supplies, according to the International Energy Agency (IEA).

To secure compliance with global emissions targets, there is a broad consensus that the shipping industry needs to transition to a new suite of fuels and propulsion technologies. The United Nations body tasked with regulating the industry, the International Maritime Organization (IMO), released its initial greenhouse gas (GHG) strategy in 2018, calling for a 50% reduction in GHG emissions relative to 2008 levels by 2050. As international trade has historically been closely correlated with GDP growth, expanding demand for shipping fuels in the future will likely require a more substantial reduction in emissions on a per-vessel basis.[2] Moreover, because the average life expectancy of a vessel is 25-30 years, prominent industry players have set a target of 5% for zero-emissions vessels entering service by 2030 to avoid steep retrofit costs and ensure a sufficient ramp-up period for new bunkering infrastructure.

Ammonia is one of several zero-carbon propulsion options being pursued within the sector. The suitability of individual zero-carbon technologies depends on the size and operational profile of a given vessel. For small and midsize vessels that make regular short voyages, such as passenger ferries, energy density requirements for fuels and propulsion systems are relatively lenient. In contrast, energy density is a critical performance indicator for large ocean-going vessels such as container ships, bulk carriers, and oil and chemical tankers. These vessel categories account for 85% of the shipping sector's net GHG emissions, according to the International Renewable Energy Agency.

Besides its high volumetric energy density and manageable boiling point, ammonia has several key advantages that make it a suitable choice for ocean-going vessels as well as smaller ships. For instance, it is already a globally traded commodity, with 20 million tons[3] of the chemical shipped each year among almost 200 ports. The presence of existing transportation and storage infrastructure provides a ready foundation for a future zero-carbon fuel value chain in shipping. Ammonia also presents greater prospects for scalability than alternative options such as methanol and biofuels, where constraints on CO_2 and sustainable biomass supplies pose barriers to widespread uptake.

The presence of existing transportation and storage infrastructure provides a ready foundation for a future zero-carbon fuel value chain in shipping.

[2] The International Chamber of Shipping estimates that per-vessel emissions need to decline by 90% to reach the IMO's GHG reduction target.

[3] This figure excludes ammonia traded in the form of urea or other derivatives.

An additional benefit is that ammonia is compatible with more than one propulsion technology. In smaller ships, it can be used as a hydrogen carrier for fuel cell-based electric propulsion systems, where an onboard cracker splits ammonia to provide the hydrogen source. In larger vessels, where energy density or efficiency considerations mitigate against fuel cell technologies, it may be suitable for injection into adapted internal combustion engines (ICEs). Use within ICEs entails relatively minor alterations to the layout of propulsion systems in comparison with fuel cell adoption. However, due to ammonia's narrow flammability range, the shipping industry envisions using the fuel in combination with a smaller quantity of ignition fuel—either MGO or hydrogen extracted from the ammonia using a cracker. Two leading engine manufacturers, Wärtsilä and MAN Energy Solutions, have already announced plans to introduce ammonia-fueled combustion engines to market by 2024.

Trucking

Road freight is a vital component of economic activity. The pandemic highlighted the sector's importance as an increasing number of trucks were deployed to deliver products to end consumers. Guidehouse Insights forecasts the global fleet of heavy duty vehicles to reach 94 million by 2030, up 30% from 2020's estimated 74 million. Most of this growth is expected to come from developing markets. Trucks currently make up around 87% of the heavy duty vehicles market and represent one of the fastest growing segments. However, trucks also represent a transport segment that is in dire need of decarbonization. In 2021, medium- and heavy duty trucks emitted 1.8 gigatons (Gt) of CO_2, thereby accounting for 23% of all transport-related emissions and 9% of global carbon emissions.

Reducing carbon emissions from the trucking sector requires a transition from diesel-powered engines to alternative fuel and drivetrain technologies. As with the shipping sector, the optimal choice of technology depends on the size and weight of the vehicle and its intended purpose and expected traveling profile. Vehicles that travel set, short routes in limited areas are more amenable to being powered by batteries. Urban delivery vehicles and city buses are prime examples as both vehicle types can be charged at predetermined stations along their routes. However, for long-range heavy duty vehicles, the weight of electric batteries and their associated charging times may present significant limitations. This scenario provides an opportunity for fuel cell-based propulsion systems as a potential solution.

Fuel cells convert hydrogen into electricity to power electric drivetrains. As a result, fuel cell trucks share many of the advantages of battery electric systems without incurring additional weight or longer refueling times. Furthermore, fuel cell trucks show higher performance than battery-powered vehicles in inclement weather conditions.

On the road, fuel cell trucks share many of the advantages of battery electric systems without incurring additional weight or longer refueling times..

Given these advantages, fuel cell trucks have also been endorsed by key automotive manufacturers. Both startups, such as Nikola Motors and Hyzon Motors, and industry stalwarts, such as Toyota and Hyundai, are investing heavily in the technology. Governments across North America[4] and Europe[5,6] have also initiated several multi-year research projects recently, focusing on scaling up refueling infrastructure and improving the technological efficiency of fuel cell propulsion systems.

Although hydrogen is typically stored onboard trucks in pressurized containers, which can be refilled at hydrogen refueling stations, the fuel economy of hydrogen trucks is contingent on the form in which hydrogen is delivered. Hydrogen can be stored in a compressed or liquid state, or it can be supplied via a chemical hydrogen carrier such as ammonia. Compared with compressed hydrogen (4.7 MJ/L at 690 bar and 15°C), liquid ammonia has an energy density (12.7 MJ/L) that is approximately 2.7 times greater, and it requires significantly less energy to store and transport safely. Ammonia also benefits from existing supply infrastructure and the ease of liquid-based transportation and storage. Using ammonia as a hydrogen carrier combined with a compact and high efficiency cracker enables fuel cell trucks to achieve higher energy efficiency and comparable ranges to present-day diesel engines.

Material-Handling Equipment

Increased online retail activity brought on by the pandemic highlighted the importance of not just shipping and road freight transportation but also material-handling heavy equipment such as forklifts at warehouses, ports, and airports. Traditionally powered by fossil fuels such as gasoline, diesel, LPG, and compressed natural gas, the material-handling equipment market has seen a drastic shift toward electrification in recent years. Electric forklifts account for nearly 60% of the forklift market[7] according to the world's biggest forklift supplier, Toyota.

Without the emissions associated with ICEs, and with quicker refill options and lighter weight than battery-driven options, fuel cell forklifts offer tremendous growth opportunities. American fuel cell developer Plug Power aims to convert electric forklifts to run on hydrogen fuel cells and has already installed 50,000 fuel cells[8] in forklifts worldwide. Users include Proctor & Gamble, Walmart, Kroger, BMW, Home Depot, and Amazon. As mega-warehouses continue to expand, hydrogen-powered fuel cell forklifts could account for 20% of forklift sales by 2030 and 60% of sales by 2050.[9] While the US is the largest market for fuel cell forklifts, Asia will see growth as well, with China expected to have 5,000 hydrogen-run forklifts in operation by 2025 and Japan expected to have a fleet of 10,000[10] by 2030.

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[4] Emissions Reduction Alberta, AZETEC Project, **https://eralberta.ca/projects/details/alberta-zero-emissions-truck-electrification-collaboration-azetec/**.

[5] H2Haul Project, **https://www.h2haul.eu/about/.**

[6] H-2Share Project**, https://www.nweurope.eu/projects/project-search/h2share-hydrogen-solutions-for-heavy-duty-transport/**.

[7] Toyota, Forklift Fuel Options and Buying Considerations**, https://www.toyotaforklift.com/resource-library/material-handling-solutions/products/forklift-fuel-options-and-buying-considerations**.

[8] Plug Power, 2021 Plug Symposium**, https://s21.q4cdn.com/824959975/files/doc_presentations/2021/2021-PLUG-SYMPOSIUM-FULL-DECK2.pdf**.

[9] Fuel Cell and Hydrogen Energy Association, Roadmap to a US Hydrogen Economy**, https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5e7ca9d6c8fb3629d399fe0c/1585228263363/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf**.

[10] Toyota, The Future is Here with Forklifts Powered with Hydrogen, **https://fuelcellsworks.com/news/toyota-the-future-is-here-with-forklifts-powered-with-hydrogen/**.

However, scaling up hydrogen fuel cells for use in material-handling equipment faces challenges related to fuel delivery and storage. Ammonia combined with an on-vehicle cracker can help to mitigate these challenges. With ammonia-handling safety guidelines already established within the industry, a mature delivery infrastructure in place and better physical properties for cost-effective onsite storage, ammonia can offer all the benefits of hydrogen fuel cells with higher user-friendliness.

Agricultural applications also present a cross-industry opportunity for ammonia. Already being consumed extensively around the world for fertilizer applications, ammonia could also be used at the same sites to drive the machines that help plant, harvest, dry, store, and refrigerate food. It can also be used to heat or cool barns, homes, and other inhabited structures in agricultural settings. The benefits of ammonia as a fuel are especially attractive in more remote locations due to its high energy density, meaning fewer replenishments.

Distributed Energy Systems and Data Centers

In 2020, at the height of the COVID-19 pandemic, global internet traffic was estimated to have increased by more than 40%. This increase was driven by spikes in video streaming, video conferencing, online gaming, and social networking. A vast majority of internet traffic is routed via data centers, which account for 1% of global final electricity demand (200 TWh-250 TWh)[11] according to the IEA. In total, data centers are estimated to account for 2%[12] of global CO_2 emissions. Given the rate at which the demand for data centers is growing, this proportion is expected to rise to 3.2% by 2025. Data storage alone is anticipated to account for 14%[13] of global emissions by 2040.

Although industry leaders such as Google (12 TWh in 2019), Apple (1.7 TWh in 2020), and Facebook (7 TWh in 2020) have taken the lead on purchasing renewable energy such as solar or wind power to satisfy data center requirements, many facilities are still not powered by renewable electricity. Servers running computations are a critical load that must be satisfied in data centers, and even small interruptions in power supplies can result in substantial financial losses. Because solar and wind power sources—two common sustainable energy sources for data centers—are intermittent, they cannot be relied on to supply continuous power that these facilities need. This reality necessitates the integration of more stable primary or backup power sources that can complement renewables in satisfying data center electricity demand.

[11] International Energy Agency, Data Centres and Data Transmission Networks, **https://www.iea.org/reports/data-centres-and-data-transmission-networks**.

[12] Yale School of the Environment, “Energy Hogs: Can World’s Huge Data Centers Be Made More Efficient?”, **https://e360.yale.edu/features/energy-hogs-can-huge-data-centers-be-made-more-efficient**.

[13] Zella DC, “How Is Your Data Center Affecting Your Carbon Footprint?,” **https://www.zelladc.com/insights/how-is-your-data-centre-affecting-your-carbon-footprint**.

Sustainable technologies that can provide continuous stationary power often in isolated locations, such as data centers can take advantage of the same benefits that ammonia and fuel cells provide to the transportation sector. Several companies are investing in fuel cells to power their data centers. In 2021, Caterpillar launched a 3-year collaborative project with Microsoft and Ballard Power Systems to demonstrate the reliability of fuel cells for supplying low carbon electricity to data centers. The European Union launched the Eco Edge Prime Power project that will demonstrate synergies between fuel cells and batteries to provide primary power to critical infrastructures such as data centers.

To further decarbonization efforts and increase energy density, fuel cells can also be powered by hydrogen that is generated from renewable energy and carried by ammonia via a cracker. Like the heavy duty transportation sector, stationary power generation can leverage ammonia's relative ease of use and cost-effectiveness to store and distribute compared with hydrogen.

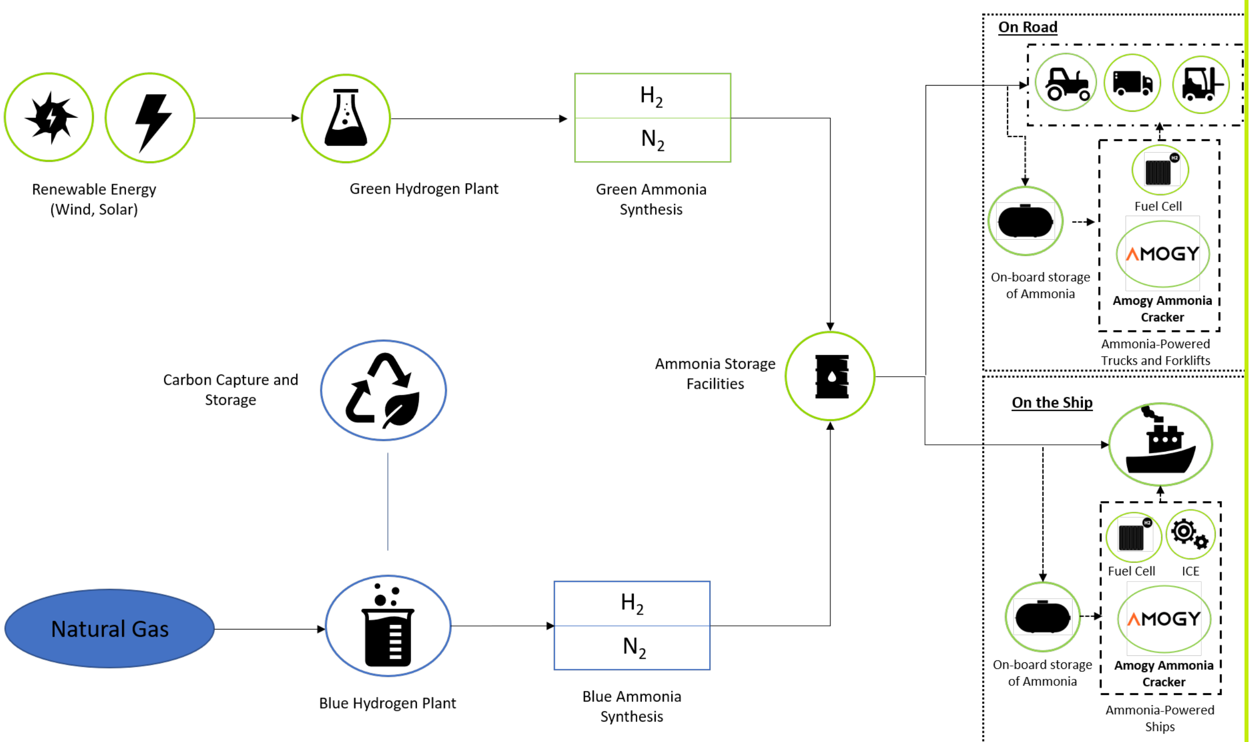
Company Profile: Amogy

Founded by four MIT PhD alumni in 2020, Amogy aims to accelerate the decarbonization of the global transportation industry using its innovative ammonia-cracking technology. In July 2021, the company successfully demonstrated its offering by engineering the world's first ammonia-powered drone flight. Later that year, it received Series A funding from investors including Amazon and AP Ventures. Between 2022 and 2024, Amogy intends to showcase its technology platform in ammonia-fueled cargo vessels and heavy duty ground transportation.

Amogy's high efficiency reactor enables the performance advantages of hydrogen to be combined 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 lower operating temperatures and higher efficiency levels than alternative designs. The company intends to supply the reactor alongside a proton exchange membrane (PEM) fuel cell as part of a compact and integrated power system, suitable for use on vessels, in land vehicles, and for stationary power generation applications. The reactor can also be used independently for other forms of hydrogen generation.

Figure 1 shows Amogy's position in the emerging ammonia fuel supply chain. Further information on Amogy can be found on the **company's website**.

Figure 1 Amogy's Ammonia-Cracking Technology



(Source: Guidehouse Insights)

Market Drivers

Although uptake of ammonia within the transportation sector is still nascent, a range of factors are expected to drive its development as both a transportation fuel and hydrogen vector. A combination of emissions-reduction policies, private sector collaborations, and infrastructural synergies could help to spur the deployment of ammonia propulsion systems, the specifics of which will depend on each market segment. The shipping industry will likely adopt ammonia as a renewable transportation fuel first among potential markets because of the long lead time to develop and build maritime technologies in response to both the existing and expected emissions-reduction regulations. Therefore, the market drivers discussed here are shipping industry-focused and will be similar for the other industries profiled earlier.

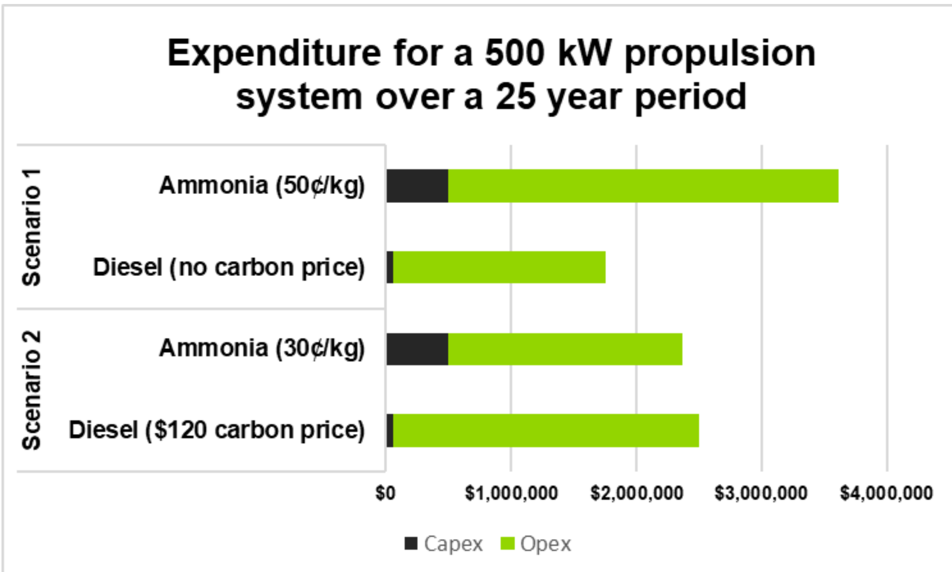
Policy Drivers

To date, targets for transport-sector emissions reductions at the national and international levels have not been backed by firm policy action beyond some public funding for R&D. There is therefore some uncertainty as to the precise mix of policies that will enable emissions targets to be met. Policymakers must decide on a range of potential policy levers, including carbon pricing, subsidies offered to low carbon fuel adoption, low carbon fuel standards, and requirements for new vessels to be equipped with zero emissions propulsion systems.

At an international level, the 2020 introduction of a cap on the sulfur content of shipping fuels, outlined in IMO 2020, provides an illustrative example of how a global carbon pricing scheme could emerge. The sulfur cap was preceded by regional Emission Control Areas in Europe and North America, which set the stage for wider adoption. An international carbon pricing scheme for the shipping industry could follow a similar trajectory, with regional emissions trading schemes offering proof of concept for global implementation.

In Europe, discussions to include international shipping within the scope of the EU's Emissions Trading Scheme (ETS) have already been underway for several years. These discussions culminated in the European Commission's recent Fit for 55 proposals, intended to prepare the union to meet its 2030 climate targets. The proposals will see the shipping sector included within the ETS if ratified by the European Council and Parliament. As carbon pricing schemes do not offer targeted technology support, they favor whichever combination of technologies and operational adjustments are able to deliver emissions reductions at the lowest cost. According to Guidehouse Insights analysis, ammonia adoption via onboard ammonia cracker and fuel cell propulsion system could lead to savings of more than $131,000 at a 500-kW power-scale over a typical vessel lifetime of 25 years, assuming a carbon price of $120 per ton and average ammonia costs of $0.30/kg, as shown in Figure 2.

Figure 2 Cost of Ammonia vs. Diesel for Propulsion



Note: Figure 2 displays the total expenditure required for a 500-kW vessel propulsion system over a 25-year period under two different pricing scenarios. Scenario one is a status quo scenario, reflecting an approximate current ammonia price of $0.5 per kg and zero-carbon price. Scenario two is a future cost scenario, assuming an ammonia price of $0.3 per kg and a carbon price of $120 per ton. CAPEX remains fixed under both scenarios, referring to the cost of installing diesel or ammonia cracking-based propulsion systems. OPEX refers to fuel costs in addition to costs imposed by carbon price compliance.

(Source: Guidehouse Insights)

A requirement for vessels to be equipped with zero emissions propulsion systems is also a distinct possibility in markets with more ambitious policy objectives. The UK government's 2019 Clean Maritime Plan already requires new vessels designed for use in UK waters to be zero emissions capable from 2025 onward, meaning that they must be equipped either with batteries or with propulsion systems capable of switching to ammonia, hydrogen, or other zero-carbon fuels once these become available.

International Ammonia Trade

Ammonia's superior properties as a storage and transportation medium for hydrogen have made it a key strategic element of many upcoming green hydrogen production projects, especially large, gigawatt scale projects located in remote regions. Since these types of projects are typically sited to take advantage of lower cost renewable energy resources, transportation costs will be the main differential compared to local production in regions with comparatively high electricity prices. Ammonia has therefore emerged as the hydrogen carrier of choice since it allows greater volumes of hydrogen to be transported on a single vessel compared to transportation of hydrogen in liquid or compressed form.

The tendency for hydrogen to be traded as ammonia will favor end users who are able to use the chemical directly, either for long-distance transportation or for fertilizer applications. The shipping industry is especially likely to benefit due to the movement of ammonia, first gray and eventually green, through maritime hubs.

Development of Green Maritime Corridors and Bunkering Hubs

The number of vessels that initially transition to ammonia as a fuel is likely to be limited. Unfortunately, this means that there will be little market incentive for the preemptive adoption of ammonia bunkering infrastructure—which in turn presents a barrier to fleet owners. In recognition of this problem, several ports have stepped forward to act as facilitators of the transition to ammonia-fueled vessels. For instance, the ports of Los Angeles and Shanghai have announced a partnership to develop a "green shipping corridor" along one of the world's busiest shipping routes. According to the ports' implementation plan, infrastructure will be deployed to enable the phase-in of zero emissions vessels throughout the 2020s, with the objective of introducing the first zero-carbon trans-Pacific container ships by 2030. Further initiatives are expected in the future from other major ports. Twenty-two countries signed the Clydebank Declaration at COP26, which calls for the decarbonization of international shipping through the establishment of at least six green shipping corridors by the end of the decade.

At the individual port level, Singapore—currently the world's largest bunkering hub—has announced a feasibility study to develop a supply chain for ammonia bunkering. The plans are expected to exploit synergies with the LPG sector, since LPG tankers and infrastructure can be used for the storage and handling of liquid ammonia. Likewise, the Port of Rotterdam aims to develop an ammonia storage and transportation terminal in line with its wider decarbonization objectives. Large ports benefit from the necessary scale to enable alternative fuel adoption, even if only a small proportion of vessels initially opt for zero-carbon propulsion systems. During the early ramp-up phase, ammonia adoption is therefore likely to be concentrated around key hubs and frequently used shipping routes prior to broader dissemination of the technology.

Large ports benefit from scale to enable alternative fuel adoption, even if only a small proportion of vessels initially opt for zero-carbon propulsion systems.

Collaborative Decarbonization of Supply Chains

Alongside new infrastructure in ports, collaborations between cargo owners, logistics companies and shipowners are also likely to play a key role in the uptake of low carbon fuels. Amazon, whose $2 billion Climate Pledge Fund invests in promising cleantech companies including Amogy, provides an illustrative example of a large multinational company responsible for significant cargo volumes that has taken early action to decarbonize its supply chain. The company has established a target to reach net-zero status across its operations by 2040, and a supplementary goal to make 50% of its shipments net-zero carbon by 2030. In support of this plan, the company has joined other major cargo owners such as Michelin, Unilever and Ikea to form the Cargo Owners for Zero Emission Vessels (coZEV) coalition. The coalition aims to support the transition to decarbonized shipping fuels by creating demand for zero emissions voyages and helping to foster zero emissions shipping corridors. Beyond shipping, Amazon's efforts will apply to delivery trucks and material-handling equipment in fulfillment centers.

Major shipowners are also taking action. Danish shipowner Maersk, which represents a 17% share of the global container fleet, has established a net-zero target for 2040, and intends to provide "green customer offerings" by 2030. Assuming zero emissions fuels continue to trade at a cost premium relative to conventional fuels within this timeframe, it is critical that both demand for decarbonized shipping and the capacity to fulfill it are in place. Complementary commitments from cargo owners and shipowners provide a positive indication that these elements are on track.

Fossil Fuel Price Volatility

Geopolitical instability in late 2021 and early 2022 has triggered a rapid escalation in the prices of oil and natural gas. While the long-term effects of these price movements are subject to uncertainty, an immediate consequence has been redoubled interest in hydrogen and other low carbon fuels as a means of reducing reliance on Russian fossil fuel exports. The EU has already committed to a fourfold increase in its hydrogen targets for 2030, which implies that approximately 10 million tons of hydrogen will need to be imported from outside the bloc each year[14]. Depending on the proximity of future exporters to European consumers, a significant proportion of this figure is likely to be supplied in the form of green ammonia.

The effects of higher fossil fuel prices are also being felt at a global level. Within oil-dependent transportation segments, elevated fuel costs create a clear incentive to seek short-term efficiency gains and reduce price exposure through increased uptake of non-fossil fuel sources. Within the ammonia sector, the reliance of existing production on natural gas feedstock has led to output curtailments as well as increased interest in renewables-based production pathways. In Guidehouse Insights' view, the precise effects of geopolitical risk factors on the ammonia sector are complex but indicate a long-term decoupling from fossil fuel inputs and increasing use of ammonia as an energy carrier.

[14] Recharge, "'Bloody hard—but possible': EU plots renewables and green hydrogen dash from Russian gas," **https://www.rechargenews.com/energy-transition/bloody-hard-but-possible-eu-plots-renewables-and-green-hydrogen-dash-from-russian-gas/2-1-1181308**.

Market Barriers

While there are many factors that drive the adoption of ammonia as a decarbonization fuel for transportation, there are certain barriers that need to be addressed to ensure its sustained growth. These barriers, include:

Safety and Social Acceptance

Even though ammonia is not a highly flammable fuel, concentrations of it above 1,000 parts per million (ppm) can be highly toxic and may even result in fatalities. Hence, to use ammonia onboard ships, fuel systems and bunkering infrastructure must be designed, manufactured, and operated to ensure safety of ship crews, port staff and fuel suppliers. Additionally, the combustion of ammonia in engines releases nitrous oxide (NO_x), which is a potent GHG. However, these emissions potentially can be reduced to negligible levels through the adoption of SCR systems and by tweaking engine's operational parameters.

From a social acceptance perspective, perceptions of ammonia outside of industries that are already familiar with its use may need to change. Ammonia-handling procedures are well established in the shipping industry due to the work of organizations such as the Ammonia Safety Training Institute, which is responsible for defining necessary standards and procedures. However, additional effort is required to define safety protocols and permitting of ammonia as a bunker fuel, and inter-governmental policy support may be required.

> *Because progress on safety and awareness is progressing quickly, barriers related to safety and social acceptance do not appear to be major hindrances to the growth of the ammonia economy.*

The safety challenges of ammonia are generally manageable. For instance, since gaseous ammonia is less dense than air, it can dissipate very quickly which minimizes the risk of explosion and fires in the event of a leakage. Because progress on safety and awareness is progressing quickly, with maritime classification societies such as DNV and ABS already drafting safety guidelines to use ammonia as a marine fuel, barriers related to safety and social acceptance do not appear to be major hindrances to the growth of the ammonia economy.

Furthermore, changing regulations for trucks and off-road mobility applications to favor alternative fuels such as ammonia will greatly improve public perception of ammonia as a fuel. Such regulations have historically leaned toward stimulating incremental improvements of diesel engine efficiency, and the incentives provided for alternative technologies have been lagging. This is expected to change with recent announcements from the Environmental Protection Agency (EPA)[15] in the US that has proposed new and stronger standards targeted at heavy duty gasoline and diesel engines. The approval of these proposals will have the potential to reduce smog- and soot-forming NO_x emissions from trucks by as much as 60% in 2045.

[15] U.S. Environmental Protection Agency, EPA Proposes Stronger Standards for Heavy-Duty Vehicles to Promote Clean Air.

Transitioning from diesel and gasoline to alternative hydrogen-derived fuels would entail a massive overhaul of the current mobility infrastructure. To facilitate this change in the US, the Zero Emission Vehicle Deployment Support and Promotion program has set a target to have 200 hydrogen refueling stations in California by 2025. Similarly, in the EU, the Fit for 55 package sets a 2.6% target for all renewable fuels to be produced from hydrogen-derived fuels. Additionally, the Alternative Fuel Infrastructure Regulation also supports the deployment of alternative refueling infrastructure including providing one hydrogen refueling station at every 150 km along the Ten-T network,[16] which is a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals.

Ship Designs and Engines

Current vessels are not equipped to operate on ammonia. The primary issue is that the lower energy density of ammonia (compared to fossil fuels) requires a larger volume of space devoted to fuel storage to deliver an equivalent amount of energy. This implies that existing ships will need to be retrofitted to facilitate the uptake of ammonia. Alternatively, vessels will need to refuel more frequently when undertaking longer voyages, unless the volume of ammonia engines and fuel cell systems is small enough to overcome the higher fuel requirement. Upgrading vessel designs in an accredited manner will require collaboration between the IMO and engine makers.

Additionally, since ammonia has a narrow flammability range, engines that can accommodate and control the ignition process need to be developed. Release of small quantities of gaseous ammonia—termed slippage—can also occur, requiring engines to be equipped with safeguards to minimize fuel losses. Hence, engines will need to comply with technical requirements set by the IMO. Nevertheless, in most respects ammonia-fueled models operate in a similar fashion to existing ICEs, and high performance designs have already been successfully tested in laboratory settings by engine manufacturers such as Wärtsilä. The first commercially available engines are expected by 2025 at the latest.

Refueling and Storage Issues in Transportation

For maritime shipping, ammonia as a new bunker fuel will require the creation of bunker terminals for storage and refueling at ports. New regulations and guidelines for the operation of these terminals will thus be required. Ammonia bunkering stakeholders may be able to leverage industry experience with the development of other cryogenic marine fuels such as LNG, as well as existing synergies with the LPG sector. New tank designs, leveraging learnings from LNG and early hydrogen applications, will also be required to ensure the safety and ease of bunkering ammonia at various ports worldwide.

With respect to trucking, improperly designed and purged metal tanks that are used for storing ammonia over long periods may suffer from stress corrosion cracking. This can result in failure of tanks, valves and other components that come in direct contact with ammonia. Furthermore, the refueling infrastructure for trucks is currently lacking. Due to ammonia's toxicity, and affinity for water ammonia, refueling would require leak-proof coupling with storage tanks. Fortunately, through industry collaboration, and by leveraging the learnings from the maritime shipping industry refueling and storage issues in the trucking industry can be addressed.

[16] European Commission, *Trans-European Transport Network*, **https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en**.

Green Ammonia Costs

While not a market barrier to the use of ammonia as a fuel, it is worth noting the current challenges facing a completely decarbonized well-to-wheel solution. Currently, green ammonia is more expensive than conventional fuel options used in the shipping industry. However, costs are expected to decline as an increasing number of large-scale production projects enter the market toward the end of this decade. The recent surge in fossil fuel prices has also improved the cost-competitiveness of clean ammonia compared to fossil fuels. Over the short-term it is nonetheless possible that a share of grey ammonia will be used to satisfy emerging transportation sector demand, depending on feedstock costs and the end user's strategic objectives.

Sustained cost-competitiveness with conventional fuels will likely require a combination of declining production costs and a long-term carbon price signal. Improving access to low cost renewable energy or large-scale development of carbon capture and storage will also both be instrumental to driving down the costs and availability of clean ammonia.

Sustained cost-competitiveness with conventional fuels will likely require a combination of declining production costs and a long-term carbon price signal.

Competitive Landscape

Of the 176 million tons of ammonia produced globally each year, 80% goes to the production of agricultural fertilizers.[17] However emerging technologies offer new uses for ammonia in transportation.

The use of ammonia as a transportation fuel or hydrogen carrier would help to decarbonize hard-to-abate sectors. However, competition with other fuels presents an obstacle for ammonia's adoption in the sector. For example, incumbent fuels such as marine fuels, diesel, and other fossil fuel derivatives offer the convenience of existing infrastructure, established markets and well-known logistics. Ammonia also faces competition from biofuels and synfuels. In some mobility applications, battery technologies can attain energy efficiencies as high as 90% compared to 60-65% for ammonia within propulsion systems. Even within the ammonia community, the best way of using the chemical as a fuel remains debated.

[17] The Royal Society, *Ammonia: zero-carbon fertiliser, fuel and energy store,* **https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf**.

Table 2 Ammonia's Key Competitive Metrics vs. Other Fuels and Vectors

Fuel or vector	Carbon content (kg carbon/kg)	Volumetric Density (MJ/L)	Gravimetric Density (MJ/kg)	Market Maturity*
Ammonia	0	12.7	18.6	medium
Lithium-Ion Battery	0	1.6	0.5	medium
Compressed Hydrogen[18]	0	4.7	120	low
Liquid Hydrogen	0	8.5	120	low
Methanol	0.38	16	20.1	medium
Ethanol	0.52	21.3	27	high
LNG	0.75	20.8	48.6	high
Biodiesel	0.78	33.3	37.5	high
Propane	0.82	23.5	46.3	high
HFO	0.85	38.2	39	very high
Diesel	0.86	35.8	42.8	very high
Gasoline	0.87	32.3	43.4	very high
MGO	0.88	36.6	42.8	very high

Note: The market maturity column in Table 2 reflects a combination of global consumption, existing technologies, infrastructure availability, policy support and commercial readiness throughout various industries.

(Sources: Guidehouse Insights, National Institute of Standards and Technology Reference Fluid Thermodynamic and Transport Properties Database, greet.es.anl.gov)

Competition with Incumbent Technologies

Aside from biofuels, most incumbent fuels in the transportation industry are fossil fuel-based, which means that they are carbon intensive. However, since many of these fuels have dominated market share for decades, they also offer the convenience of established markets, technologies, business models, value chains, and industry participants.

Incumbent fuels in the shipping sector are especially carbon heavy. Historically, the most common maritime fuels such as MGO and HFO also carry some of the highest concentrations of carbon and other elements that cause GHGs. In 2018, the IMO set a goal to reduce global GHG emissions from the shipping sector by at least 50% by 2050 compared with a 2008 baseline, with carbon intensity reduction targets for 2030 and 2050. As a result, the industry is focused on hydrogen and its carriers and derivatives as the shipping fuels of the future, albeit with concerns around the availability of hydrogen supplies to meet the needs of the maritime industry.

[18] Compressed hydrogen assumes pressure of 69 MPa and a temperature of 15C

In long-haul trucking, gasoline and diesel are the incumbent fuels, presenting similar environmental concerns to the shipping sector. In recent years, EVs have increased their market share for passenger vehicles, and Tesla is currently working on a medium-haul electric truck that can travel up to 500 miles before recharging[19]. Electrification faces greater challenges in the trucking sector since the size and weight of the 0.5 MWh to 1 MWh electric battery needed for long-haul trucking would reduce cargo space and cut into the bottom line. Hydrogen fuel cell systems are also viewed as a solution, since they take up far less cargo space, refuel faster than an EV would charge, and eliminate the tailpipe emissions associated with fossil fuels.

Compared with incumbent fuels, hydrogen is best positioned to aid the energy transition by allowing ships and trucks to see the same performance metrics with far fewer emissions. In the coming years, a lack of infrastructure for transporting and storing hydrogen will be the primary obstacle impeding its widescale deployment. However, ammonia can help to circumvent these issues. Led by a century of growth in the fertilizer market, ammonia also benefits from existing pipelines, trucking routes, shipping vessels and safety standards. For these reasons, ammonia also may play a key role in the energy transition, as a direct fuel, a vector for hydrogen or both.

Competition with Non-Hydrogen-Based Low Carbon Technologies

As a source of low carbon energy for transportation, ammonia faces competition not just from hydrogen and fossil fuels, but also from batteries and biofuels.

Battery technologies are rapidly advancing but also face challenges in transportation. In the maritime sector, the size of the battery needed to carry a ship across an ocean is prohibitively large, thus reducing the payload of the shipment. The added weight of the battery also increases the energy required for propulsion. In addition, vessels would need to stop for recharging, thus adding time to the shipment delivery. Similar issues arise on the road. Time is money and, whether on the sea or on the road, battery technology for transportation can costs for companies and consumers. Hydrogen fuel cells offer an alternative but also face logistical issues around fuel delivery and storage.

Biofuels present another option in transportation with ethanol and biodiesel already in use commercially. E10 and E15 blends, which contain 10% or 15% ethanol, are already in regular use at US gasoline filling stations. B20, which is a blend of 20% biodiesel and 80% fossil-based diesel, also can be used in current diesel engines without modifications. The adoption of these blends was facilitated by the Energy Policy Act of 1992, which granted funds for US filling stations in need of upgrades or retrofits to accommodate the change in fuel. However, both ethanol and biodiesel face challenges of their own. For instance, both are more expensive than incumbent fuels (i.e., fossil fuel derivatives) and both face an uncertain future with regard to sustainability as the use of land for biofuels is finite and competes with the use and transformation of land to grow food. Nevertheless, biofuel is not considered carbon neutral and highly dependent on geological location and land type usage. In addition, a higher blend for either fuel would require engine retrofits or replacement. The GHG savings obtained from the use of most crop-based biofuels are also much less attractive than for other low carbon options.

[19] Tesla, Semi, **https://www.tesla.com/semi**.

Competition with Alternative Hydrogen Vectors

Throughout the transportation sector, hydrogen shows immense potential as a source of efficient and carbon-free fuel. However, a lack of infrastructure for delivery and storage presents the foremost obstacle to its full-scale deployment and adoption. As a carrier for hydrogen, ammonia can work around a lot of the logistical issues that hydrogen faces. In fact, many roadmaps for a future hydrogen economy include converting hydrogen into ammonia before shipping it over long distances. However, ammonia is not the only hydrogen vector.

When supercooled into liquid form, hydrogen is much more manageable in terms of transportation and storage and might be the best carrier of itself per weight basis, especially if high purity hydrogen is what the end user needs. This approach would also bypass the need for cracking before use. However, volumetric energy density of liquid hydrogen is lower than ammonia. Liquifying hydrogen further requires a temperature of -253°C and without a network of pipelines, all deliveries would have to be made by ship, truck, or rail, which presents additional obstacles when attempting to scale up supply to meet the demand of global transportation fuel.

By comparison, methanol already has global infrastructure in place with a commercial presence spanning decades in the petrochemical and manufacturing sector. As a liquid at ambient temperatures, methanol is a dense hydrogen carrier that can be easily stored. However, methanol production requires a source of CO_2 and its capacity to carry hydrogen is less than liquid hydrogen or ammonia. Moreover, the cracking of methanol produces CO, which requires additional purification before the fuel cell.

Liquid organic hydrogen carriers (LOHC) such as toluene or dibenzyl toluene can leverage existing diesel infrastructure to transport and store hydrogen for long periods without losses. In addition, since dibenzyl toluene is non-toxic and non-flammable, it does not require additional safety regulations. However, LOHC's hydrogen carrying capacity is less than that of liquid hydrogen, ammonia or methanol, and the dehydrogenation process is slow and energy intensive, requiring about two times the energy than ammonia dehydrogenation.

Other Ways of Consuming Ammonia for Transportation

Another way to directly use ammonia as a transportation fuel is by feeding it into a Direct Ammonia Fuel Cell (DAFC) to create electricity. Solid-oxide fuel cells have shown the most promise for this application but need to operate at high temperatures. Other lower-temperature fuel cell types are also being researched. However commercial availability of DAFC technology remains extremely limited.

Using hydrogen cracked in situ to release hydrogen that is then fed into a fuel cell is a technology being actively developed by Amogy, which successfully showcased its use in a drone demonstration in 2021. The company is now looking to scale into pilot projects to demonstrate its use in trucking (2022) and shipping (2023). Typical drawbacks of using ammonia as a hydrogen carrier—large volume, heavy crackers, the high costs of cracking and the achievable purity levels—are all avoided with Amogy's technology.

Blending ammonia, or hydrogen produced from ammonia, is yet another way of consuming ammonia or its derivatives for transportation. Blending ammonia with conventional hydrocarbon fuels such as gasoline and diesel results in higher flame speeds, heat release rates and radiation intensity than ammonia alone.

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Case Study

Ammonia is integral for decarbonizing the transportation sector, and its potential is particularly pronounced in the shipping industry, where Amogy's technology could play a key role. As a nascent transportation fuel, ammonia faces several challenges pertaining to onboard storage and the need to retrofit engines for vessel propulsion. However, through multi-stakeholder collaborations, these limitations are being addressed, which could enable ammonia-powered ships to be commercially available around late 2025.

How to best store ammonia onboard a vessel is a large challenge facing its widespread adoption. In July 2021, Gaztransport & Technigaz (GTT) announced that its Mark III membrane tanks for storing ammonia received the Approval in Principle (AiP) from the Bureau Veritas. Having acquired this certification, GTT now aims to scale the operation of ammonia-ready ships through collaboration with industry participants. In one such partnership, GTT will design ammonia-ready LNG fuel tanks on five 15,000 TEU containerships for Samsung Heavy Industries. These ships will be owned by Seaspan Corporation and the fuel tank on each ship will offer a capacity of 12,000 m^3. GTT expects to deliver these vessels between the third quarter of 2023 and the first quarter of 2024. In addition to the ammonia storage tanks, GTT will also help with tank commissioning, fuel bunkering operations, and operation and maintenance services.

Several companies around the world are addressing the challenges in designing and constructing ammonia-fueled propulsions systems. For example, companies such as MAN Energy Solutions and Wärtsilä are presently working on flexi-fuel engines. MAN Energy Solutions aims to have a commercially available two-stroke ammonia engine by 2024, in addition to providing retrofit packages for existing vessels by 2025. To support its endeavor, MAN Energy Solutions is leading the AmmoniaMot industrial consortium. The consortium includes the Technical University of Munich (to develop a combustion model using rapid-compression expansion machine); Neptun Ship Design (to evaluate compliance of ship design with international technical and safety requirements); WTZ (to develop combustion concept for new engine and define requirements for exhaust-gas aftertreatment); and Woodward L'Orange (to produce injection system for the ammonia tests). Furthermore, Trafigura Group, which is among the world's largest ship charterers and an advocate for the decarbonization of the shipping industry, will cosponsor MAN Energy Solution's ammonia engine project. Japanese shipping major Mitsui O.S.K. Lines is expected to be an early adopter of MAN Energy Solution's ammonia ships with a purchasing contract that will be finalized in 2023.

In 2021, Wärtsilä initiated its full-scale testing of a four-stroke marine engine that operates on ammonia. To further develop and test these engines, Wärtsilä entered a collaboration with Aker Solutions, DFDS, Equinor, and Grieg Star through the Zero Emission Energy Distribution at Sea (ZEEDS) initiative. The objective of this initiative is to build a new tanker vessel, called the MS Green Ammonia, that will both transport and operate on green ammonia and become operational by 2024. It is expected that the MS Green Ammonia will distribute green ammonia produced in the north of Norway to various locations and end users along the Norwegian coast including a power station in the Arctic Circle. This initiative has also attracted the interest of the Norwegian government, which is supporting it with a grant of 46.3M NOK (4.9M EUR). Also in October 2021, Wärtsilä signed a collaboration agreement with Simon Møkster Shipping to demonstrate the safety, efficiency, and feasibility of converting vessels for dual ammonia-LNG operation. Similarly, Wärtsilä has also signed a joint development program agreement with Samsung Heavy Industries to deploy the four-stroke ammonia-powered engines for future newbuild projects.

In addition to combustion engines, fuel cells are an option for ship propulsion systems. ShipFC, another Norwegian project, is exploring the use of solid-oxide fuel cell (SOFC) technology to pioneer an ammonia-powered vessel. This 2MW project is a collaboration between the NCE Maritime CleanTech cluster, Equinor, Eidesvik, Wärtsilä, Clara Venture Labs, and others. It is expected to install the SOFC in 2023 and begin pilot testing in 2024, and it represents a major milestone in the development of ammonia solutions for long-range, high power ships. The project will also include similar studies on other types of vessels, such as bunker and cargo vessels, to understand the applicability of this technology to other sectors of the shipping industry and pave a path for commercialization of ammonia SOFCs.

PEM fuel cells, which is a more mature & economical technology than SOFC, are a preferred choice for mobility applications due to their high efficiency and flexible operational ranges. However, PEM fuel cells require high purity hydrogen, a constraint that had previously reduced the applicability of ammonia as a hydrogen-carrying transportation fuel. The challenge of reducing the high concentrations of ammonia entering the fuel cell has been addressed by Amogy’s ammonia cracker technology, which removes the unreacted ammonia from the fuel cell feed stream. The same ammonia-cracking technology could also be coupled with combustion engines that have multi-fuel flexibility, thereby driving the ship's propulsion system without any harmful emissions. For testing and delivering ammonia-powered ships, Amogy is also actively involved in the NCE Maritime CleanTech consortium. This consortium focuses on establishing sustainable innovation projects for new clean maritime solutions using the Norwegian maritime expertise. Through continuous research and innovation, Amogy aims to commercially deploy its integrated ammonia cracker and PEM fuel cell-based propulsion system in ships starting in 2024. Furthermore, Amogy's innovative technology has also gained attention from Amazon, which has invested in it with the aim of decarbonizing its supply chain infrastructure.

Conclusions and Recommendations

Ammonia shows immense promise as a clean fuel suitable for use in short-range and ocean-going vessels, trucking, off-road vehicles, and stationary power generation applications. Among hydrogen carriers, it combines high volumetric energy density with the promise of scalability and the advantage of zero-carbon emissions at the point of use. Drawbacks such as nitrous oxide emissions from direct combustion can be effectively mitigated through the adoption of the appropriate onboard technologies. Moreover, the efficiency of energy conversions at the production and end-use stages of the ammonia supply chain is continually being improved as production methods and propulsion systems evolve.

Although a range of deployment cases are likely to be successfully explored, the volume of fuel demand from the ocean-going vessel segment and the lack of scalable alternative fuels means that it will be the largest demand driver for clean ammonia within the transportation sector, even under relatively modest deployment assumptions. The long-term demand prospects for ammonia in the transportation sector are therefore very favorable. However, the timeline over which end users are able to switch over to ammonia and hydrogen fueled systems is more uncertain. Technological innovation, collaboration between stakeholders and policy support will all be key to unlocking ammonia's potential as a decarbonization driver. Guidehouse Insights provides the following recommendations to industry stakeholders to accelerate ammonia uptake:

Shipowners

Given the long average lifetimes of ocean-going vessels and the urgent need to reduce emissions ahead of the IMO's 2050 deadline, it is imperative that shipowners take swift action to prepare their fleets for low carbon fuels and propulsion systems. Although other options such as methanol and biofuels are expected to play complementary roles in the sector, the scalability, performance advantages and carbon-free character of ammonia means that it is very likely to be the pre-eminent decarbonization pathway for ocean-going vessels. Maritime stakeholders should adjust their investment behavior and business strategies in line with this expectation.

For shipowners that have not already done so, establishing company-level emissions-reduction targets sends a clear signal to stakeholders in the ammonia sector that there is a ready market for adoption. These targets can help to accelerate necessary investments in ammonia production, bunkering and port infrastructure, and technology R&D. Another priority should be demonstrating the performance and safety of ammonia-fueled systems by promoting early commercial-scale projects in collaboration with companies developing ammonia-powered technologies and infrastructure. Successful demonstrations are key to widespread adoption of clean maritime fuels and will encourage faster adoption of ammonia as a suitable zero-carbon fuel, which can in turn enable the achievement of the IMO emissions-reduction targets. Finally, when investing in fleet renewals, shipowners should pay close attention to the asset life of vessels and the declining cost outlook for zero-carbon fuels as a result of technological advancements and wider adoption of carbon taxes. Otherwise, they could face expensive retrofit requirements post-2030.

Trucking Companies

There is a growing consensus that hydrogen technologies will be integral to the decarbonization of the road freight sector. However, space limitations are a key technical barrier to the uptake of hydrogen (and even more so for battery electric systems). Efficient onboard ammonia-cracking technologies can enable considerable reductions in fuel tank volumes, extending the range of fuel cell trucks and increasing the space available for cargo. Moreover, the comparative simplicity of handling ammonia in its liquid state reduces the difficulty of distributing the fuel to refueling infrastructure. For these reasons, ammonia is likely to be a key enabler of hydrogen uptake in the road freight sector. Trucking companies should assess their operations to identify which routes and vehicle types are most suitable for near-term adoption and invest accordingly. They should also advocate for sector-level emissions-reduction (or carbon intensity) targets and financial support to ensure that first movers are not penalized with higher operational costs.

Cargo Owners and Logistics Companies

Cargo owners should step up collaborative efforts across their supply chains to ensure that the capability to deliver emissions reductions is available. Critical studies evaluating ammonia propulsion systems can help accelerate their entry into the market and enable logistics stakeholders to reap a share of the rewards from the adoption of new technologies. Effective communication to customers of the emissions intensity of a product's supply chain can also help to leverage consumer preferences for low carbon products. Because shipping costs make up only a fraction of the price customers pay for delivered products[20], cargo owners are uniquely positioned to absorb the costs of ammonia-enabled supply chain decarbonization without incurring a competitive disadvantage.

Ports and Logistics Hubs

Ports have a central role to play in the build-out of new bunkering and refueling infrastructure. Since the number of ports that have entered into green shipping corridor and ammonia bunkering projects is still relatively limited, the further development of these initiatives is key, especially for larger ports. Those ports that have already adopted plans should ensure that new infrastructure is deployed on a transparent timeline in collaboration with shipowners and other stakeholders. Ports should also explore the potential of ammonia for material-handling applications onsite.

[20] Shipping costs account for 0.1% of the price of a cup of coffee, 4% for a cheap bottle of wine and 5% for a pair of trainers, according to the International Chamber of Shipping

Hydrogen and Ammonia Producers and Electrolyzer Manufacturers

Cost reductions will be an important driver of hydrogen and ammonia uptake across sectors. The actions that upstream players and technology manufacturers are already taking to secure competitive advantage in the market for low carbon fuels are therefore already closely aligned with the decarbonization agenda of stakeholders in the transportation sector. However, more can be done. Cost reduction measures can include the upscaling of project capacities, deployment in geographies with untapped renewable energy potential, increasing automation of electrolyzer manufacturing processes, development of electrolyzer technologies less exposed to volatility in the price of critical minerals, and economies of scale from shared carbon transportation infrastructure in the case of blue ammonia produced from natural gas. Uptake of more efficient ammonia production methods such as electrochemical processing could help to lower costs over the long-term. Ammonia producers should also explore long-term supply agreements with transportation sector off-takers as well as pricing models optimized to lower purchasing risks.

Material-Handling Equipment

While often overlooked in conversations around the transportation industry, the market for material-handling equipment could benefit greatly through the use of ammonia so manufacturers should consider making the switch in fuels. Forklifts in North America and Europe alone number in the millions, and tens of millions of other material-handling equipment can be found globally in the form of conveyors, cranes, and pallet jacks. Many of these small vehicles have already converted to hydrogen fuel cells in lieu of fossil fuels or electrification. However, hydrogen is not available everywhere due to a lack of pipelines and storage infrastructure, which presents the manufacturing sector with an attractive alternative in the form of ammonia as either a direct-use fuel or as a vector for hydrogen using in situ cracking technology such as Amogy's.

Farmers and Ranchers

Like manufacturing, the agriculture industry is accustomed to using small off-road vehicles such as tractors and combines as a usual course of business, and like factories, farms can incur hefty expenses to fuel this equipment. Farmers and ranchers are in a unique position to build upon and benefit from their existing widespread use of ammonia as a fertilizer. Already well understood and easily accessible in the farming community, ammonia can be stored onsite safely and affordably. In addition, its applications can extend beyond transportation as ammonia could also be used to refrigerate food, or to heat or cool barns, homes, and other inhabited structures in agricultural settings, which can be especially appealing in remote locations.

Data Centers

As grid outages become increasingly common, many businesses that critically rely on uninterrupted energy to run their operations are turning toward microgrids and fuel cells for resiliency. However, ammonia could provide the same benefits cheaper and without many logistical challenges. Microgrids can be complex and onsite fossil fuel-based energy such as diesel generators is being widely phased out for environmental reasons. Fuel cells offer a great solution to maintaining uninterrupted supply, however the availability of hydrogen, as well as the difficulty of storing it onsite, pose distinct challenges. Data centers and other stationary mission-critical sites should view ammonia as a compelling solution to these problems since it is reliable, affordable, scalable, well understood, readily available and can be stored onsite.

Policymakers

Policy support for low carbon fuel uptake in the transportation sector varies across regions, but in general lags the levels required to satisfy global climate targets. At the international scale, regulatory bodies such as the IMO should work with national governments to extend emissions trading schemes to include international shipping. At the national level, policymakers should take inspiration from policies that have had an observable effect on the deployment of alternative fuels, such as California's Low Carbon Fuel Standard.

Many countries have already launched detailed hydrogen strategies, covering a range of end-uses including industrial applications, mobility, and grid injection. Due to the lack of alternative decarbonization options, long-distance transportation should be a key priority in all national strategies, ahead of alternative uses such as passenger mobility or residential heating, where electrified pathways are already technologically mature. Ammonia infrastructure should also be emphasized in national strategies due to its role in facilitating hydrogen imports and usage. Specific policy measures to support ammonia adoption should be considered, including contracts-for-difference for ammonia uptake within key transportation segments, public private partnerships spanning ammonia production and end-uses, and targets for transportation sector consumption of renewable fuels of non-biological origin.

Acronym and Abbreviation List

AiP .... Approval in Principle

CAPEX .... Capital Expenditure

CO_2 .... Carbon Dioxide

coZEV .... Cargo Owners for Zero Emission Vessels

DAFC .... Direct Ammonia Fuel Cell

EPA .... Environmental Protection Agency

ETS .... Emissions Trading Scheme

EU .... European Union

EV .... Electric Vehicle

GDP .... Gross Domestic Product

GHG .... Greenhouse Gas

Gt .... Gigaton

GTT .... Gaztransport & Technigaz

HFO .... Heavy Fuel Oil

IEA .... International Energy Agency

ICE .... Internal Combustion Engine

IMO .... International Maritime Organization

kg .... Kilogram

kWh .... Kilowatt-Hour

LNG .... Liquefied Natural Gas

LOHC .... Liquid Organic Hydrogen Carrier

LPG .... Liquefied Petroleum Gas

MGO .... Marine Gas Oil

MJ/L .... MegaJoule per Liter

MPa .... Megapascal

NO_x .... Nitrous Oxide

OPEX .... Operating Expenditure

ppm .... Parts per Million

SCR .... Selective Catalytic Reduction

SOFC .... Solid-oxide fuel cell

TWh .... Terawatt hours

ZEEDS .... Zero Emission Energy Distribution at Sea

Scope of Study

Guidehouse Insights has prepared this white paper, commissioned by Amogy, to provide a roadmap for the use of ammonia as a hydrogen carrier and zero-carbon transportation fuel. It provides an overview of the key characteristics of ammonia and its value in supporting decarbonization; examples from a diverse range of organizations that are using ammonia to improve energy efficiency and reduce GHG emissions; and recommendations for organizations getting started with ammonia and advice on how to tackle the most common challenges.

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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