THE AMMONIA SOLUTION

Ammonia engines and fuel cells in cargo ships could slash their carbon emissions

BY MARIA GALLUCCI

ILLUSTRATIONS BY MCKIBILLO

There's a lot to like about ammonia.

This colorless fuel emits no carbon dioxide when burned. It's abundant and common, and it can be made using renewable electricity, water, and air. Both fuel cells and internal combustion engines can use it. Unlike hydrogen, it doesn't need to be stored in high-pressure tanks or cryogenic dewars. And it has 10 times the energy density of a lithium-ion battery.

For all these reasons, ammonia (NH_3) is gaining favor in the global shipping industry, a multitrillion-dollar machine in need of cleaner fuels to power the freighters and tankers that haul manufactured goods and bulk materials across the ocean. Shipping companies seek climate-friendlier alternatives to petroleum that can propel their behemoth vessels for days or weeks at sea and still leave room on board for cargo.

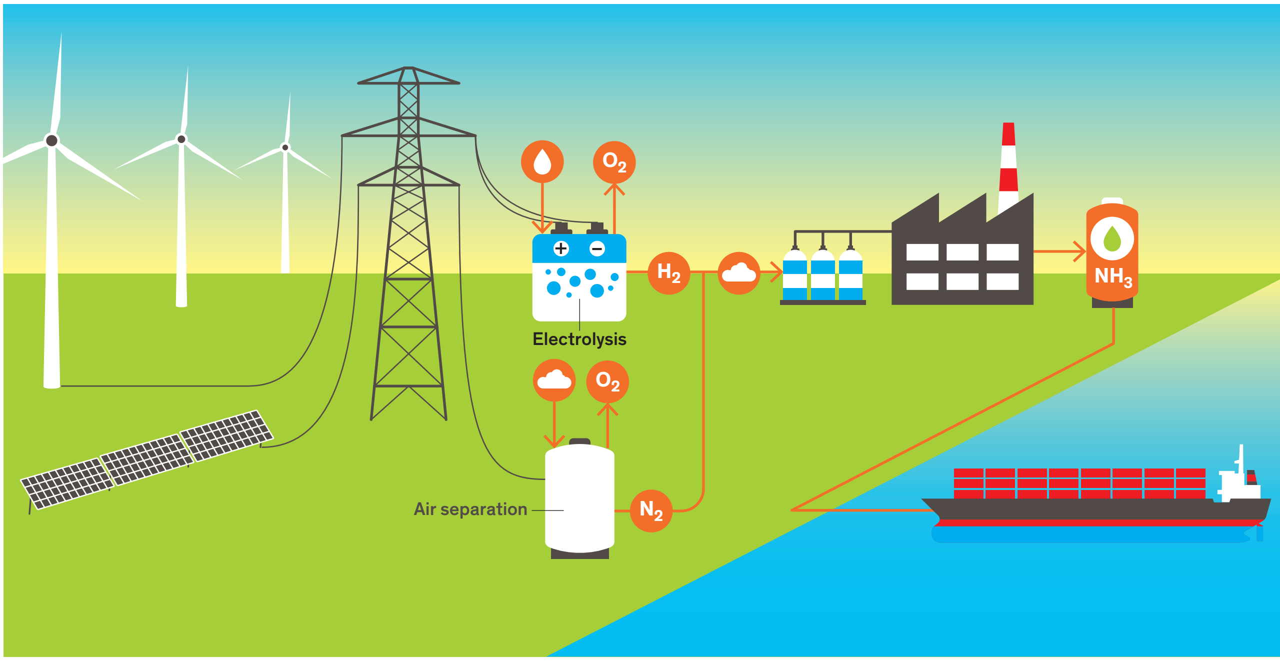
Maritime shipping contributes nearly 3 percent of annual carbon-dioxide emissions, according to the International Maritime Organization (IMO), the United Nations body that regulates the industry. In 2018, delegates agreed to reduce emissions by 50 percent from 2008 levels by 2050. Meeting that target will require swift and widespread development of diesel-fuel alternatives and new designs for freighters, tankers, and container ships.

Shipowners and industry analysts say they expect ammonia to play a pivotal role in decarbonizing cargo ships. But there's a crucial caveat: No vessels of any size today are equipped to use the fuel. Even if they were, the supply of renewable, or "green," ammonia produced using carbon-neutral methods is virtually nonexistent. Most ammonia is the product of a highly carbon-intensive process and is primarily used to make fertilizers and chemicals.

Recently, though, a handful of projects aim to change that. Finland's Wärtsilä plans to begin testing ammonia in a marine combustion engine in Stord, Norway, by late March. Germany's MAN Energy Solutions and Korean shipbuilder Samsung Heavy Industries are part of an initiative to develop the first ammonia-fueled oil tanker by 2024.

Also by 2024, the *Viking Energy* is poised to become the first vessel propelled by ammonia fuel cells. The Norwegian energy company Equinor (formerly Statoil) charters this offshore supply vessel, which currently runs on liquefied natural gas. Chemical giant Yara will provide the green ammonia, which it plans to produce at a plant in southern Norway.

The initiative "will open up a completely new option for zero-emission shipping," says Henriette Undrum, Equinor's vice president of renewable and low-carbon technology. "We are not just solving one small problem for one ship. It's part of the bigger picture. It will be a starting point to build up the market for zero-carbon fuels."



HOW TO PRODUCE "GREEN" AMMONIA

The traditional Haber-Bosch process is used to produce virtually all of the world's ammonia, but it is energy and carbon intensive. To decarbonize the ammonia-making process, electricity from renewable sources, such as wind and solar power, is used to electrolyze water, yielding hydrogen (as well as oxygen). The electricity is also used to separate air, yielding nitrogen (as well as oxygen and some argon and carbon dioxide). The hydrogen is then reacted with the nitrogen to produce ammonia, NH_3. Cargo ships equipped with ammonia-burning internal combustion engines or ammonia fuel cells are expected to help the shipping industry halve its carbon-dioxide emissions by midcentury.

Still, industry experts say that revamping the global shipping fleet will be extraordinarily expensive. Researchers estimate that up to US $1.4 trillion will be needed to achieve the IMO's emissions-reduction target. And fully eliminating emissions will require an additional $500 billion, according to a January 2020 study by a panel of maritime experts.

A number of climate-friendly technologies are being considered to reach that goal, including fuel cells, hydrogen-storage systems, and large battery packs. Spinning metal cylinders, towing kites, and other propulsion methods are already helping to curb diesel-fuel consumption by harnessing the wind. But ammonia will likely dominate among ocean-crossing vessels, which sail for days or weeks between refueling and rely on common infrastructure worldwide. For such ships, "ammonia is the lowest-cost zero-emission fuel that we could find," says Tristan Smith, a researcher at University College London's Energy Institute, which evaluated more than 30 different shipping fuels.

Smith predicts that green ammonia will be produced in large volumes and will start to be used on ships during the coming decade. Other researchers make similar predictions. According to a September 2019 report from the international consultancy DNV, ammonia could make up 25 percent of the maritime fuel mix by midcentury, with nearly all newly built ships running on ammonia from 2044 onward.

For ammonia-fueled shipping to become a reality, though, several things need to go right. Manufacturers and engineers must overcome technical hurdles and safety issues in the design of ammonia engines and fuel cells. Port operators and fuel suppliers must build vast "bunkering" infrastructure so ships can fill ammonia tanks wherever they dock. And energy companies and governments will need to invest heavily in solar, wind, and other renewable-energy capacity to produce enough green ammonia for thousands of ships. Globally, ships consume an estimated 300 million tons of marine fuels every year. Given that ammonia's energy density is half that of diesel, ammonia producers would need to provide twice as much liquid ammonia, and ships will

SOURCE: MAN ENERGY SOLUTIONS

need to accommodate larger storage tanks, potentially eating into cargo space.

But if these efforts succeed, it will mark a dramatic revival for a transportation fuel that's largely sat on the sidelines since World War II.

Diesel shortages prompted the first real-world use of ammonia as a fuel. In 1942, German-occupied Belgium was struggling to find enough diesel to run its public buses, just as ridership was increasing. Engineers considered using compressed coal gas, but that fuel's low energy density and awkward storage requirements made it impractical.

In April 1943, Ammonia Casale (now part of the Swiss fertilizer maker Casale) introduced an internal combustion engine that could run on a blend of ammonia and coal gas. Some 100 buses in Belgium adopted the system, dubbed Gazamo. But the bus operator returned to using diesel once supplies reappeared.

SHIP SHAPE: The supply vessel *Viking Energy* is being retrofitted with a 2-megawatt ammonia fuel-cell system. Ammonia has only half the energy density of traditional fuel, so storing it on board requires more space.

EIDESVIK

Over the ensuing decades, research on ammonia engines has come in fits and starts, even as ammonia supplies have soared. In the 1930s, worldwide production of ammonia was about 300,000 metric tons per year. Today, it's about 150 million metric tons. While ammonia is valuable as a chemical feedstock, the transportation sector has had little incentive to use it as a fuel. Petroleum has a higher energy density and is easier and cheaper to produce.

"Now, with a focus on having carbon-neutral fuels, it's obviously a different discussion. The economics around [ammonia] are very different," says Peter Kirkeby of MAN Energy Solutions. "Everybody wants to know, 'When can we have the ammonia engine?' "

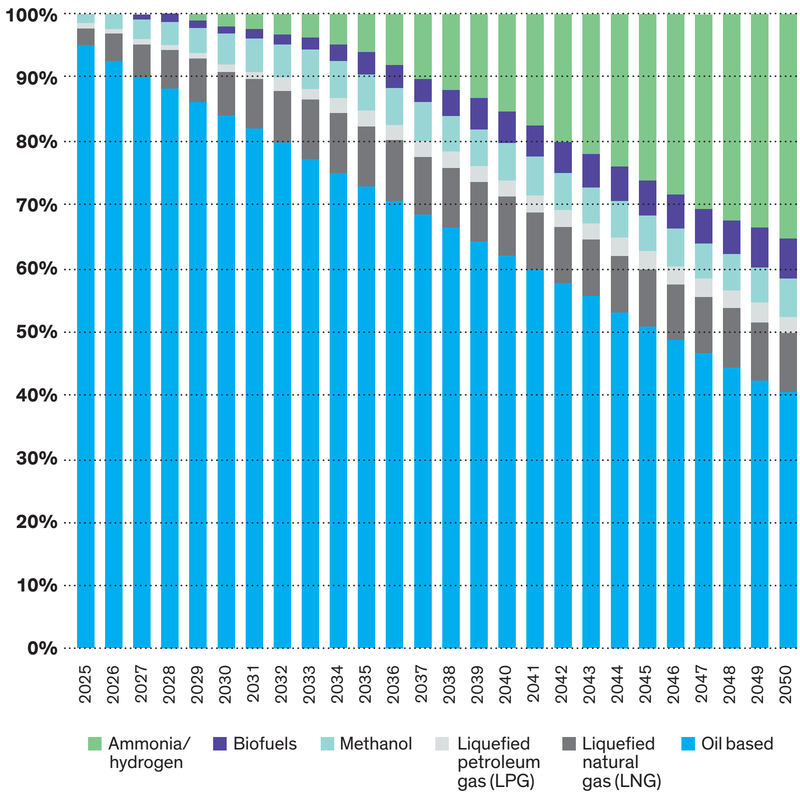
Kirkeby spoke from Copenhagen, where the company has a large waterfront facility on the city's south harbor. MAN, a subsidiary of Volkswagen, develops multimegawatt diesel engines for ships and power generators. The Danish outpost is looking beyond diesel, designing marine engines that run on methanol, liquefied natural gas, liquid petroleum gas, and other alternative fuels. Kirkeby says the industry's recent push for ammonia comes as renewable-energy producers are seeking new markets, and as shipping companies look for emission-cutting solutions.

Ammonia is a simple molecule, composed of three hydrogen atoms bonded to a single nitrogen atom. Today, most industrial hydrogen is produced using an energy-intensive method called steam methane reforming, which causes the methane in natural gas to react with steam and releases hydrogen, carbon monoxide, and a small amount of carbon dioxide. Nitrogen is mainly produced by cooling air to separate it into its constituent gases: nitrogen, oxygen, argon, and carbon dioxide.

To make ammonia, hydrogen and nitrogen are reacted with a catalyst at high temperature (about 500 °C) and high pressure (20 to 40 megapascals) via an industrial process developed by the German chemists Fritz Haber and Carl Bosch more than a century ago. To be stored in large quantities, ammonia can be liquefied by being pressurized (to about 1 MPa at 25 °C) or refrigerated (to –33 °C). All told, the Haber-Bosch process accounts for 1.8 percent, or half a billion metric tons, of human-caused global CO_2 emissions each year.

If ammonia is to play a part in reducing maritime emissions, the fuel must be made in a cleaner way. For example, the hydrogen can be made through electrolysis, splitting water into hydrogen and oxygen using electricity from a renewable source such as wind or solar power. Renewable energy can also be used to separate nitrogen from air.

Boosting fuel supplies and building fuel-distribution infrastructure are the biggest challenges to ammonia-powered shipping, experts say. Only tiny amounts of green ammonia are now being produced. A trial plant at the Fukushima Renewable Energy Institute in Japan uses solar power and water electrolysis to produce 20 to 50 kilograms of green ammonia per day. A demonstration system at the Rutherford Appleton Laboratory, in Oxfordshire, England, is powered by an on-site wind turbine and makes up to 30 kg of green



PROJECTED MARINE FUEL USE TO 2050

As the shipping industry moves to reduce greenhouse-gas emissions, as mandated by the International Maritime Organization, ammonia is projected to be a leading alternative to traditional oil-based fuels by 2050. For that to happen in an environmentally sound way, renewable energy sources to supply green ammonia will need to be built, along with infrastructure for distributing ammonia to far-flung ports.

CHART: MICHAEL SOLITA; DATA SOURCE: AMERICAN BUREAU OF SHIPPING

ammonia daily. [For a look at how a farmer in Iowa is using solar power to produce green ammonia, see "The Carbon-Free Farm," *IEEE Spectrum*, November 2019.]

Larger initiatives are underway in Australia, Chile, and New Zealand. In Queensland, for example, the Australian Renewable Energy Agency recently backed a A$3.9 million (US $3.0 million) feasibility project for a plant that could produce 20,000 metric tons of ammonia annually, using 208 gigawatt-hours of electricity from solar and wind. The global shipping industry used the equivalent of 3.05 million GWh in 2015. Substituting just 10 percent of that total with green ammonia will require some 550,000 GWh of renewable electricity, according to the Korean Register of Shipping.

As green ammonia slowly scales up, the shipping industry will have to solve some other problems. The top concern is ammonia's toxicity. In concentrated form, the pungent, colorless gas can be deadly. In January 2020, a spill of nearly 3,000 liters of liquefied ammonia fertilizer in Illinois sent more than 80 people to the hospital with chest pain, eye irritation, cough, and severe headache. Ammonia manufacturers and distributors must follow strict handling and safety guidelines to minimize the potential for disaster. To use ammonia fuel, ships will need additional safety equipment, such as emergency ventilation and gas-absorption systems.

Fortunately, operators of chemical tankers—large vessels designed to transport hazardous products—already have experience handling ammonia. About 10 percent of annual production is transported by sea. These ammonia tankers may be among the first vessels to use the chemical for fuel, in the same way that today's liquefied natural gas carriers burn some of their own cargo while sailing.

Still, using ammonia in the engine room poses new risks. MAN's engine will likely include double-walled fuel pipes to prevent gas from escaping should the inner pipe leak or rupture. A mechanical ventilation system will intercept any leaking gas and alert the ship's crew.

Ammonia is also corrosive to some alloys containing copper, nickel, and certain plastics. The fuel is difficult to ignite and doesn't sustain combustion well. Engineers could solve the ignition problem by combining ammonia with a liquid pilot fuel, such as diesel, though that would boost the ship's carbon footprint. Or they could potentially combine it with better-burning liquid hydrogen; that would require adding hydrogen tanks or equipment to separate hydrogen from the ammonia as needed.

Air pollution from burning ammonia presents another puzzle for engineers to solve. When burned at high temperatures, ammonia produces nitrogen dioxide, which contributes to smog and acid rain and can harm people's respiratory systems. Combustion also yields small amounts of nitrous oxide—a greenhouse gas that's significantly more potent than carbon dioxide and methane. If necessary, shipbuilders could install special equipment, such as for selective catalytic reduction, to avoid such outcomes. Japan Engine Corp. and the National Maritime Research Institute, in Tokyo, evaluated such devices on a 7.7-kilowatt, single-cylinder engine using a diesel-ammonia mixture.

Another option for eliminating harmful emissions is to use fuel cells rather than an internal combustion engine. In simple terms, a fuel cell converts chemical energy into electrical energy without burning the fuel, thus avoiding the release of harmful gases or particles into the air. Although existing fuel cells don't have an adequate power capacity for ships, experts believe the devices will eventually be able to provide higher efficiency and lower emissions than internal combustion engines can.

About two dozen projects have successfully demonstrated that fuel cells can power and propel smaller vessels. Many of these involve the electrochemical reaction of hydrogen and oxygen in what's known as a proton-exchange membrane fuel cell, which operates at low temperature and pressure. But ammonia is not a suitable fuel for these devices.

NH_3 is also more difficult to oxidize than hydrogen is, and so it requires higher temperatures to speed up the reaction. Researchers say a better fit for ammonia may be the solid-oxide fuel cell, which uses a solid ceramic material such as zirconia as the electrolyte. These devices can operate at high temperatures of about 1,000 °C. A 2-megawatt system is being installed on the *Viking Energy* supply ship in Norway and will be tested beginning in 2024.

In France, meanwhile, a new cruise vessel will demonstrate a 50-kW solid-oxide fuel cell system when delivered in 2022. Shipbuilder Chantiers de l'Atlantique and the Swiss line MSC Cruises are spearheading the initiative. Although the fuel cell will initially run on liquefied natural gas, it will also be compatible with ammonia, methanol, and other gaseous fuels, the partners say.

In the near term, fuel cells are expected to play only a complementary role on ships, supplying electricity for auxiliary systems and navigational equipment. If developers can scale up the technology to propel large ships and bring down manufacturing costs, fuel cells could eventually provide the least expensive way to operate ammonia vessels, says Carlo Raucci, who was a principal consultant of University Maritime Advisory Services, in London, at the time of our interview. A big container ship would need more than 60 MW of fuel-cell capacity, while a small bulk carrier might need only 2 MW, he says.

Other experimental systems aim to prove the viability of ammonia at sea. MAN Energy Solutions plans to start full-scale tests on a two-stroke ammonia-burning engine in Copenhagen this year, Kirkeby says. In 2019, the company partnered with Japan's Kyushu University to assess the combustion and heat-release characteristics of ammonia on a smaller combustion rig. Separately, MAN is developing an ammonia engine for a medium-size container vessel in a project with the Shanghai Merchant Ship Design & Research Institute.

"On the technology side, we see some work ahead for ammonia," Kirkeby says. "But it's doable."

All of the forecasting and speculation around ammonia, fuel cells, and the like assume that the shipping industry will embrace such climate-friendly approaches. Critics say the International Maritime Organization's emission-reduction goals aren't ambitious enough, and it's unclear how the IMO will ultimately enforce the rules. Regulators will need to compel, not just encourage, companies to eliminate greenhouse-gas emissions, Raucci says. "There is a need for policy-driven objectives to decarbonize the shipping industry."

A May 2020 survey by the American Bureau of Shipping captures the uncertainty sowed by today's vague policies. Nearly two-thirds of shipowners and operators said they have no decarbonization strategy in place. Even so, nearly 60 percent of respondents said they view hydrogen and ammonia as the most attractive fuel choices in the long term—even if they don't have plans to use them yet.

"We think that the major reason behind this [disparity] was the lack of regulatory framework so far," says Sotirios Mamalis, who manages the American Bureau of Shipping's sustainability, fuels, and technology program from Houston. "A lot of the owners, management companies, and operators are not necessarily aware of what they need to do in order to develop a decarbonization strategy."

One policy tool would be to set a global price on CO_2 emissions, Raucci says. This would make it more expensive to use fossil-fuel products, allowing alternative fuels like ammonia to compete. International regulators could also establish standards limiting a fuel's carbon content by mass, similar to existing restrictions on the sulfur content of fuels.

The new initiatives by MAN Energy Solutions, Samsung, Equinor, and other companies will be critical for determining ammonia's potential within the shipping industry. Given that vessels can operate for decades, companies "need to make sure that they're investing in a fuel that has a good chance of being used long-term," Raucci says. "The maritime industry at this moment has a very complex choice to make." ■

POST YOUR COMMENTS AT spectrum.ieee.org/ammonia-mar2021