The Problem with Green Ammonia

The sustainable production of combustion fuels is at the forefront of many industry conversations around decarbonization. The popularity of the concept of "clean" hydrogen has led to a new potential sustainable fuel derived from hydrogen: green ammonia. Green ammonia is made using only renewables while conventional ammonia is produced with fossil fuels. Nearly all of the ammonia produced today is conventional, and 85 percent of it is used to make nitrogen fertilizer. While some green ammonia projects are proposed to decarbonize its existing uses, others are testing it as an alternative fuel for maritime shipping due to its ability to store hydrogen and produce energy. The shipping industry emitted over 700 million metric tons of carbon dioxide (CO_2) in 2022, and industry players are betting on green ammonia to help them adhere to a recent carbon reduction mandate from the International Maritime Organization (IMO). Various green ammonia demonstration projects are moving forward around the world, despite uncertainties surrounding emissions, leakage rates, and pollution.

Green ammonia is produced using green hydrogen

Ammonia is made up of hydrogen and nitrogen. Ammonia gas is produced through a process that pairs hydrogen with nitrogen from the air, known as the Haber-Bosch process. It can then remain as a gas or be liquefied.

- The hydrogen used to create ammonia is typically produced through methane reforming, a process that results in extensive CO_2 emissions. This carbon impact along with the fossil fuels needed to power the Haber-Bosch process means that ammonia production has the highest carbon footprint of any chemical product (source). For every kilogram of ammonia produced, 1.5–2.6 kilograms of CO_2 equivalent emissions are released (source).
- Green ammonia is produced through the same process, but the hydrogen used is green hydrogen, which is made from the electrolysis of water using renewable energy, thus theoretically reducing the greenhouse gas footprint of the resulting ammonia (source).
- While there are a few green ammonia plants in operation today, the sheer amount of renewable energy needed to produce green hydrogen and then generate ammonia creates substantial hurdles in the build out and scalability of green ammonia infrastructure.

Ammonia offers storage and transportation benefits compared to hydrogen

Hydrogen is very tricky to store as a gas due to its low volumetric density, and as a liquid due to the extremely low temperature needed to convert and maintain its temperature. Industries, including martitime shipping and fertizlier production, are looking to ammonia as an easier to store and transport alternative..

- Ammonia carries three hydrogen molecules while hydrogen gas only carries two, making it an attractive alternative to some of the storage and transportation hurdles that come with using hydrogen as a fuel (source).
- Because ammonia can be stored as a liquid at higher temperatures than hydrogen (see Table 1, p. 2), less energy is required, and some of the risks associated with cryogenic temperatures are reduced. Ammonia is also 70 percent more energy dense by volume compared to hydrogen, so it requires less space to store the same amount of energy (source 1, source 2).

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Concerns about Green Hydrogen and Green Ammonia

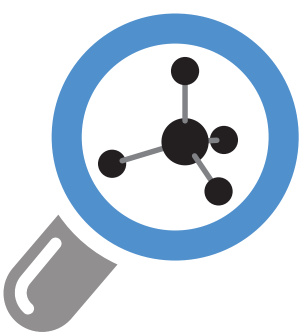
Green ammonia is gaining attention in several different industries despite uncertainties around emissions and efficiency. Green ammonia production and use compound the existing concerns about green hydrogen, its main component, and add new concerns regarding energy usage and emissions.

COMBUSTION EMISSIONS

Burning hydrogen or ammonia releases nitrogen oxide (NO_x) emissions. Burning ammonia also emits nitrous oxide (N_2O), a potent greenhouse gas almost 300 times more powerful than carbon dioxide.

AIR QUALITY

During production and end use, some ammonia ends up in the air, whether from leakages or fertilizer applications. Ammonia is a precursor to $PM_{2.5}$ and smog, contributing to adverse health outcomes from poor air quality.



INDIRECT WARMING

All hydrogen is an indirect greenhouse gas which extends the lifetime of methane in the atmosphere. This effect is so powerful that in the first 20 years of its atmospheric lifetime, hydrogen produces 35x the climate warming impacts of CO_2. Learn more here.

ENERGY USE

Green hydrogen and green ammonia production are extremely energy intensive, diverting renewable resources away from more directly beneficial uses, like powering the grid. The amount of energy needed to produce one ton of green ammonia is equivalent to the amount that the average household uses monthly. Learn more here.

WATER USE

Green hydrogen production facilities require significant amounts of water, up to nearly two million gallons per day. Much of this water cannot be recycled. Learn more here.

GHG-INTENSIVE PRODUCTION

Many types of "clean" hydrogen production can produce more greenhouse gas emissions than they reduce. If green hydrogen is not produced via electrolysis that is matched hourly with new, nearby renewable energy, it can have double the carbon intensity of hydrogen produced with fossil fuels. Learn more here.

TABLE 1: Ammonia and Hydrogen Comparison

	Ammonia	Hydrogen
Molecule	NH_3	H_2
Temperature to liquefy	-33°C	-253°C
Energy by volume (liquid)	15.6 MJ/l	9.1 MJ/l

Getting energy from ammonia is not a simple process

There are several different methods to extract energy from ammonia. Because ammonia is typically used as an ingredient in industrial production, and using ammonia for energy is relatively new, the most efficient method has yet to be determined.

- **Ammonia combustion:** Ammonia doesn't ignite easily, so a pilot fuel needs to be used to initiate ammonia combustion like in an internal combustion engine to power cargo ship, for example. The pilot fuel would likely be a fossil fuel (source).
- **Ammonia cracking and hydrogen combustion:** Ammonia can be separated back into nitrogen and hydrogen through a process called cracking. While this pathway requires extra energy to power the cracking, the resulting hydrogen will combust more easily than ammonia, eliminating the need for a pilot fuel (source).
- **Solid oxide fuel cell:** Using a solid oxide fuel cell to extract energy from ammonia or hydrogen (after cracking) is an alternative to combustion. Utilizing a high-temperature solid oxide fuel cell to convert ammonia into electricity provides the most efficient energy, but technological advancements are needed before this can be commercially viable on ships (source 1, source 2).

Green ammonia production and combustion could result in increased greenhouse gas emissions and air pollution

- **Diverting renewable energy:** The green hydrogen needed for green ammonia production could result in increased emissions if the renewable energy required for green hydrogen production is diverted away from directly decarbonizing the electric grid. To produce one ton of ammonia,10,000 kilowatt-hours (kWh) of renewable electricity is needed; this is the amount of energy that an average household uses in a month (source 1, source 2).

The International Energy Agency estimates in a net-zero scenario for the year 2050 that 233 million tons of clean ammonia will be required to fuel the shipping industry (source).

- **Ammonia leakage:** Leakage rate estimates for ammonia vary greatly (between 0.3% and 6%) and are often guesses extrapolated from leakage rates of other fuels (source 1, source 2). When leaked, ammonia combines with other compounds, creating harmful air pollutants like fine particulates ($PM_{2.5}$) and smog, which increase risks of cardiovascular, respiratory and neurodegenerative disease and premature death (source 1, source 2). Some ammonia is also released when the gas is burned due to incomplete combustion.
- **Hydrogen leakage:** Hydrogen is the smallest and least dense element, making it extremely leak prone. As an indirect greenhouse gas, hydrogen extends the life of methane in the atmosphere, so increasing hydrogen production in order to make more ammonia would subsequently increase global warming risks from hydrogen leakage (source 1, source 2).
- **NO_x emissions from combustion:** Burning ammonia and hydrogen releases nitrogen oxides (NO_x) emissions, a potent air pollutant that damages the respiratory system and contributes to the formation of $PM_{2.5}$ and ozone (source). Due to an emphasis on NO_x emissions reductions within the shipping industry, ammonia combustion in shipping would likely be paired with NO_x emissions controls called selective catalytic reduction (SCR). While it reduces NO_x emissions, SCR may increase ammonia leakage and nitrous oxide (N_2O) emissions (source).
- **Nitrous oxide emissions:** Ammonia combustion also results in direct N_2O. N_2O is a lesser known but very potent greenhouse gas that is 273 times more harmful than CO_2 (source). Studies have found that if just 0.4 percent of the nitrogen in combusted ammonia was released as nitrous oxide, the climate benefits of switching from diesel fuel to ammonia would be negated (source 1, source 2).
  - Ammonia and NO_x emissions can also convert to N_2O in the atmosphere, air, soil, and water. These chemical and biological transformations are not well understood and vary based on geography, environmental conditions, and composition of microbial communities (source). Conversion rates are estimated to be between 0.1 and 21 percent, a wide range that carries a variety of climate implications (source 1, source 2).

- One study found that if ammonia production increased to the levels necessary to supply shipping fuel, N_2O emissions could be equivalent to 15 percent of the global greenhouse gas annual emissions rate (source).

Accurate measurements of emissions, leakage, and conversion rates from ammonia production, storage, and combustion are needed to determine the best route forward for the use of green ammonia driven shipping decarbonization. Ramping up production without these data points could lead to unforeseen consequences for global warming and air pollution.

Ammonia use impacts the nitrogen cycle

As a result of leaks and emissions throughout the supply chain, ammonia production and use increase the levels of a type of nitrogen, called reactive nitrogen, in the air, water, and soil. Ammonia, NO_X, and N_2O are all types of reactive nitrogen and lead to increased ocean acidification, algae blooms, and biodiversity loss. Ramping up green ammonia production would only intensify these effects (source 1, source 2).

Using ammonia for energy generation on ships would require robust safety guidelines

Ammonia gas is highly toxic. Human exposure to ammonia gas, even for a short period of time. can result in respiratory issues, burns, and even death. Ammonia is also corrosive and needs specialized materials for its storage and combustion (source).

- Safety protocols, training, and emergency response planning are needed to keep maritime workers and coastal communities safe in the event of any accidental ammonia release. While ammonia is widely produced and handled globally, regulations regarding its use as a fuel on ships are nascent, needing more robust research and inspection. Existing ammonia industries still suffer from accidental leakages and hazardous events resulting in casualties, even after over a century of trial and error, pointing to the need for rigorous guidelines (source).
- In late 2024, the IMO published interim guidelines on the use of ammonia as a maritime fuel, emphasizing requirements regarding fuel containment and storage and a classification of toxic areas during a potential leakage event (source).

Green ammonia production needs further research to determine if it will be helpful or harmful

Despite the excitement growing around green ammonia, both to decarbonize existing uses and to expand into new applications, the lack of data about its true emissions and leakage rates is a reason to give pause. Increasing green ammonia production on the scale needed to replace conventional ammonia in fertilizer production and to decarbonize an industry as vast and energy intensive as maritime shipping would divert an untold amount of renewable energy resources away from the electric grid. Production at that scale could also increase greenhouse gas emissions and air pollutants through the release of more N_2O, NO_X, hydrogen, and ammonia into the air; and in the case of shipping, from the use of a fossil pilot fuel. Green ammonia may play a role in the path to decarbonization, but cleaner alternatives like batteries and wind power for shipping, and increased fertilizer efficiency for agriculture, should be prioritized in order to refrain from building out yet another polluting industry.

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To learn more about other harms associated with hydrogen's production and use, visit www.cleanegroup.org/initiatives/hydrogen.