Ammonia fuel offers great benefits but demands careful action, says study

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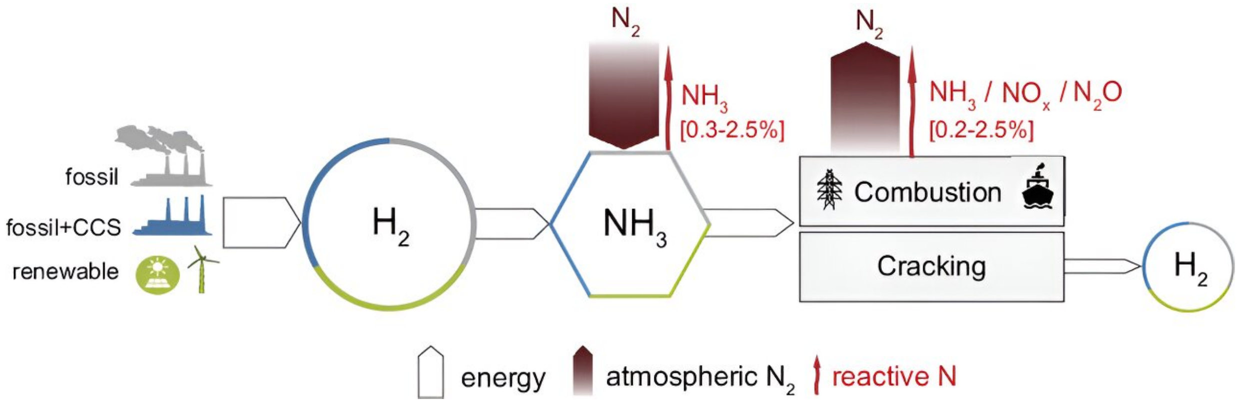

Schematic of the ammonia value chain and its potential impact on the nitrogen cycle. Credit: *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2311728120

Ammonia, a main component of many fertilizers, could play a key role in a carbon-free fuel system as a convenient way to transport and store clean hydrogen. The chemical, made of hydrogen and nitrogen (NH_3), can also itself be burned as a zero-carbon fuel. However, new research led by Princeton University illustrates that even though it may not be a source of carbon pollution, ammonia's widespread use in the energy sector could pose a grave risk to the nitrogen cycle and climate without proper engineering precautions.

Publishing their findings Nov. 6 in *PNAS*, the interdisciplinary team of 12 researchers found that a well-engineered ammonia economy could help the world achieve its decarbonization goals and secure a sustainable energy future. The paper is titled, "Minimizing the Impacts of the Ammonia Economy on the Nitrogen Cycle and Climate."

A mismanaged ammonia economy, on the other hand, could ramp up emissions of nitrous oxide (N_2O), a long-lived greenhouse gas around 300 times more potent than CO_2 and a major contributor to the thinning of the stratospheric ozone layer. It could lead to substantial emissions of nitrogen oxides (NO_x), a class of pollutants that contribute to the formation of smog and acid rain. And it could directly leak fugitive ammonia emissions into the environment, also forming air pollutants, impacting water quality, and stressing ecosystems by disturbing the global nitrogen cycle.

Fortunately, the researchers found that the potential negative impacts of an ammonia economy can be minimized with proactive engineering practices. They argued that now is the time to start seriously preparing for an ammonia economy, tackling the potential sticking points of ammonia fuel before its widespread deployment.

"We know an ammonia economy of some scale is likely coming," said research leader Amilcare Porporato, the Thomas J. Wu Professor of Civil and Environmental Engineering and the High Meadows Environmental Institute. "And if we are proactive and future-facing in our approach, an ammonia economy could be a great thing. But we cannot afford to take the risks of ammonia lightly. We cannot afford to be sloppy."

Translating ammonia from agriculture to energy

As interest in hydrogen as a zero-carbon fuel has grown, so too has an inconvenient reality: it is notoriously difficult to store and transport over long distances. The tiny molecule must be stored at either temperatures below -253° Celsius or at pressures as high as 700 times atmospheric pressure, conditions that are infeasible for widespread transport and prone to leakage.

Ammonia, on the other hand, is much easier to liquify, transport, and store, capable of being moved around similarly to tanks of propane.

Moreover, an established process for converting hydrogen into ammonia has existed since the early 20th century. Known as the Haber-Bosch process, the reaction combines atmospheric nitrogen with hydrogen to form ammonia. While the process was originally developed as a cost-effective way to turn atmospheric nitrogen into ammonia for use in fertilizers, cleaning products, and even explosives, the energy sector has looked to the Haber-Bosch process as a way to store and transport hydrogen fuel in the form of ammonia.

Ammonia synthesis is inherently energy-intensive, and fossil fuels without CO_2 capture are currently used to meet almost all of its feedstock and energy demands. But as the researchers pointed out in their article, if new, electricity-driven processes that are currently under development can replace conventional fossil-fuel-derived ammonia synthesis, then the Haber-Bosch process—or a different process altogether—could be widely used to convert clean hydrogen into ammonia, which can itself be burned as a zero-carbon fuel.

"Ammonia is an easy way to transport hydrogen over long distances, and its widespread use in agriculture means there is already an established infrastructure for producing and moving ammonia," said Matteo Bertagni, postdoctoral researcher at the High Meadows Environmental Institute working on the Carbon Mitigation Initiative. "You could therefore create hydrogen in a resource-rich area, transform it into ammonia, and then transport it anywhere it's needed around the globe."

Ammonia's transportability is especially attractive to industries reliant on long-distance transportation, such as maritime shipping, and countries with limited available space for renewable resources. Japan, for example, already has a national energy strategy in place that incorporates the use of ammonia as a clean fuel. Straightforward storage requirements mean that ammonia might also find use as a vessel for long-term energy storage, complementary to or even replacing batteries.

"At first glance, ammonia seems like an ideal cure for the problem of decarbonization," Porporato said. "But almost every medicine comes with a set of potential side effects."

'Look before we leap'

In theory, burning ammonia should yield only harmless nitrogen gas (N_2) and water as products. But in practice, Michael E. Mueller, associate chair and professor of mechanical and aerospace engineering, stated that ammonia combustion can release harmful NO_x and N_2O pollutants.

Most N_2O emissions from ammonia combustion are the result of disruptions to the combustion process. "N_2O is essentially an intermediate species in the combustion process," Mueller said. "If the combustion process is allowed to finish, then there will be essentially no N_2O emissions."

Yet Mueller said that under certain conditions, such as when a turbine is ramping up or down or if the hot combustion gases impinge upon cold walls, the ammonia combustion process can become disrupted and N_2O emissions can quickly accumulate.

For instance, the researchers found that if ammonia fuel achieves a market penetration equal to around 5% of the current global primary energy demand (which would require 1.6 billion metric tons of ammonia production, or ten times current production levels), and if 1% of the nitrogen in that ammonia is lost as N_2O, then ammonia combustion could produce greenhouse gas emissions equivalent to 15% of today's emissions from fossil fuels. The greenhouse gas intensity of such a loss rate would mean that burning ammonia fuel would be more polluting than coal.

Like ammonia's N_2O emissions, Robert Socolow, a professor of mechanical and aerospace engineering, emeritus, and senior scholar at Princeton, said that widespread usage of ammonia in the energy sector will add to all the other impacts that fertilizer has already had on the global nitrogen cycle.

In a seminal paper published in 1999, Socolow discussed the environmental impacts of the food system's widespread use of nitrogen-enriched fertilizers to promote crop growth, writing that, "Excess fixed nitrogen, in various guises, augments the greenhouse effect…contaminates drinking water, acidifies rain…and stresses ecosystems."

As the energy sector looks toward ammonia as a fuel, Socolow said that it can learn from agriculture's use of ammonia as a fertilizer. He urged those in the energy sector to consult the decades of work from ecologists and agricultural scientists to understand the role of excess nitrogen in disturbing natural systems.

"Ammonia fuel can be done, but it cannot be done in any way we wish," said Socolow, whose 2004 paper with Stephen Pacala, the Frederick D. Petrie Professor in Ecology and Evolutionary Biology, emeritus, on stabilization wedges has become a foundation of modern climate policy. "It's important that we look before we leap."

While the environmental consequences of an ammonia economy gone wrong are serious, the researchers emphasized that the potential stumbling blocks they identified are solvable through proactive engineering.

"I interpret this paper as a handbook for engineers," Mueller said. "By identifying the worst-case scenario for an ammonia economy, we're really identifying what we need to be aware of as we develop, design, and optimize new ammonia-based energy systems."

For instance, Mueller said there are alternative combustion strategies that could help to minimize unwanted NO_x and N_2O emissions. While each strategy has its own set of pros and cons, he said that taking the time now to evaluate candidate systems with an eye toward mitigating emissions will ensure that combustion systems are poised to operate optimally for ammonia fuel.

Another option for accessing the energy in ammonia involves partially or fully splitting ammonia back into hydrogen and atmospheric nitrogen through a process known as cracking. Ammonia cracking, a line of research being actively pursued by Emily A. Carter, could help to make the fuel composition more favorable for combustion or even bypass the environmental concerns of ammonia burning by regenerating hydrogen fuel at the point of use.

Carter is the Gerhard R. Andlinger Professor of Energy and the Environment and senior strategic advisor and associate laboratory director for applied materials and sustainability sciences at the Princeton Plasma Physics Laboratory (PPPL).

Furthermore, several technologies already exist at the industrial scale to convert unwanted NO_x emissions from combustion back into N_2 through a process known as selective catalytic reduction. These technologies could be straightforward to transfer to ammonia-based fuel applications. And as a convenient bonus, many of them rely on ammonia as a feedstock to remove NO_x—something that there would already be plenty of in an ammonia-based system.

Beyond the engineering practices that could be developed to minimize the environmental impacts of an ammonia economy, Porporato said future work will also look beyond engineering approaches to identify policies and regulatory strategies that would ensure the best-case scenario for ammonia fuel.

"Imagine the problems we could have avoided if we knew the risks and environmental impacts of burning fossil fuels before the Industrial Revolution began," Porporato said. "With the ammonia economy, we have the chance to learn from our carbon-emitting past. We have the opportunity to solve the challenges we've identified before they become an issue in the real world."

More information: Matteo B. Bertagni et al, Minimizing the impacts of the ammonia economy on the nitrogen cycle and climate, *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2311728120

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