Producing nitrogen fertiliser with net-zero CO_2 emissions

Decarbonising the production of synthetic nitrogen fertilisers can have the twin benefits of reducing both the industry's CO_2 emissions and its reliance on fossil fuel imports. But is such a process at all possible, and if it is, at what price? Considering the importance of nitrogen fertilisers for global food production, our authors have examined this question applying a country-specific analysis. Their findings, published in a recent scientific study, are summarised below.

By Paolo Gabrielli and Lorenzo Rosa

For centuries, nitrogen has been a bottleneck limiting global agricultural productivity. Despite its abundance in the Earth's atmosphere, nitrogen is generally not immediately available for human use, being present in the unreactive N_2 form. In 1908, the Haber-Bosch process to industrially produce the chemically reactive compound ammonia (NH_3) was invented, enabling an abundant supply of nitrogen fertilisers to boost agricultural productivity. While synthetic nitrogen fertilisers have a key role in global food production, excess reactive nitrogen has caused several environmental impacts, including groundwater contamination, eutrophication of water bodies and associated biodiversity loss, air pollution, greenhouse gas emissions, and stratospheric ozone depletion.

Anhydrous ammonia is transferred and stored as a liquefied, compressed gas.

Photo: Jon Rehg/ shutterstock.com

Fertiliser production and consumption, trade and food security

Synthetic nitrogen fertilisers are used to produce food for 3.8 billion people world-wide. According to the UN Food and Agriculture Organization (FAO), in 2019, 107 Mt of synthetic nitrogen fertilisers were used in agriculture globally. With 27 million tons of nitrogen (Mt N) per year, China is the largest consumer of synthetic nitrogen fertilisers, followed by India (19 Mt N) and the USA (12 Mt N). But considering country-specific nitrogen use efficiencies (i.e. the fraction of nitrogen lost in the field and not used to produce food), nitrogen waste and losses in crops from farm to fork, and country-specific per capita nitrogen intakes in diets, we found that India is the country feeding the largest number of people with synthetic nitrogen fertilisers, 646 million people, followed by China (530 mill.) and the USA (480 mill.).

In 2019, synthetic nitrogen fertiliser exports equated 38 per cent (47 Mt N per year) of global production. Exports are concentrated in just a few countries (see Figure, upper part), with Russia being the largest net exporter (9.2 Mt N per year), followed by China (5.6 Mt N) and Egypt (3 Mt N). However, some net exporters of synthetic nitrogen fertilisers are large importers of natural gas, which make these countries vulnerable to energy shocks – as highlighted by the current energy crisis. Accounting for natural gas imports lowers the number of countries that can produce synthetic nitrogen fertilisers self-sufficiently. The lower part of the Figure shows that while a number of countries, including China, Germany and Poland, have become net-importers of synthetic nitrogen fertilisers (via natural gas imports), major fossil fuel producers like Russia and Saudi Arabia remain net exporters.

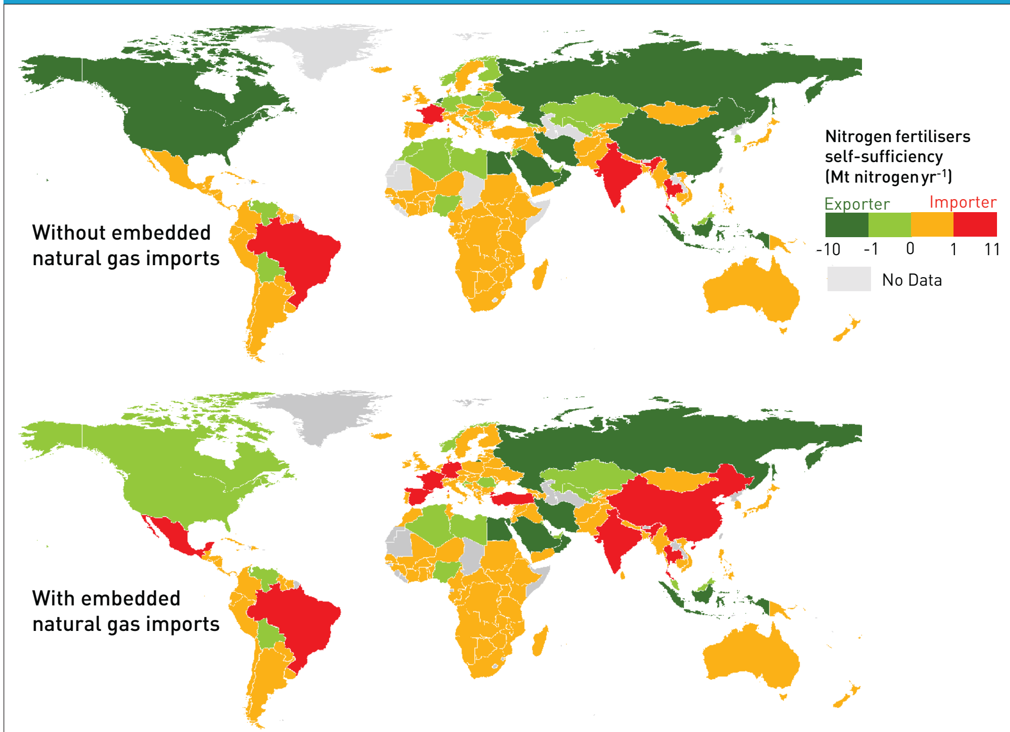
The reliance of synthetic nitrogen fertiliser on international trade makes global food security and food systems vulnerable. According to the FAO, food security is achieved "when all people, at all times, have physical, economic and social access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active healthy life". Considering safe physical access to proteins, we found that 1.07 billion people a year consume food reliant on fertiliser imports. But an additional 710 million people depend on natural gas imports used to produce synthetic nitrogen fertilisers. Thus, globally, 1.78 billion people per year are fed from food reliant on imports of either fertilisers or natural gas. So without trading of these commodities food shortages would spread, having devastating impacts on millions of people.

Carbon emissions embedded in ammonia production

NH_3 is the precursor to most synthetic nitrogen fertilisers, and NH_3 production accounts for roughly 90 per cent of the nitrogen fertiliser industry's total energy consumption and CO_2 emissions. Therefore, achieving net-zero CO_2 emissions in NH_3 production would represent a major step towards net-zero fertilisers. The global production of NH_3 is about 183 Mt per year, roughly 70 per cent of which goes into synthetic nitrogen fertilisers, whereas the remaining fraction is used for plastics, explosives and textile production. NH_3 synthesis is energy- and carbon-intensive. The global greenhouse gas emissions from NH_3 production are about 450 Mt CO_2 a year. However, country-specific carbon emissions from synthetic nitrogen fertiliser production have been overlooked until recently. Our analysis shows that 310 Mt CO_2 per year are emitted globally by ammonia production to produce synthetic nitrogen fertilisers. China is responsible for the largest amount of CO_2 emissions (117 Mt CO_2/year), followed by India (45 Mt CO_2/year) and the USA (31 Mt CO_2/year).

Conventional production of NH_3 via the Haber-Bosch process uses natural gas (70 %), coal (26 %), oil (1 %), and electricity (4 %) as feedstock. This is a highly integrated process, but can be divided into two main steps: hydrogen production from fossil fuels and NH_3 synthesis from the Haber-Bosch reaction. In most countries, hydrogen is currently manufactured through steam methane reforming (SMR) of natural gas, although China applies coal gasification. While improvements in energy efficiency and carbon intensity are underway and have reduced the emission intensity of NH_3 production by 12 per cent over the last 15 years, net-zero NH_3 production requires a fossil fuel phase-out.

Global nitrogen fertiliser self-sufficiency with and without embedded fossil fuel imports



Source: Gabrielli and Rosa, 2023.

Three net zero production routes and their energy-land-water implications

Net-zero CO_2 emissions in NH_3 production can be achieved through a) the production of hydrogen from fossil fuels integrated with carbon capture and storage, b) water electrolysis using low-carbon electricity, and c) biomass gasification, such as wood chips from crop and forestry residues. In the carbon capture and storage route, NH_3 is still produced from fossil fuels via the conventional Haber-Bosch process. Carbon dioxide emissions generated during NH_3 synthesis are captured, transported, and permanently stored in suitable underground geological structures. In the electrification route, hydrogen is produced from water electrolysis via low-carbon electricity, which also powers the Haber-Bosch process. In the biomass route, CO_2 is captured from air via photosynthesis during biomass growth and then emitted upon synthesis and disposal of the biomass-based product, thus resulting in net-zero CO_2 emissions. Biomass contains both the carbon and hydrogen atoms, as well as the energy required for the synthesis of NH_3.

While all net-zero routes described above are technically feasible, and some allow avoiding reliance on fossil fuels, a holistic approach is needed to quantify their environmental feasibility and avert unintended environmental consequences. The table on page 38 reports the reference values of global CO_2 emissions, energy requirements, land use, and water consumption. For example, decarbonising NH_3 production with the electrification route will require about 1,200 terrawatt-hours (TWh) of electricity (or 5 per cent of global total electricity consumption in 2019), compared to the 48 TWh currently used under a business-as-usual production pathway. All in all, net-zero routes are more land-, energy- and water-intensive than the business-as-usual route; this is the price of achieving net-zero emissions. Overall, the biomass route is the most water- and land-intensive one (mostly through the high water and land intensity for growing the biomass feedstock), while the electrification route is most energy-intensive (mostly because of the electricity amount required to produce hydrogen via water electrolysis). Let's look at this a little closer:

Being more energy-intensive, net-zero NH_3 production will not necessarily decrease vulnerability to energy shocks. For example, net-zero NH_3 production based on the electrification route could reduce vulnerability to shocks on commodity markets, at least in terms of oil, methane, and coal, but would be still vulnerable to electricity prices. The deployment of processes to synthesise nitrogen fertilisers from renewable energy (i.e. electrification and biomass route) can reduce CO_2 emissions while averting reliance on imports of fossil fuels. In contrast, whereas carbon capture and storage promotes net-zero emissions, it does not reduce the reliance of the food system on fossil fuels; still using an average of 77 Mt of carbon from fossil fuels per year, it makes the global food system vulnerable to energy shocks. In addition, carbon capture and storage would require a widely spread infrastructure to transport and permanently store the CO_2 captured at the production site. Whereas recent assessments indicate that between 7,000 and 55,000 Gt CO_2 can be stored world-wide, CO_2 storage still faces issues concerning the actual availability, accessibility, and acceptance of storage sites.

Importantly, our assessment accounts for natural gas leaks along the supply chain, here assumed to be 1.5 per cent of the required natural gas. However, it is worth noting that natural gas leaks affect carbon emissions, hence land, energy, and water consumption required to achieve net-zero emissions of the carbon capture and storage route only. Arguably, the carbon capture and storage route would find a better use for carbon-rich chemical products, such as methanol and plastics, which, contrary to NH_3, contain the carbon molecule in the final product, as we have shown in previous research. Unlike carbon capture and storage, the electrification and biomass routes can achieve net-zero emissions while avoiding fossil fuels. However, the electrification route would require 25 times more energy than the business-as-usual route. The biomass route would require 1,000 times more land and water than the business-as-usual route, using 26 million hectares of land and 255 billion cubic metres of water. To grow this vast increase in biomass, further nitrogen inputs as well as transport and processing facilities would be needed. In addition, both biomass and electricity would be required to achieve net-zero emissions in other sectors, and competition for these limited resources could constrain their use for NH_3 production. To avert unintended impacts on natural resources and biodiversity and additional land, water, and fertiliser use, biomass should be sourced sustainably from waste biomass, and forestry and crop residues.

While net-zero nitrogen production routes could solve energy and food security issues present in business-as-usual NH_3 production, they could also create inequalities in NH_3 nitrogen fertiliser production, with more technically advanced economies continuing to dominate the sector.

Global energy, land, and water required to achieve net-zero emissions in synthetic nitrogen fertiliser production

	CO_2 emissions ($Mt\ CO_2$)	Electricity requirements (TWh)	Land use (Mha)	Water consumption (km^3)
Business-as-usual	310	48	0.03	0.04
Carbon capture and storage	0	76	0.06	0.13
Electrification	0	1,219	0.9	2.03
Biomass	0	49	26	255

How to reduce global ammonia demand

By emitting 310 Mt CO_2 per year, business-as-usual NH_3 synthesis for synthetic nitrogen fertilisers production commits humanity to emissions levels not compatible with the net-zero targets required to keep global warming below 1.5 °C. An additional 30 Mt CO_2 per year are estimated to come from NH_3 transport. Although NH_3 is not a greenhouse gas, its overuse leads microbes in the soil to convert it into nitrous oxide, a greenhouse gas 300 times more powerful than carbon dioxide and responsible for stratospheric ozone depletion. It is estimated that each year, nitrogen fertilisers emit 2.3 Mt of nitrous oxide, equivalent to 670 Mt CO_2 emissions, bringing global total emissions (direct and indirect emissions) from synthetic nitrogen fertilisers to 1,010 Mt CO_2 per year when accounting for emissions from NH_3 synthesis for nitrogen fertilisers, or 2 per cent of global greenhouse gas emissions.

Economic and population growth are expected to double global food demand by 2050. So, synthetic nitrogen fertilisers are envisaged to continue to be a major and growing component of agricultural productivity this century. While the net-zero routes analysed here can abate emissions on the supply side, demand-side measures can lower future NH_3 demand and significantly ease the task of achieving net-zero emissions while considering environmental trade-offs and socio-political shocks (e.g. related to food and energy supply). Encouraging diets with low nitrogen footprint or less meat, reducing food losses and waste, and improving nitrogen use efficiencies can reduce future NH_3 demand. First, global average nitrogen use efficiency – the share of applied nitrogen incorporated in food production – is estimated to be around 46 per cent, meaning that more than half of synthetic nitrogen is dispersed in the environment and not used to grow crops. Precision agriculture can increase the efficiency of nitrogen fertiliser application to crops. Second, nitrogen losses from farm to fork are put at between 41 per cent and 44 per cent and are mainly due to harvesting and distribution losses, and food waste. Such losses can be reduced by reducing food waste and improving efficiencies in food supply chains. Third, a dietary transformation to less nitrogen-intensive diets can reduce nitrogen demand. While the recommended per capita daily protein intake for a healthy diet is estimated to be roughly 50 g (or about 9 g of nitrogen), today the global median intake is 84 g of protein. Moderating the consumption of animal-based food can reduce nitrogen demand. Importantly, while average protein intake is above the recommended value for healthy diets, one billion people still suffer from protein deficiency world-wide, indicating inequalities in our food systems.

Considering losses, inefficiencies, and waste, it is estimated that only approximately 20 per cent of produced synthetic nitrogen fertilisers feeds global population. Therefore, roughly 80 per cent of synthetic nitrogen fertilisers is lost through inefficiencies in our food systems. Transitioning from a linear to a circular economy capturing and recycling nitrogen from waste can moderate the use of resources and energy required to produce synthetic nitrogen fertilisers. Promoting the use of organic fertilisers such as manure or compost can reduce NH_3 demand. Animal manure nitrogen outputs are a major source of nitrogen recovery and recycling globally. The digestate produced from anaerobic digestion of livestock manure can be spread over croplands to recover nitrogen. However, organic fertilisers are often more expensive, slower in releasing nutrients and presently not capable of supporting the demands of current or future generations. While promising scientific developments are underway for alternative fertilisers, many of these approaches need further development. Bioinformatics and plant genomics can both reduce fertiliser usage. Electrochemical synthesis and plasma activated processes are other promising approaches that could be deployed as an alternative to the Haber-Bosch process.

Conclusions

Going beyond the status quo and investigating the interplay between food security and climate targets, we have analysed alternative routes that are already available today to abate the carbon footprint of fertilisers via net-zero CO_2 emissions in NH_3 production. These net-zero routes hold the potential to align food system with global climate targets, while increasing food and nutrient security by reducing the reliance of the food system on fossil fuels. However, they will require more land, water, and energy than business-as-usual production. This highlights the relevance of location-specific analyses to determine optimal net-zero routes for producing fertilisers based on technical, environmental, and geo-political circumstances.

Paolo Gabrielli is a Senior Scientist at ETH Zurich/Switzerland and currently a Visiting Investigator at Carnegie Institution for Science at Stanford, California/USA. His research deals with the optimisation and assessment of net-zero energy systems, focusing on the assessment of energy storage technologies and the optimal design of integrated energy and chemical systems and supply chains.
Lorenzo Rosa is a Principal Investigator at Carnegie Institution for Science at Stanford. His research aims to assess the potential benefits and unintended climate and environmental consequences of innovations engineered to satisfy the increasing global demands for energy, water and food.
Contact: gapaolo@ethz.ch

References: **www.rural21.com**