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The Growing Ambitions for Greener Ammonia

Ammonia is a critical component of biological life on Earth. It is a naturally occurring compound that is found in humans (as a by-product of protein metabolism in the gut), in organic matter (plants and animals) during decomposition, in soil and in the wider environment. But ammonia is also artificially synthesised as it is paramount for many industrial processes and products. At 176 million tonnes of production globally each year, it is one of the most widely produced industrial chemicals. This is primarily because it acts as a medium between abundantly available atmospheric nitrogen and many of the fertilisers that help us to grow food – it is thought that half of global food production is possible today because of synthetic fertilisers.[1] As well as this, it is used extensively in the manufacture of products like plastics, pesticides, refrigerants, and dyes. To summarise, it is crucial for our global economy and standards of living.

But the production of ammonia has a dirty secret. It emits approximately 450Mt CO_2 per annum as it relies entirely on fossil fuels[2], which equates to 1-2% of global carbon dioxide emissions, making it more polluting than countries like the UK or South Africa.[3,4] Since Russia's invasion of Ukraine, ammonia prices have spiked due to the incredibly high cost of natural gas (ammonia's current primary feedstock input) so much so that the fertiliser industry in Europe has seen widespread production suspensions or even facility closures. To compound matters further, the supply of ammonia is also heavily reliant on Russia's own domestic production facilities, for example, Russia accounts for roughly 45% of the ammonia nitrate market. Despite sanction exemptions due to its criticality in the global food market, this has led to significant supply chain disruption and food price inflation which is impacting all of us.[5]

However, as its production process begins to decarbonise, market signals suggest that the fate of ammonia is far from doomed, and that ammonia could even play a key role in facilitating a global transition to net zero.

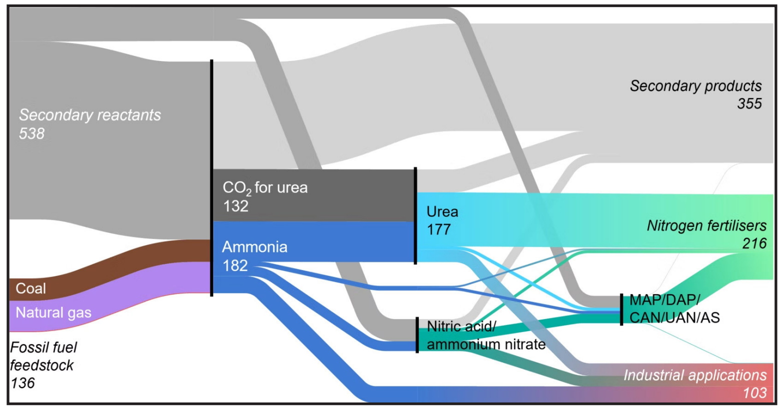
A renewable production solution?

The outlook for the ammonia and fertiliser industry has been transformed in recent years by the increasing momentum behind renewable hydrogen, especially as the levelised cost of its production falls. Ammonia (NH_3) is synthesised by combining nitrogen and hydrogen at high temperature (420°C) and intense pressure in the celebrated century-old Haber-Bosch process. Until now, all hydrogen used in this process has been derived from hydrocarbons, giving it the name 'grey hydrogen' due to the fact the separated carbon dioxide is mostly released into the atmosphere. To give a sense of scale, 27% of all grey hydrogen produced globally – a colossal 1,000TWh – is used for ammonia production, highlighting the importance of a structural change for climate change mitigation.[6]

With the arrival of low carbon hydrogen comes the potential for low carbon ammonia, produced without the eye-wateringly high greenhouse gas emissions (GHG) currently associated with the global ammonia industry. Electrolytic (green) hydrogen is produced using an electrolyser, which is a device that is capable of splitting water (H_2O) using renewable electricity, thereby only releasing oxygen as a by-product. CCUS-enabled (blue) hydrogen is produced in the same way as grey hydrogen (as described above) but involves the capture, storage or utilisation of the carbon by-product. If these forms of hydrogen are used for the Haber-Bosch process, the ammonia produced can be classified as 'green' or 'blue' ammonia respectively which gives it its low carbon status.

Green ammonia is preferred from an emissions perspective as it is zero carbon, whereas blue ammonia still has residual emissions associated with fossil fuel extraction and failed CO_2 capture.[7] However, as some ammonia-based products require carbon as an input, there remains a barrier in the short term to displacing hydrocarbon-derived (grey or blue) ammonia with electrolytic (green) ammonia. One example of this is urea, the most common type of nitrogen fertiliser (55% ammonia is used for its production), which contains carbon dioxide that is later released when the fertiliser is applied to cropland (a further 130Mt CO_2 per year).[8] Clearly, if carbon captured during blue ammonia production is utilised for urea production instead of stored underground, the environmental benefit associated with this decarbonised ammonia production is negated downstream. Given this, and as demonstrated by the Sankey diagram below, it is clear that there are significant complexities to decarbonising the ammonia value chain and a whole lifecycle analysis is required. Possible solutions to overcome this challenge include using biogenic CO_2 derived from organic matter to produce urea, or reducing demand for urea-based and synthetic fertilisers, either through enhanced product efficiency, efficient application practices, or through the utilisation of safe carbon-free or sustainable alternatives.

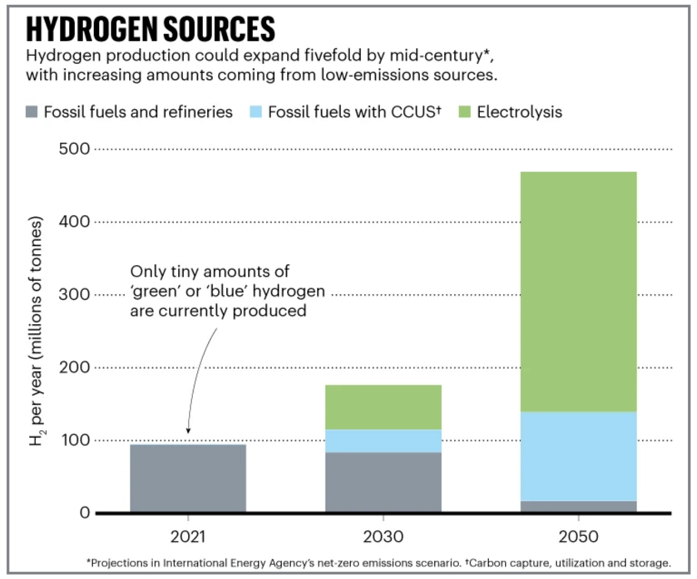
From an economic perspective, the current inflated price of natural gas is making conventional European ammonia production unfeasible, let alone blue ammonia which also comprises of the still uncertain cost of carbon capture and storage. While it is forecast that gas prices will fall, green ammonia production costs could be preferable, especially in instances where it is possible to shield it from gas price volatility. But such is the required abundance of renewable power and upscaling of electrolyser manufacture to produce enough ammonia by these means, that the speed with which a transition to green ammonia occurs is up for debate. While unknown, what is evident is that a growing global pipeline of renewables projects, combined with innovative developments in ammonia generation (such as that of Nel Hydrogen's Danish dynamic production facility which uses curtailed surplus electricity that would otherwise go to waste) make this environmentally friendly eventuality seem ever more tangible.[9]



Notes: The thickness of the lines in the Sankey diagram are proportional to the magnitude of the mass flows. All numeric values are in million tonnes per year of production using production data for 2019. Only the fossil fuel quantities consumed as feedstock are shown; the diagram does not represent process energy inputs.

MAP = monoammonium phosphate;
DAP = diammonium phosphate;
CAN = calcium ammonium nitrate;
UAN = urea ammonium nitrate;
AS = ammonium sulphate.

Mass flows in the ammonia supply chain from fossil fuel feedstocks to nitrogen fertilisers and industrial products 'Ammonia Technology Roadmap' IEA October 2021



*Projections in International Energy Agency's net-zero emissions scenario. †Carbon capture, utilization and storage.

Hydrogen source production forecast to 2050.
IEA World Energy Outlook 2022

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[1] 'How many people does synthetic fertilizer feed?' Our World in Data 2017.
[2] 'Ammonia Technology Roadmap' IEA October 2021
[3] '2020 UK Greenhouse Gas Emissions' Final Figures. BEIS 2022
[4] 'CO_2 and Greenhouse Gas Emissions' Our World in Data 2020
[5] 'Europe's Widening Fertilizer Crisis Threatens Food Supplies' Bloomberg UK 2022
[6] 'Hydrogen for Beginners' Bloomberg New Energy Finance 2021
[7] Carbon capture rates are expected to be between 90-95%. 'How green are green and blue hydrogen?' (Ammonia Energy Association 2021)
[8] 'Ammonia Technology Roadmap' IEA October 2021
[9] 'Nel – Danish Dynamic Ammonia Production is World First' Hydrogen Central Sept 2022

Clean fuel of the future?

While eradicating the ammonia industry's reliance on the volatile energy market and removing its greenhouse gas emissions is critical, green ammonia as a hydrogen derivative could also unlock far wider opportunities that extend beyond the reaches of the fertiliser industry (and associated sectors), and in turn substantially impact global efforts to reach zero carbon.

Some of the benefits can be summarised by 4 T's below:

Turbines

Firstly, in the future, ammonia could be used as a clean fuel to displace fossil fuels where carbon-heavy processes cannot conceivably be electrified. Ammonia's energy density makes it highly capable of fuelling heavy (or larger) air, land or sea vessels, either in specially designed turbines, internal combustion engines or ammonia fuel cells. For example, the shipping industry, which currently accounts for about 3% of global CO_2 emissions, sees ammonia fuel as a potential route to decarbonisation as it is forecast to be the lowest cost zero-carbon fuel per km for long-range maritime travel.[10] Amazingly, it is conceivable that ammonia or hydrogen will be transported around the world by tanker ships powered by ammonia itself, releasing no GHG emissions in the process. In the UK, the Clean Maritime Demonstration Competition (CMDC) is providing funding to develop new zero carbon marine technologies using ammonia and other hydrogen derivatives. Further afield in Singapore, a 100% ammonia-powered 60MW gas turbine will be demonstrated at a port to test its value as a fuel for power generation.[11] That said, the nitrogen present within ammonia reduces its flammability and there are significant NOx emissions associated with its production. This leads us on to:

Transmission

Hydrogen – the same stuff required to make ammonia – is poised to play a key role as a clean fuel in the energy transition. Hydrogen is highly combustible which makes it a suitable fuel to replace natural gas in producing heat, and it can be used in vehicular (or stationary) fuel cells to produce electricity without emitting any GHG emissions. It therefore offers a credible decarbonisation option for various applications such as high-temperature heat or heavy-duty transport, where electrification isn't feasible. For this reason, and because of its favourable chemical properties (see next section), ammonia is regarded as an important energy carrier, containing hydrogen molecules that can later be separated from the nitrogen. The cracking of ammonia into fuel cell grade hydrogen for bus refuelling is currently being demonstrated at Tyseley Energy Park, where Equans are operating as principal contractor on an innovation project funded by the Department for Business, Energy and Industrial Strategy (BEIS). It is important to note that the roundtrip efficiency of producing hydrogen to generate ammonia and then later convert this back to hydrogen is low, and therefore, this process should be utilised where storing hydrogen is less viable. The reasons for doing so are because:

Tanks

Ammonia is being touted as a good form of long-term energy storage as it can be expensive and volumetrically insufficient to store hydrogen in tanks for long periods. Although long-term hydrogen storage is being explored in geological subsurface structures, these are somewhat scarce in the UK, and ammonia presents itself as a better solution for inter-seasonal storage due to its high volumetric density (10x higher than compressed hydrogen) and moderate storage temperature (-33°C).

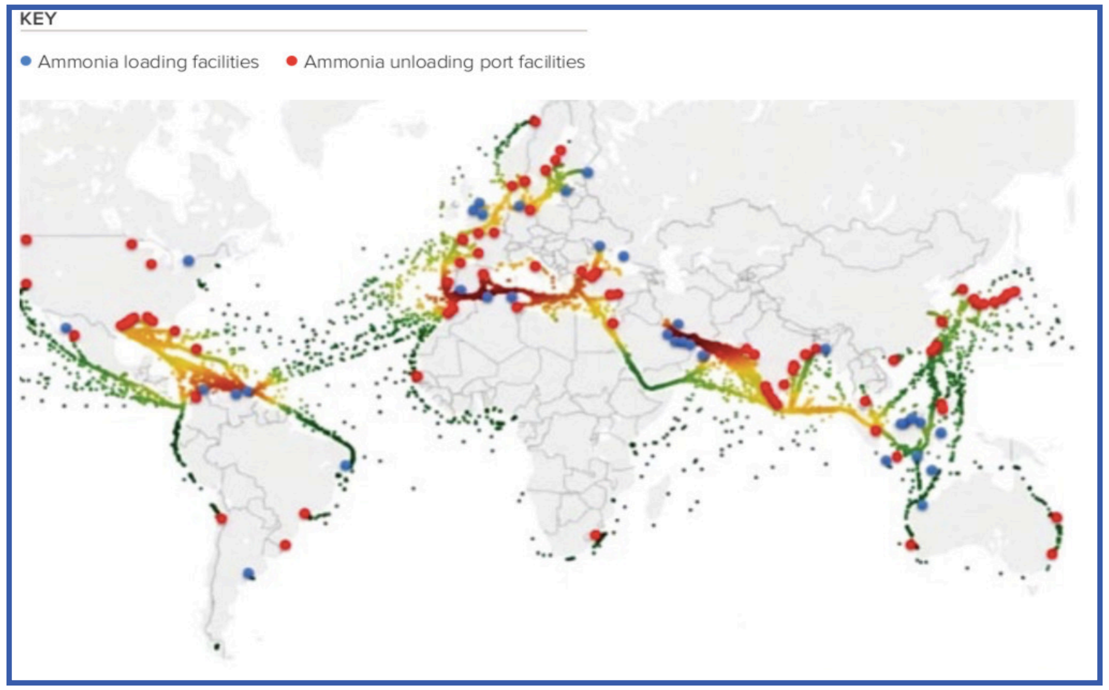
A power plant CCGT

AB Achema 15,000T Ammonia Storage Tank, Lithuania.
Source: Thyssenkrupp Industrial Solutions

To put it into context, hypothetically operating a power-plant-size combined cycle gas turbine (CCGT) combustingpure hydrogen on an average week would require about ~2,600 tonnes of the fuel.[12] Storing this is roughly equivalent to 2.5x large size UK salt caverns; a requirement so excessive that it would potentially inhibit the widespread use of hydrogen for dispatchable power, due to the geological constraints associated with subsurface salt formations.[13] Conversely, storing a week's worth of hydrogen in the form of ammonia (~15,000 tonnes) would require just one medium size (38m x 20m) storage tank, which already exist today and could foreseeably be constructed near power plants at a cost similar to that of salt cavern storage.[14] Another example of long-term storage is through the UK Research and Innovation (UKRI) Ocean Fuel project, which is exploring offshore hydrogen production and the role of ammonia solutions to overcome wind energy intermittency.

Terminals

Lastly, ammonia is a good transportation medium for the same reasons outlined above: its high volumetric density and its moderate storage temperature. This makes it a more efficient solution than storing and transporting compressed or liquid hydrogen, which requires more space to contain it and a lot more energy to get it into and remain in this state (-253°C for liquid hydrogen). What is also key is that ammonia is already commonly transported and traded on a large scale today with vast amounts of distribution infrastructure in place or in development. Given that there are 270 pre-existing ammonia sea terminals worldwide,[15] the usual chicken vs egg predicament does not apply, and so it is seen as a credible and scalable solution to transport shipborne hydrogen which will be central to creating a global marketplace for hydrogen trading across borders. This year has already seen the shipping of clean ammonia from areas of bountiful cheap renewable supply where hydrogen production costs are very low (e.g. Middle East and Australia), to areas less well endowed with domestic hydrogen production potential.[16] One recent example is the trade deal between Canada and Germany to export renewable hydrogen and ammonia produced in North America, which will be shipped across the Atlantic for use in Europe.[17] This type of supply chain link is expected to flourish as the global hydrogen market matures.



Ammonia shipping infrastructure, including a heat map of liquid ammonia carriers and existing port facilities (2017).
'Ammonia: zero-carbon fertiliser, fuel and energy store policy briefing' The Royal Society 2020

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[10] 'How ammonia could help clean up global shipping' MIT Technology Review 2022

[11] 'Ammonia combustion for power generation: updates from Korea, Malaysia and Singapore' AEA 2022

[12] Assumptions made: 900MW CCGT would require ~40 tonnesH2/hr and operate for 9.5hrs per day (0.4 plant load factor 24hrs*0.4=9.5hrs)

[13] Salt cavern working hydrogen gas volume is ~1100 tonnes 'Project Hysecure Phase 1 Summary' INOVYN 2019

[14] 15,000 tonnes ammonia ≈ 2,600 tonnes hydrogen. 'Ammonia: zero-carbon fertiliser, fuel and energy store policy briefing' The Royal Society 2020. Pg.24

[15] 'The Green Ammonia Boom is Coming' Yahoo Finance UK 2022.

[16] 'Inpex, two other Japanese companies transport clean ammonia from UAE's ADNOC' S&P Global 2022.

[17] 'Germany's Uniper, E.ON to import green ammonia from Canada' Reuters 2022

A toxic relationship?

While ammonia does provide value to the transition to a cleaner, greener future, it does possess certain qualities that challenge its proliferation. Firstly, despite ammonia alone being a non-flammable gas, it can explode when ignited if mixed with certain concentrations of air, which naturally represents a hazard. Secondly, if combusted, it will release nitrogen oxides (NOx) which are an air pollutant that can cause harm to human and animals, although its impact can be curbed by catalytic technologies. Its ability to impact the environment is also possible through leaching. If high concentrations in soil and bodies of water are reached, it can cause eutrophication and biodiversity losses. But the main challenge with ammonia is its toxicity. If not stored carefully, ammonia can cause harm to those exposed to it, with the greatest risk posed by the inhalation of ammonia vapours which can have highly irritative or corrosive effects depending on exposure. All the hazards outlined above are already faced by the ammonia industry today; however, the widespread scale of its potential future use rightfully brings these issues under further scrutiny.

Fortunately, its potent odour gives some early warning of its presence and stringent regulations are already in place for the established ammonia industry. These regulations are now front and centre of all future developments and should be rigorous enough to deliver reassurances that ammonia won't be causing issues any greater than the flammable fossil fuels generated, stored and used today. More international coordination is clearly required to ensure sufficient standards of safety are guaranteed as ammonia will be traded across borders, and transported out at sea which itself represents a risk. It is feasible that ammonia's role will be restricted to transportation, storage and other limited uses, where it is unlikely if leaked to cause detrimental harm to mass human populations. To this end, it is unlikely that ammonia would ever be used in domestic settings. Ultimately, the development of ammonia as a clean fuel is contingent on those managing it to prove that it can be handled safely at large volumes, otherwise its role will certainly become stunted.

Cracking the problem?

While ammonia is more easily transported and stored than hydrogen, its use as a fuel source isn't ideal, due to the reasons outlined above (e.g. toxicity, NOx, combustibility). Therefore, it will often be necessary to return it to its historic hydrogen state at the point of its use. This is where decentralised ammonia cracking technology comes in. An ammonia cracker can split ammonia into its component hydrogen and nitrogen and then membrane technology separates the gases, delivering a supply of pure hydrogen, requiring limited amounts of energy input in the process. Equans are demonstrating the use of such technology at the strategic energy and resource hub Tyseley Energy Park in Birmingham as part of a consortium known as Ammogen. An ammonia cracker will be supplied with ammonia and will produce 200kg of transport-grade hydrogen per day. In this demonstration plant, the liquid ammonia will be stored at pressure in 600kg cylinders and fed into a vaporisation system which in turn will supply the cracker unit. The output from the plant is planned to be piped to the adjacent refuelling station that delivers hydrogen to local buses. Equans are the principal contractor on-site and are responsible for providing multi-disciplinary engineering services. The project is supported by £6.7 million from BEIS through the Net Zero Innovation Portfolio's Low Carbon Hydrogen Supply 2 Competition. Design is currently underway with construction set to begin in the first half of 2023. You can read more about the Ammogen project on their website.

Tyseley Energy Park

The cracker works by funnelling ammonia (heated to about 375°C) into a chamber with a low-temperature catalyst which breaks down the ammonia into its components, nitrogen and hydrogen. This mixture is simultaneously passed through a hydrogen-selective membrane which removes the hydrogen from the nitrogen mixture. This generates an offtake of pure (fuel cell grade) hydrogen, and nitrogen retentate, the heat from which is recovered for further use. This innovative project will also include both hydrogen burners and electric heaters to heat the ammonia prior to cracking. The key learnings will be in how best to optimise this system, which is designed to integrate ammonia conversion, recovery and purification processes into one single unit to improve cost and efficiency. For instance, it will look at using grid electricity at times of low demand to power the electric heaters, the use of which in turn increases the conversion efficiency of ammonia to hydrogen.

This membrane technology could also prove valuable to other sectors where gases require deblending. The UK government are due to make a decision on blending hydrogen into the existing gas grid in 2023, which could begin on a commercial scale in 2025. By enabling surplus volumes to be injected up to a 20% hydrogen concentration, blending could act as a guaranteed hydrogen offtaker, which avoids hydrogen going to waste, provides carbon savings and gives revenue certainties to hydrogen producers while large-scale hydrogen transport and storage infrastructure is still under development.[18] There is the potential to heat some UK homes in the future on this blend or even on a 100% hydrogen supply closer to 2050 (if the gas grid is fully converted), although the latter is likely to be highly region-specific depending on grid constraints for electrification and proximity to industrial clusters where the demand pool for hydrogen and need to convert the existing gas network is greatest. In the event that blending does get the green light and where pure hydrogen is required at certain points on the grid, technologies like the membrane being demonstrated by Ammogen will be crucial for enabling fuel switching in the absence of a dedicated hydrogen grid.

To conclude, ammonia is already a chemical of significance, both in terms of its importance for agricultural and industrial processes, but also the carbon impact that its production generates. But new ways of producing renewable hydrogen (through electrolysis or similar) at scale are enabling the arrival of green ammonia. This could have a transformative impact in achieving net zero as ammonia has a broad number of other potential applications due its favourable chemical properties.

As a hydrogen carrier, it could be used as an efficient chemical store of energy, with a significant head-start against other forms of storage due to the abundance of pre-existing transport & storage infrastructure, and safety & handling regulations. Equally, it could even be used as a zero carbon fuel directly, with several industries keenly keeping an eye on its propulsion and power-generating potentialities. There are still unknowns, but for now, watch this space...

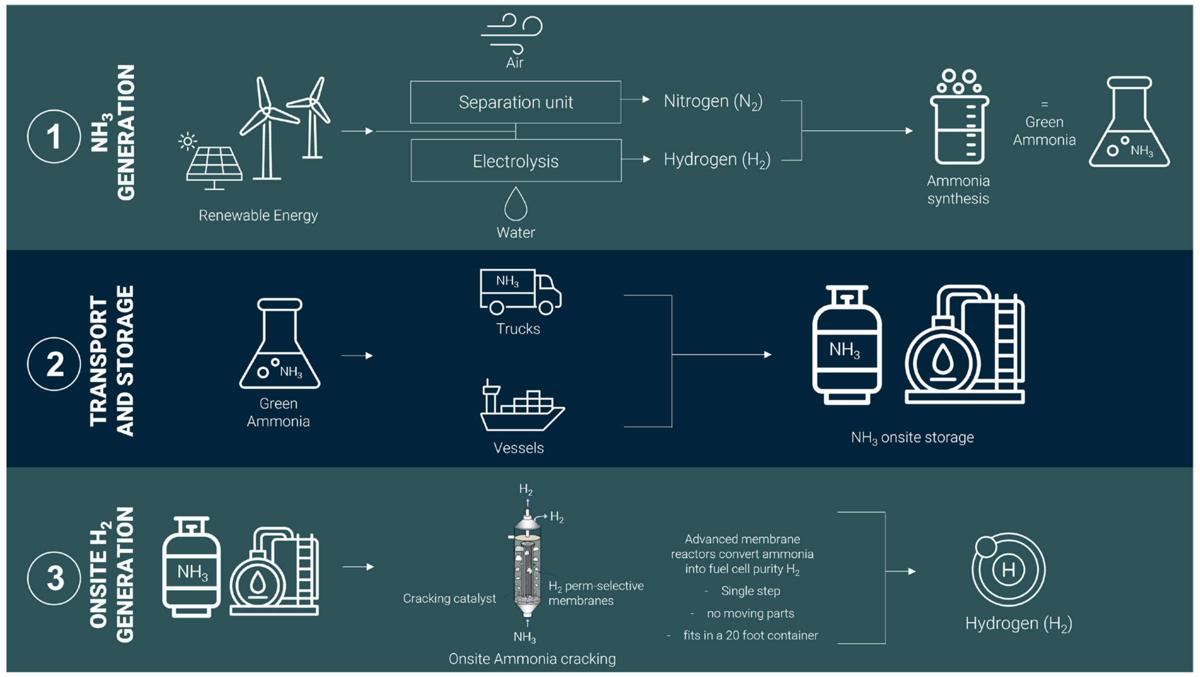
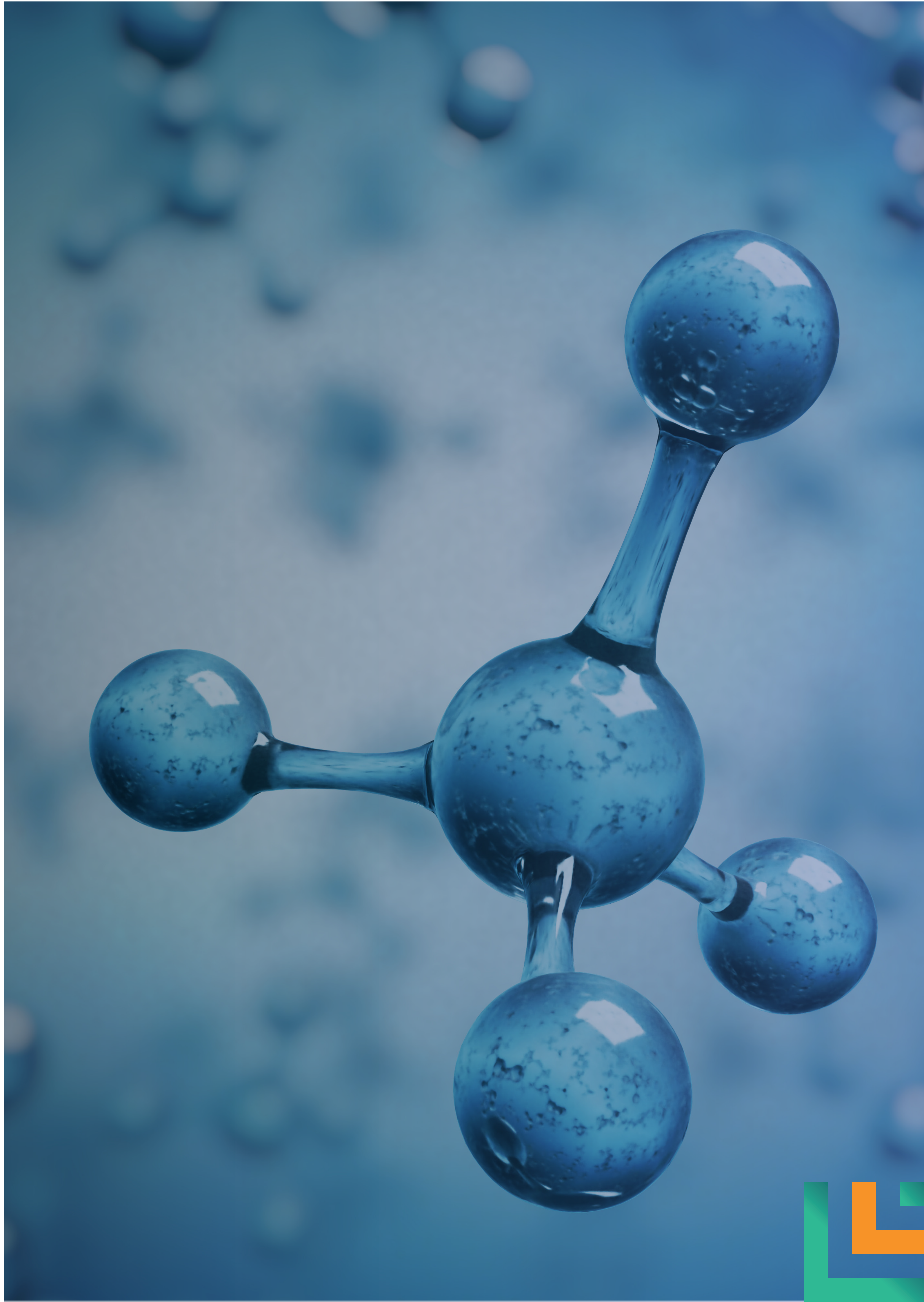


Figure C: Tyseley Ammonia Cracker project flow diagram



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[18] Blending hydrogen into natural gas at a 20:80 ratio is understood to be the maximum hydrogen concentration that is feasible with the current UK gas infrastructure. It would provide a net carbon saving of 7%

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