Sustainable ammonia for food and power

Technologies for small ammonia plants are becoming increasingly important as ammonia production is moving toward more sustainable and renewable feedstocks. As the availability of these feedstocks cannot match that of fossil fuels, small and distributed plants are required, as well as dedicated technical solutions to match new and unconventional needs.

Climate change and pollution are the undesirable consequences of a growing world population, increasing wealth and the desire for protein. They are also the cause of diseases, loss of arable land and extreme weather events – also caused by the increase of carbon dioxide (CO_2) in the atmosphere. Because of this, world leaders have announced drastic CO_2 reduction targets at world climate conferences. In order to reach lower CO_2 emission targets, nations have established incentive programs for a renewable energy sector to substitute fossil fuel-based energy production by renewable energy production. The renewable energy market is politically supported because of the CO_2-free production of electric power combined with high acceptance amongst stakeholders. Some countries have gone one step further and have introduced CO_2 taxes. This trend for "green" energy is growing uninterrupted. Specific capital expenditure (capex) for wind and solar energy systems has been decreasing for years and these systems are also becoming more efficient, resulting in a constantly declining energy cost. These are the facts, which make renewable energy interesting, not only for power, but also for other applications such as fertilizer production.

Ammonia from sustainable and renewable feedstocks

Modern ammonia production based on natural gas (NG) or coal has been optimised over more than 80 years. Specific energy consumption is close to the theoretical minimum and the economy of scale for plants with world-scale capacities of more than 3,000 t/d makes this process very cost competitive. However, the capital investment of these energy intensive plants is significant and so too is the high level of greenhouse gas (GHG) emissions that these plants produce.

Until recently the feedstocks for ammonia production were never questioned, but as ammonia production moves toward more sustainable and renewable feedstocks the ammonia market is facing a potentially radical change. The availability of new feedstocks at present cannot compete with fossil fuels, hence small and distributed plants are required, as well as dedicated technical solutions to match new and unconventional needs.

Looking to the future, in some regions it may become feasible to produce green ammonia, where hydrogen is produced from the electrolysis of water instead of steam methane reforming and nitrogen is provided by an air separation unit (ASU), for further processing into nitrate fertilizers or DeNOx fluid. The main drivers could be self-sufficiency, independency, substituting coal or natural gas due to more favourable electric power cost, avoidance of high logistic costs e.g. due to safety considerations or worse accessibility and avoidance of other costs such as fees, custom duties, import taxes or CO_2 taxes. Hence, it could turn out that localised production of a small quantity of ammonia in the direct vicinity of the consumer is an economically favourable option, despite the higher specific investment cost which naturally exists for a smaller plant.

Ammonia as an energy carrier

As the electricity system transforms towards a low carbon system, with the increasing deployment of variable renewable electricity sources in the electricity system, balancing supply and demand in the grids becomes increasingly challenging. By nature, intermittent renewable sources such as wind and solar are not always available. Therefore, fossil fuel-fired power plants currently have an important function in balancing the electricity system. In addition, the efficiency of renewable power plants is highly dependent on their location. To overcome this, proper energy storage and carrier solutions or other downstream applications have to be considered and developed. Hydrogen, SNG, methanol, redox flow batteries and ammonia have all been considered in the energy sector as potential energy storage and carrier solutions.

Ammonia is particularly promising as an energy carrier due to its relatively low cost, high energy density, and ease of liquefaction. Furthermore, infrastructure for international shipping of ammonia is readily available and it creates less safety concerns compared to hydrogen.

Benefits of using ammonia as a green solution for long term energy storage include:

- utilisation of stranded energy sources (e.g. solar, wind, tidal energy);
- peak energy saving by flexibly producing NH_3 when excess available renewable energy cannot be put back in the grid;
- no CO_2 emitted when utilising ammonia or producing it from electrolysis;
- NH_3 has a 45% higher volume energy density than H_2;
- NH_3 is stored in inexpensive pressure vessels at ambient temperature (e.g. NH_3 is liquid @ 7,6 barg);
- NH_3 solves the long term storage issue as opposed to batteries that self-discharge after a short period of time.

NFUEL® mini ammonia plants

Dutch mini-ammonia plant developer Proton Ventures offers modern technical solutions which make it possible to move away from large-scale plants towards small-scale ammonia production units (NFUEL® units).

Proton Ventures can provide customers with small-scale ammonia plants, ensuring customer's independence of transport costs and ammonia price fluctuations. Natural gas, associated gas, flare gas, hydrogen or biogas can be used as feedstock (Fig. 9).

By developing and implementing sustainable, decentralised and small-scale ammonia plants, Proton Ventures' goal is to become a global leader in the supply of NFUEL® mini ammonia production units and contribute to the reduction of the global CO_2 footprint.

NFUEL® mini ammonia plants are based on the Haber Bosch process and are available in three different capacities: 1,000 t/a, 4,000 t/a and 20,000 t/a (see Table 1). Electric power produced from renewable resources (wind, solar and tidal energy) can be used as energy source for these units. This makes it possible to produce green decentralised ammonia which can be used for:

- nitrogen carrier (fertilizer);
- hydrogen carrier;
- energy storage;
- chemical precursor (e.g. for urea, nitric acid, ammonium nitrate);
- fuel (maritime or agricultural);
- deNOx;
- feedstock for fuel cells.

Key consumables for the NFUEL® units are given in Table 2.

The NFUEL® units compensate for variations in the supply and demand of the energy market by employing ammonia as an energy carrier.

The NFUEL® system can use various feedstocks.

Feedstocks for gas-to-ammonia (using SMR) include:

- natural gas from stranded locations (e.g. oil well flares);
- natural gas from smaller gas fields in relation to conventional plants;
- (upgraded) biogas (green gas) (landfill gas or from anaerobic digestors, etc.).

Feedstocks for power-to-ammonia (using electrolysers) include:

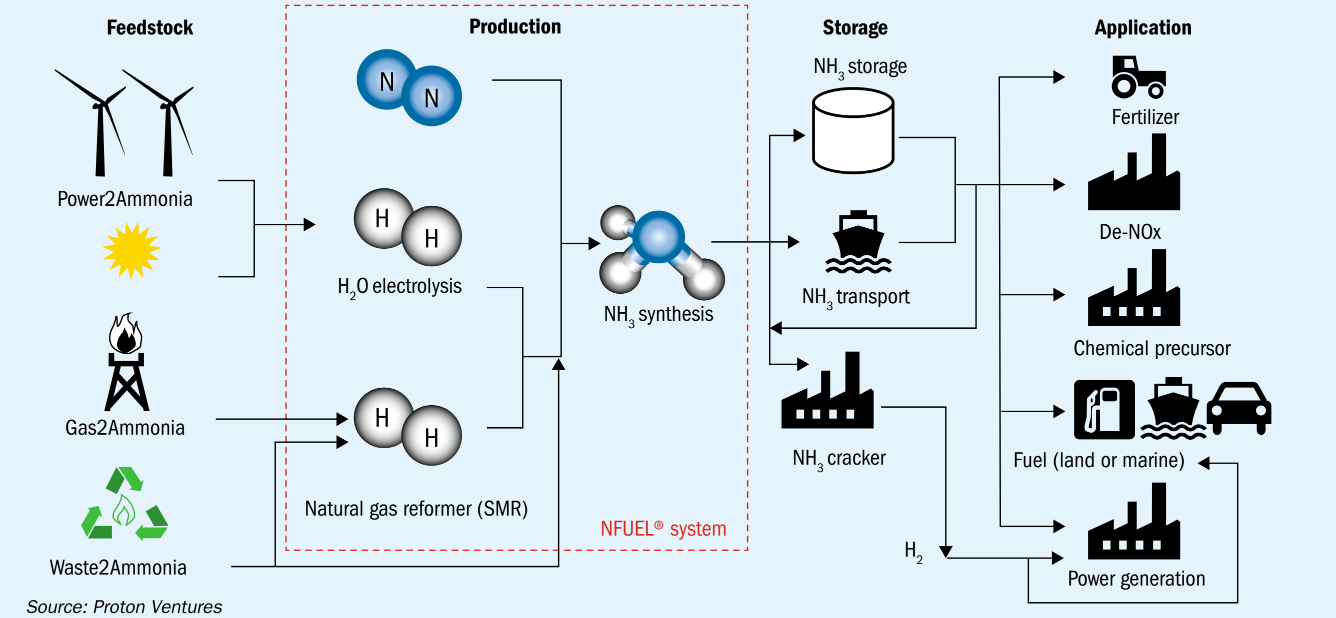
- solar, wind, tidal or geothermal (onshore or offshore);
- stranded (cheap) electricity sources.

Feedstocks for waste-to-ammonia include:

- by-product hydrogen from industrial processes;
- flared hydrogen.

Standardised designs are available for minimum capex and optimised opex. Site activities are minimal thanks to its plug-and-play designed skids.

Fig. 9: **NFUEL® overview**



Source: Proton Ventures

Table 1: **NFUEL® mini ammonia plants**

	NFUEL® 1	NFUEL® 4	NFUEL® 20
Capacity, t/a (t/d)	1,000 (3)	4,000 (10)	20,000 (60)
Power consumption, MW	1.5	5-6	25-30

Source: Proton Ventures

Table 2: **NFUEL® system key consumables**

Natural gas, Nm^3/tonne NH_3	835
Hydrogen, Nm^3/tonne NH_3	2,080
Electricity (when H_2 from NG), kWh/tonne NH_3	800-1,000
Electricity (when H_2 from H_2O), kWh/tonne NH_3	10,000-11,000

Source: Proton Ventures

The gas-to-ammonia concept (using SMR) benefits from a lower global emission footprint and can create value-added products from stranded sources. It is only economically viable if there are no large ammonia plants nearby or in places where the feedstock is basically free.

Advantages of the power-to-ammonia concept (using electrolysers) include: the efficient storage of energy in liquid form, it is CO_2-free and it creates a carbon-free fuel.

A key benefit of the waste-to-ammonia concept is that it makes a value-added product from waste sources. Mini ammonia units are modular, fully transportable, skids/containerised and can be installed in various locations with minimum installation costs. Take, for example, the 180 million Nm^3 of high purity associated gas being flared in the Bakken shale play, North Dakota, USA, corresponding to 180,000 t of NH_3 production. The otherwise flared associated gas can be at close to zero costs, resulting in a market competitive ammonia price.

Industrial references

Feasibility studies for mini ammonia plants of 4,000 to 20,000 t/a have been carried out for companies in the USA, Canada, Germany and Angola, as well as various feasibility studies for governmental organisations in The Netherlands. Industrial references for 20,000 t/a NH_3 reactors include two units in China, one in Argentina and one in Switzerland.

ISPT feasibility study on power to ammonia

In a recent power-to-ammonia (P2A) study the Institute for Sustainable Process Technology (ISPT) brought together various parties from different sectors of industry to study the storage of electricity in ammonia (NH_3) with the objective to investigate under what conditions:

- NH_3 can be produced using renewable electricity;
- NH_3 can be used to store electricity and;
- NH_3 can be used as a CO_2-neutral fuel for a power plant.

In the P2A study the following parties were involved: ISPT, Stedin Infradiensten, Nuon, ECN, Technical University Delft, University Twente, Proton Ventures, OCI Nitrogen, CE Delft and AkzoNobel.

Ammonia was investigated in this study because it provides a pathway to fully CO_2-neutral electricity storage and generation of CO_2-neutral electricity on a scale that is not limited by scarcity of materials or storage space.

The partners in this project studied three cases. The first case relates to electrochemical production, storage and use of ammonia for a rural setting (Goeree-Overflakkee), avoiding grid modification costs and allowing local production of CO_2-free ammonia. The second case allows use of ammonia as a CO_2-neutral fuel in the highly efficient Nuon Magnum gas turbine combined cycle (CCGT) power plant in Eemshaven, thus generating flexible and CO_2-free electricity. The third case assesses the electrochemical production of ammonia at OCI Nitrogen to replace (some of) the current, natural gas based production. In addition, other relevant aspects related to power-to-ammonia including technical, operational, financial, legislative and safety issues were also evaluated.

Study findings

It was determined that CO_2-neutral ammonia produced in an electrochemical way from sustainable electricity will be a feasible alternative to ammonia produced from natural gas in the longer term.

Comparing the processes for the electrochemical production of ammonia resulted in the following ranking in order of decreasing efficiency: solid oxide electrolytic cell (SOEC), low temperature solid state ammonia synthesis (LT SSAS), Battolyser, proton exchange membrane (PEM) and high temperature solid state ammonia synthesis (HT SSAS).

A competitive price for electrochemically produced CO_2-free ammonia versus conventional natural gas based produced ammonia (300-350 €/ton) can be achieved when investment costs for electrolysers drastically come down, when costs for emitting CO_2 increase significantly and when there is sufficient supply of relatively cheap CO_2-free electricity.

Electrolysers require a high on-stream time to minimise costs per ton, but due to the production patterns of wind and solar energy, large scale availability of renewable energy is intermittent.

Use of ammonia as a fuel in a CCGT power station is possible by cracking the ammonia into hydrogen and nitrogen before combusting the hydrogen in the gas turbine. Time to market for large scale application is estimated to be five to ten years. As the ammonia will be cracked into hydrogen prior to combustion in the gas turbine, application of ammonia as a fuel in the power sector enables a seamless integration with a hydrogen economy. Use of ammonia as a CO_2-neutral fuel in the Nuon Magnum power station has the potential to reduce CO_2 emissions by 3.5 million t/a when operating on base load producing 10 TWh of electricity. This reduction is equivalent to 7% of the power related carbon emissions in The Netherlands in 2015.

Locally produced CO_2-neutral ammonia, as investigated in the Goeree-Overflakkee case, will be sold on the market. The ammonia can be distributed via the ammonia terminal in the port of Rotterdam.

Since the study results were presented, various other options have been discussed including ammonia as:

- a fertilizer;
- a hydrogen carrier;
- a maritime fuel, or
- ammonia transported to an industrial ammonia producer, labelled as "green ammonia".

Study conclusions

In the cases studied, the production of ammonia using (excess) renewable energy cannot compete with existing fossil based ammonia production. Drastic changes in the production cost of electrolysers to less than 70% of the reference price of 1000 €/kW, supply of renewable energy and a global increase in CO_2 price are needed to make this production route competitive.

Reduction of the CO_2 footprint of ammonia by producing it via electrochemistry rather than by the conventional process from natural gas is only possible if the electricity used is renewable. For grid owners, an advantage of producing ammonia with wind and solar power will be that investments in the grid can be reduced. If the share of wind and solar power increases without demand side management and without energy storage the investment requirements in increasing grid capacity will be substantial. The combination of demand side management and local energy storage can contribute to the reduction of the necessary investments in the grid. Power-to-ammonia enables energy to be transported and stored for periods of days, weeks or even months.

Electricity storage in the form of ammonia will add cost to the overall electricity system. However, large scale CO_2-neutral energy storage will introduce important benefits for the system, enabling a further penetration of intermittent renewable electricity sources, enabling further electrification and providing CO_2-free ammonia as a fuel and chemical commodity.

At deep decarbonisation, flexible electricity production based on application of fossil fuels during periods when supply from intermittent renewable sources is insufficient, cannot be applied unless carbon capture and storage will be deployed. In other words, the initially more costly use of ammonia as a CO_2-neutral fuel for electricity production becomes very attractive and one of the few realistic alternatives.

The installation of additional renewable wind and solar capacity on its own is not sufficient to meet ambitious CO_2 reduction targets of 80-95% by 2050. Large scale storage and import of renewable electricity is required to meet these targets. Power-to-ammonia enables both storage and import and has the potential to contribute substantially to CO_2 reduction targets, offering flexibility for the electricity system and allowing for an alternative to investments in electricity grid infrastructure.

References

3. ISPT "Power to Ammonia" – Feasibility study for the value chains and business cases to produce CO_2-free ammonia suitable for various market applications.