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Producing ammonia and fertilizers: new opportunities from renewables

Thanks to the recent cost reductions of solar and wind technologies, ammonia production in large-scale plants based on electrolysis of water can compete with ammonia production based on natural gas, in areas with world-best combined solar and wind resources. This concept note explores these opportunities, which could help significantly cut global greenhouse gas emissions

Over 60 million tonnes of hydrogen gas or dihydrogen (H₂) are produced annually for industrial purposes, with roughly one half being used for producing ammonia. Ammonia (NH₃) is an essential precursor of fertilizers, bringing nitrogen from the air to the soils and plants. It has several other uses in various industries – to manufacture explosives, cleansers, as a refrigerant, etc. The second large use of dihydrogen is in refineries.

Currently over 95% of industrial hydrogen is produced from fossil fuels: from natural gas with steam methane reforming (SMR), from cracking oil products in refineries, and from coal gasification, essentially in China. The remainder is produced from electrolysis. Ammonia production alone is responsible for about 420 million tonnes of CO₂ emissions, over 1% of global energy-related CO₂ emissions.

The recent and drastic cost reductions of solar and wind power open new possibilities for competitive ammonia production in large-scale plants. Indeed, the cost of fuel (as fuel and feedstock) is the main cost factor in ammonia production. Where solar or wind resources are excellent, the cost of electricity from solar or wind power plants could be at or below \$ 30/MWh¹, as suggested by the prices recently announced for new-built wind farms in Morocco and solar plants in Chile and Dubai. At such prices and with sufficient load factors, the cost of hydrogen would not exceed \$ 2/kg and could compete with SMR (see Box 1).

Storing ammonia for long time, and shipping it on long distance, on sea or on land through pipelines, are much more convenient than storing and shipping hydrogen. Therefore, NH₃ synthesis is sited next to hydrogen-producing units in ammonia plants. These integrated ammonia plants are large to benefit from significant economies of scale.

After electricity prices and plant size, high load factors would be the next important factor for ammonia plants. This is another reason why new opportunities for ammonia production based on solar and wind must be considered in best resources areas, where load factors can reach up to 3 000 full load hours (FLH) for solar photovoltaics (PV) and up to 5 000 FLH for wind turbines. Variability of combined solar and wind resources can be addressed relatively easily with high load factors.

¹ All \$ in this note are US dollars.

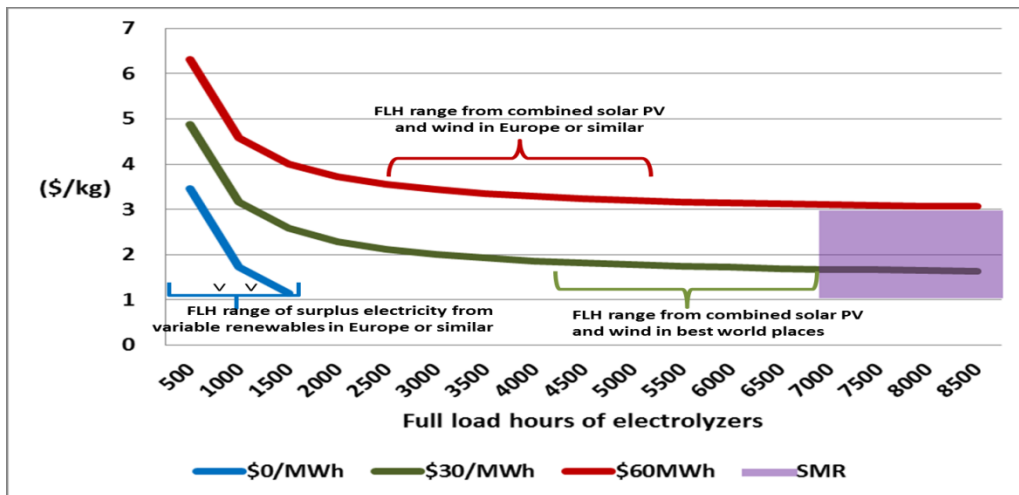
Box 1: The cost of hydrogen from electrolysis of water in various situations

Figure 1 shows the costs of producing hydrogen for different electricity costs and load factors (expressed in full load hours per year). Large-scale (e.g. 400 MW) alkaline electrolyzers now cost \$ 450/kW (NEL, 2017).

The purple rectangle shows the cost range of H₂ from SMRT with a large range of variations, due to large disparities in the prices of natural gas, for its usual range of utilisation durations. Carbon capture with 90% efficiency would increase the cost of hydrogen by \$ 0.67/kg H₂ (~\$ 75/tCO₂, IEAGHG 2017).

The green line reveals that in countries with very good combined solar and wind resources (and maybe in some cases with off-shore wind alone), renewable-energy based hydrogen generation can compete with SMR.

Figure 1: Cost of hydrogen from electrolyzers at USD 450/kW Capex for different electricity costs and load factors.



Assumptions: Capex of electrolyzers \$ 450/kW (NEL 2017), WACC 7%, lifetime 30 years, efficiency 70% (IEA 2015); cost of hydrogen from SMR \$ 1 to 3/kg H₂, depending on natural gas prices.

The red line shows the cost of H₂ with electricity at \$ 60/MWh, which currently characterises best opportunities in countries with good but not excellent resources, such as European countries. A combination of solar and wind in Europe would result in a cost of hydrogen ranging from \$ 3 to \$ 4/kg.

The blue line illustrates the case of “free” surplus variable renewable electricity from grid, which could otherwise be curtailed. Assuming that large-scale electrolyzers could be utilised in these circumstances to feed a large-scale ammonia plant, which is far from certain, they would need to run around 1000 hours a year to manufacture hydrogen at a cost of about \$ 2/kg H₂.

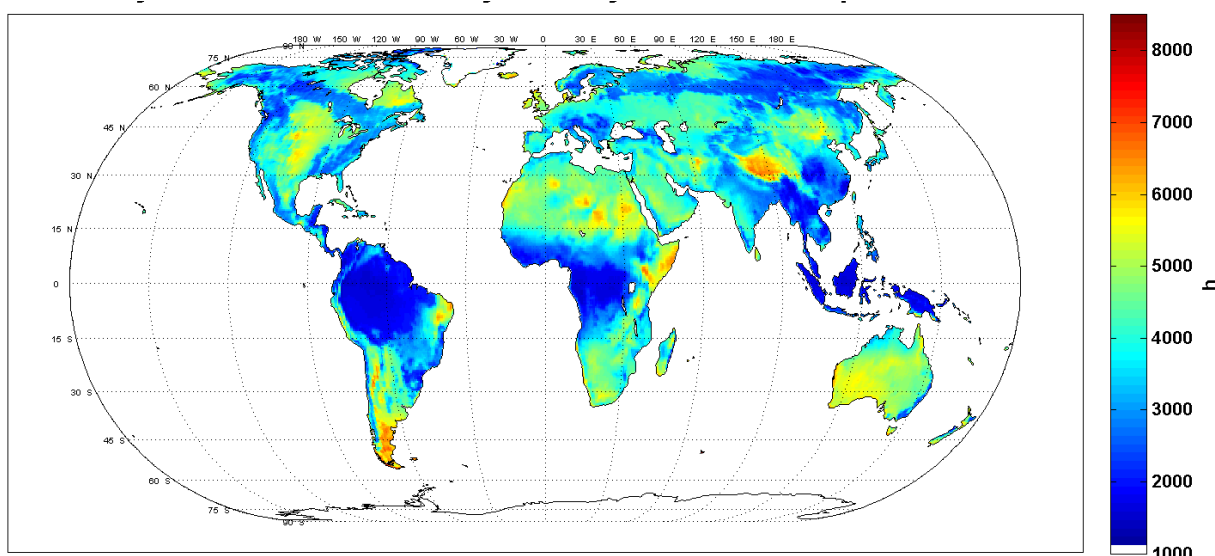
Box 2: Ammonia manufacturing based on hydropower

Areas with abundant hydropower, (and/or geothermal resources) such as Iceland, Norway and others are possible choices for siting electrolyzers. Indeed, up to the 1960s, most fertilizers sold in Europe came from hydropower-based electrolysis and ammonia production at Vemork and Rjukan in Norway. Low gas prices and emergence of SMR led to close these plants as carbon emissions were not considered. Of the few all-electric ammonia plants that have remained until recently, the largest, in Egypt, is now being converted to natural gas reforming, mostly to “free up” more electricity for the growing needs of the country. Forthcoming hydropower plants in Africa may provide large output in excess of regional needs, providing new opportunities for manufacturing NH₃ and fertilizers in sub-Saharan Africa.

While similar H₂ prices could be reached in countries with lower-quality renewable resources if “surplus” electricity is considered free, it would not likely be available in sufficient quantity to run large-scale all-electric ammonia plants. Furthermore, issues arising from the true intermittency of this surplus electricity supply from variable renewables could pose intractable issues to ammonia plants.

Based on extensive wind and solar geospatial data, Figure 2 below reveals vast areas (from light green to yellow and orange) where a combination of 1-axis sun-tracking solar PV capacities and modern wind turbines combined would supply a load with load factors over 50%, and up to 6000 FLH or more in the few red areas. This would apply, for example, to a 100 MW electrolyser supplied with 100 MW wind and 100 MW solar. The sum of the respective capacity factors of solar and wind has been duly adjusted for overlap and surplus in this calculation made on an hourly basis, all year round. Complementing this mix with some cheap, dispatchable hydropower would likely have merits but is not considered here.

Figure 2: Hybrid solar and wind load factors adjusted for overlap



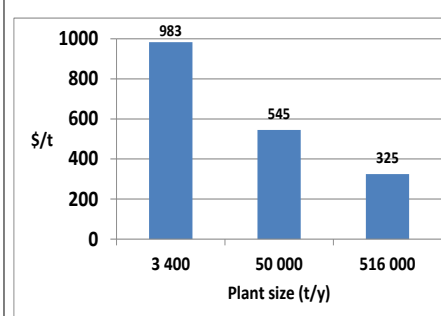
Source: Adapted and based on Fasihi et al. 2016

Ammonia production

Since the 1920s the production of NH₃ has been based on the Haber-Bosch process to synthesize nitrogen and hydrogen under pressures of 10 to 25 MPa (100 to 250 bars) and temperatures of 400-500°C over an iron catalyst. The synthesis reaction is exothermic, and no heat needs to be delivered to the synthesis loop. Most NH₃ plants produce 300 000 to 600 000 t/y, some up to 1 Mt/y. They are designed to be available for 330 days, or about 8000 hours per year.

NH₃ plants emit on average over 1.6 t CO₂/t NH₃ using natural gas, 2.5 t CO₂/t NH₃ using naphtha, 3 t CO₂/t NH₃ using heavy fuel oil, and 3.8 t CO₂/t NH₃ using coal (IFA, 2009). In some plants, however, a

Figure 3: Costs of ammonia from SMR (at natural gas price \$ 5/MMBtu)



Source: arpa-e, 2017

fraction (up to 40%) of the CO₂ produced is captured and used in combination with NH₃ to manufacture urea, the simplest safely-handled fertilizer.

Electrolysis of water is a well-known alternative to using fossil fuels to produce hydrogen – and so far hydropower has run it (see box 2). Despite being largely modular, electrolyzers exhibit economies of scale as the compressors, gas holding tanks, transformers and balance of plant equipment scale up (Morgan, 2013). Capital costs for NH₃ plants vary even more with scale, exerting a considerable influence on the production costs (see Figure 3).

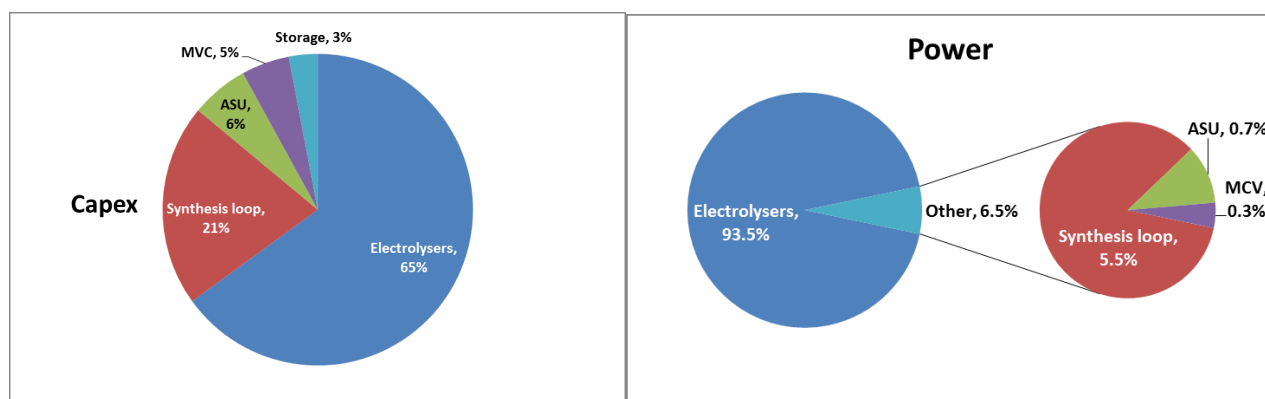
The only raw inputs for an all-electric ammonia plant, besides energy, are air and water – over 1.5 t H₂O per t NH₃. Air, made of 78% dinitrogen (N₂) is the source of nitrogen. If freshwater is not an option, plants located near seashore could use desalinated seawater. Seawater intakes and rejection of brines in the ocean are the most significant issues to consider from an environmental standpoint.

In natural gas-based ammonia plants, besides generation of hydrogen all sub-systems are electric (Morgan, 2013) and consist of the following:

- *Cryogenic air separation units*, for producing nitrogen
- *Centrifugal compressor* running the synthesis loop (Haber-Bosch process)
- *Mechanical vapor compression (MCV)*, for desalinating seawater (if needed), the most likely large- scale option to provide water with sufficient degree of purity to feed electrolyzers.

For all-electric plants, alkaline electrolyzers currently represent the only commercial option at scale. Electrolyzers would represent about two-thirds of the total capital expenditures of an electric ammonia plant and absorbs over nine tenths of the electricity it consumes. Figure 4 below provides for indicative breakdowns of capital expenditures and power needs (in either load or annual energy) of a baseload electric plant of 10 000 t/y.

Figure 4: Indicative breakdowns of an all-electric ammonia plant capital expenditures (left) and its power needs (right)



Source: Morgan, 2013

Solid oxide electrolyser cell (SOEC) technology, working at high temperatures, offer the best prospects for efficiency improvements and cost reductions but are not yet commercially available. Proton exchange membrane (PEM) technology for electrolyzers is not yet available at the required scale but would presumably offer the most flexible operations.

Ammonia production from variable renewables

Best resource areas might be remote from densely populated areas and therefore be isolated from, or weakly connected to, main electric grids. Hence large scale all-electric ammonia plants, primarily run by dedicated new-built assets, would most likely not be connected to the country's grid, or only with a connection that might be much less in capacity. Furthermore, if solar and wind capacities are an important part of the power mix in the country, the country and the NH₃ plants may find each other in synchronism with excess power or deficit. For both reasons, the plants cannot be designed for steady-state operations expecting to use the country's power system as a convenient storage.

The variability of power creates various challenges. Alkaline electrolyzers can operate between 20% and 100% of their nominal load. ASU and MCV consumption units need small amounts of power and their outputs are storable. The synthesis loop, however, would best work with continuous operations and requires continuous feed-in – but it only consumes about 5% of the total.

A plant run by solar and wind, or in some cases by wind power alone, with capacity factors of 5 000 to 7 000 full load hours (FLH), will have 25% of its load available most of the time, and times with less than 5% will be relatively rare – some hundreds hours². Short-time storage of compressed hydrogen and nitrogen could be extended somewhat to ensure continuous operations of the synthesis loop. The added cost would be small as the H₂ need to be compressed anyway before the synthesis loops.

A large ammonia plant aimed at producing 500 000 t/y would consume about 4.8 TWh annually for producing over 88 000 t H₂ and running all sub-systems. Assuming 6 000 FLH for combined solar and wind power capacities, the required deployment could be, for example, of 785 MW wind turbines and up to 785 MW solar PV plants, for 735 MW electrolyzers.

These are, however, rough indications. Solar capacities may be adjusted downward to minimise critical overlap with daytime wind power. Only detailed, specific studies with hourly output of solar and wind can help optimise the respective capacities of solar, wind and electrolyzers, the design of the NH₃ plant, the means – battery, grid connection, or (NH₃/H₂) back-up – to ensure steady-state operation of the synthesis loop, and the capacity of the latter.

Alternative to the Haber-Bosch process, technologies of direct electro chemical ammonia synthesis in molten-salt electrolytes and on membranes are still under development. In transferring hydrogen ions from water or steam to nitrogen, they would bypass the formation of dihydrogen molecules, potentially reducing electricity consumption by up to 30%.

Fertiliser markets and beyond

While overuse of fertilizers in some places has led to soil pollution and in some case damaged water systems, in most parts of sub-Saharan Africa the under-use of fertilizers is leading to land degradation and declining yields. Global ammonia consumption (180 Mt/y) is expected to increase by ~50% by 2050. A half-million tonnes NH₃ plant represents less than 0.3% of the current global demand, and it

² On the contrary, a plant only run on solar PV faces a greater challenge, as it will have no power at all at least half of the time. The technicalities and economics of solar-only ammonia plants are not considered here.

can be produced at a lower price than natural gas-based ammonia in many places. As global population grows, food quality improves and the world strives for decarbonising its economy, there will be growing room for emissions-free ammonia in the fertiliser industry.

However, the story may not stop here. Countries with rich renewable energy resources will possibly see growing opportunities to providing renewable energy and renewable-based, hydrogen-rich chemicals to less-resource-rich countries striving to decarbonise their economies while improving energy security in reducing dependence on fossil fuel producers. In particular, one major option for green iron and steel making, a major source of CO₂ emissions today, would be the use of hydrogen as a reducing agent of iron ores, adapting from the current technological route of direct iron reduction.

NH₃ is not the sole possible energy carrier that could serve such purpose, but it has interesting features in this respect. It contains no carbon atom. As it liquefies at -33°C, while H₂ liquefies at -253°C, NH₃ is much less costly to store for a long time – e.g. \$0.5/kg H₂ for NH₃ vs. \$15 kg H₂ for H₂ for half-year storage – and at least three times less costly to ship on sea or on land (Bartels & Pate, 2008). NH₃ is an already well-established global industry, with a decades-long record of safety, and it can serve a variety of end-uses in all sectors, either directly as a precursor, a reducing agent or a fuel, or indirectly as a simple renewable-based H₂ carrier to facilitate shipping and storage.

References:

- Advanced Research Program Agency – Energy (arpa-e)(2017), *Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids (REFUEL) Program Overview*, Washington DC.
- Bartels, Jeffrey R and Michael B. Pate (2008), *A feasibility study of implementing an Ammonia Economy*, Iowa State University, December.
- Fasihi, Mahdi, Dmitrii Bogdanov and Christian Breyer (2016), Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants, *Energy Procedia* **99**: 243-268.
- International Energy Agency (IEA) (2015), *Technology Roadmap Hydrogen and Fuel Cells, Technical Annex*, IEA/OECD Paris.
- International Fertiliser Association (IFA)(2009) *Energy Efficiency and CO₂ Emissions in Ammonia Production*, Paris, Dec.
- IEA Greenhouse Gas Technology Collaboration Programme (IEAGHG) (2017) *Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS*, IEAGHG Technical Report 2017-02, February, Cheltenham, UK.
- Morgan, Eric R. (2013), *Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind*, Dissertations. 69, University of Massachusetts – Amherst.
- NEL (2017), Private communication.

Abbreviations, acronyms and units

°C: Celsius degree

ASU: air separation units

Capex: capital expenditures

CO₂: carbon dioxide

FLH: full load hours

H₂: dihydrogen (casually, hydrogen)

H₂O: water

kg: kilogram

kW: kilowatt

kWh: kilowatthour

MCV: mechanical vapor compression

MBtu: million British thermal units

MPa: megapascal (million pascal)

MW: million watt

MWh: Megawatthour (thousand kWh)

N₂: dinitrogen (casually, nitrogen)

NH₃: ammonia

SMR: steam methane reforming

t/y: tonne per year

TWh: terawatthour (billion kWh)

WACC: weighted average capital cost