HyDelta 3

WP3b – NH_3 Future Proof Commodity: Direct Utilization and Conversion to Hydrogen

D3b.1 – Factsheet Ammonia Cracking Technologies

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Executive Summary

Hydrogen can be imported from overseas in the form of ammonia. The ammonia needs to be reconverted to hydrogen in so-called cracker plants. The present study explores the possibility to dynamically adapt the production rate of these cracker plants in order to match time-varying hydrogen demand. Operated in this way, the crackers could potentially offer a control lever to enhance the stability of the entire energy system, similar to what can be achieved with underground hydrogen storage. A review of the scientific literature and interviews with several cracking technology providers reveal that there are no technological obstacles foreseen to operating cracker plants at dynamic production rate: projected ramp rates are 3% per minute, and stable operation is expected to be possible down to 20% or even 10% of the peak capacity of the plant. Since the levelized cost of hydrogen produced from cracking ammonia is projected to be dominated (80%-90%) by the cost of the ammonia feedstock rather than the CAPEX of the cracker plant, building in some headspace in the cracker capacity does not seem economically impossible. The detailed techno-economical trade-off between hydrogen storage volume and cracker overcapacity should be explored in a future study.

Samenvatting

Waterstof kan worden geïmporteerd per schip in de vorm van ammoniak. De ammoniak moet worden omgezet in waterstof in zogenaamde ammoniakkrakers. Deze studie onderzoekt de mogelijkheid om de productiesnelheid van de ammoniakkrakers dynamisch aan te passen aan de variabele waterstofvraag. Daarmee zouden krakers mogelijk kunnen worden gebruikt als actuator om het energiesysteem dynamisch te stabiliseren, vergelijkbaar met wat kan worden bereikt met ondergrondse waterstofopslag. Een literatuurstudie en gesprekken met diverse technologieleveranciers tonen aan dat er geen technologische obstakels te verwachten zijn om krakers op deze wijze te opereren: de verwachting is dat de productiesnelheid kan worden verhoogd of verlaagd met 3% per minuut, en dat krakers stabiel kunnen draaien tot 20% of zelfs 10% van hun maximale productiesnelheid. De verwachting is dat de genivelleerde kosten van waterstof geproduceerd uit ammoniak voor het grootste deel (80%-90%) uit de kosten van de ammoniak zullen bestaan – CAPEX voor de ammoniakkraker is minder belangrijk. Daarom is het inbouwen van overcapaciteit in het productievolume van de kraker economisch wellicht haalbaar. De precieze techno-economische afweging tussen het volume waterstofopslag en de overcapaciteit van ammoniakkrakers moet nader worden onderzocht.

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1. Introduction

In **Figure 1.** System view of a potential future Dutch energy system, a model of an energy system is shown. Electricity can be imported and exported. It can also be generated locally by renewable sources and by hydrogen power plants. Hydrogen is imported in the form of ammonia, and also generated locally by electrolysis. The main figures of merit of the system are:

- Maximum security of energy supply to the end users in various forms;
- Minimal cost;
- Minimal environmental impact.

The H_2 storage acts as an energy buffer for security of supply – it can absorb H_2 if there's a surplus in electricity and release H_2 if electricity is scarce. **Figure 1** suggests that this balancing function can potentially be fulfilled by NH_3 crackers as well. The cracker production rate should then be dynamically varied around the average to match varying electricity (and hydrogen) demand. This is outlined in the following paragraph.

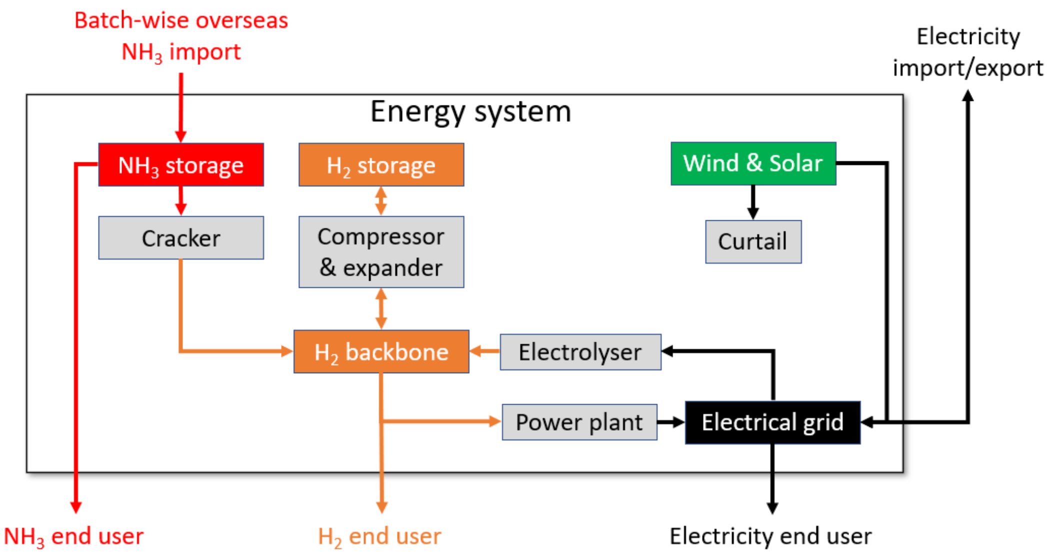

Figure 1. System view of a potential future Dutch energy system

When renewable electricity supply is lower than average, the electrolysis plants are idle, while the power plants are guzzling hydrogen from the backbone. Therefore, the cracker production rate should be increased to a higher-than-average rate to boost the pressure in the backbone. Conversely, when renewable electricity supply is higher than average, the hydrogen power plants will be idle, while the electrolysers are flooding the backbone with hydrogen. Therefore, the cracker production rate should be dialed down to below-average value to prevent excessive pressure in the backbone.

By operating cracker plants in this way, one could opt for smaller H_2 storage capacity. The flipside is that the installed capacity of cracker plants needs to be increased, and the average load factor of the crackers would be lower. This tradeoff is illustrated in **Figure 2.**

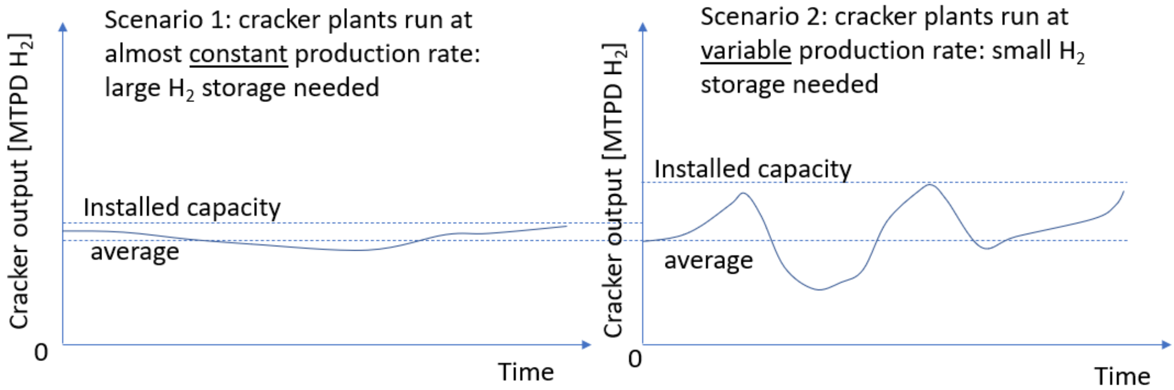

Figure 2. Running a cracking plant at variable production rate. MTPD stands for Metric Tonnes Per Day.

The problem of striking an optimal balance between H_2 storage and cracker over-capacity is beyond the scope of this report. In the following, we limit ourselves to identifying some economic and technological constraints imposed by the NH_3 crackers, which should be useful input for a future trade-off analysis. We wish to address the following technical and economical questions about such plants:

- What is the minimum load factor at which a cracker plant can be run stably? At what rate can load factor be ramped up and down?
- If dynamic production rate is achieved by switching off/on entire production trains: what is the typical production rate per train foreseen by technology providers? How long can a train be kept at ‘hot standby’ (zero production rate)? How long does a ‘cold start’ take?
- What are the implications for the levelized cost of hydrogen (LCOH) if a cracker is run at low load factor?

2. NH_3 Cracker Plants: Fact Sheet

First, we need to specify what technology a future NH_3 cracker plant might employ. Haldor Topsoe (CEL presentation 4a (ammoniaenergy.org); slide 6) talks about three cracking technologies:

1. Auto-thermal ammonia cracker
2. Electrically heated ammonia cracker
3. Fired ammonia cracker (like traditional SMR; Figure 3)

We descope technology (1) because it has a low TRL of 4 [1], and during interviews with technology providers we learned that it has sub-optimal H_2-recovery. We descope technology (2) because the electricity consumption of an industrially sized cracker plant would be so high that a dedicated powerplant would be needed. Running this dedicated powerplant on hydrogen, and then using the electricity in the ammonia cracker would likely be less energetically efficient than simply using a hydrogen fired furnace in the cracker. Running the cracker plant on renewable electricity would preclude adapting hydrogen production rate to match demand, which is the main motivation for the present study. We shall therefore limit our scope to technology (3), where the fuel is understood to be NH_3 or H_2. **Figure 3** gives a system view of this type of cracker plant.

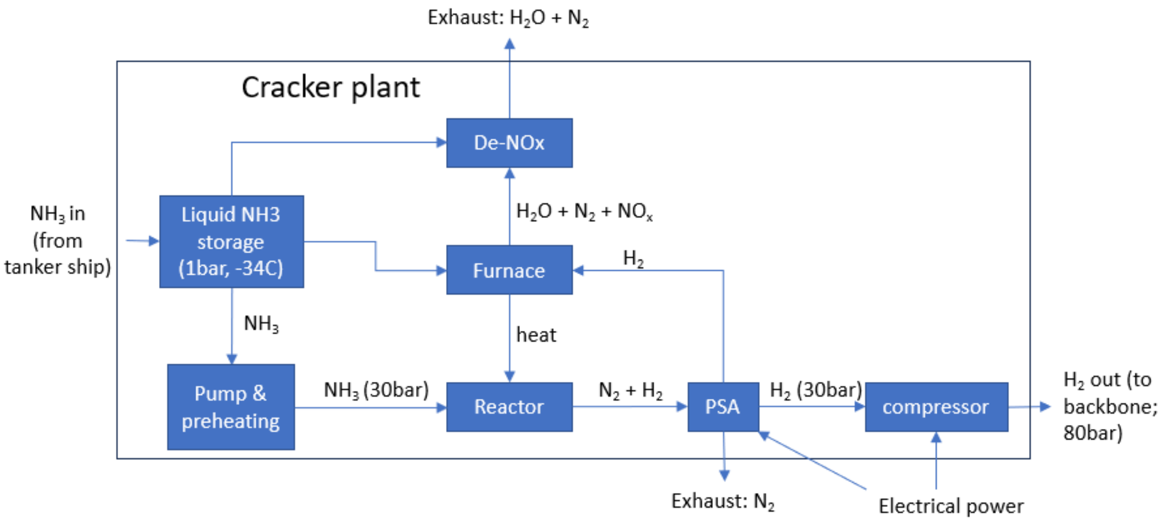

Figure 3. System view of a NH_3 or H_2 fired SMR-type cracker plant.

Table 1. summarizes the results of a survey of the publicly available literature and interviews with various cracker technology providers.

Table 1: Fact Sheet on H_2/NH_3 fired SMR-like ammonia crackers.

Description	Unit	Value
Technological Readiness Level	TRL	8-9 [1]
Max H_2 output per train (MTPD)	Tonne H_2/Day	275 [2]-1200 [3]
NH_3 in per H_2 out	Tonne NH_3/Tonne H_2	7.2 [4, 5] (– 8.7 [6])
Electrical power consumption	MWhe/tonne H_2	0.99 [7]
Minimum turn-down ratio of a train	-	10% - 20% [8]
Max ramp rate of a train	%-nameplate / minute	3%/min [9]
Max duration of hot standby at 0% production rate	Days	1-2 [2]
Duration of cold start	Days	1 [10]
Purity of H_2 at output	Mol%	>99.9 [11]
Footprint per nameplate capacity	m^2/MTDP H_2	67-150 [11]
Plant CAPEX per nameplate capacity	MEUR/MTPD H_2	0.13-0.63 [12]
CAPEX for NH_3 storage per nameplate capacity	MEUR/MTPD H_2	0.032 [13]
Projected cost of green NH_3 feedstock in 2040	EUR/kg.NH_3	0.3 [14]-0.57 [6]

3. Conclusions and Recommendations

The most important conclusion is that H_2 production rate of SMR-like NH_3 crackers can be varied between at least 20% and 100% of name-plate capacity within half an hour. So, from a technological perspective cracker plant can clearly be used to balance the H_2 backbone pressure, even on the fastest timescales of interest. This gives designers of the energy system an extra parameter to play with: over-dimensioning the cracker plant fleet (time-averaged load factor lower than 1) allows achieving security of supply with a smaller H_2 storage capacity.

Let us briefly consider the dependence on levelized cost of hydrogen (LCOH) (**Fig. 4**).

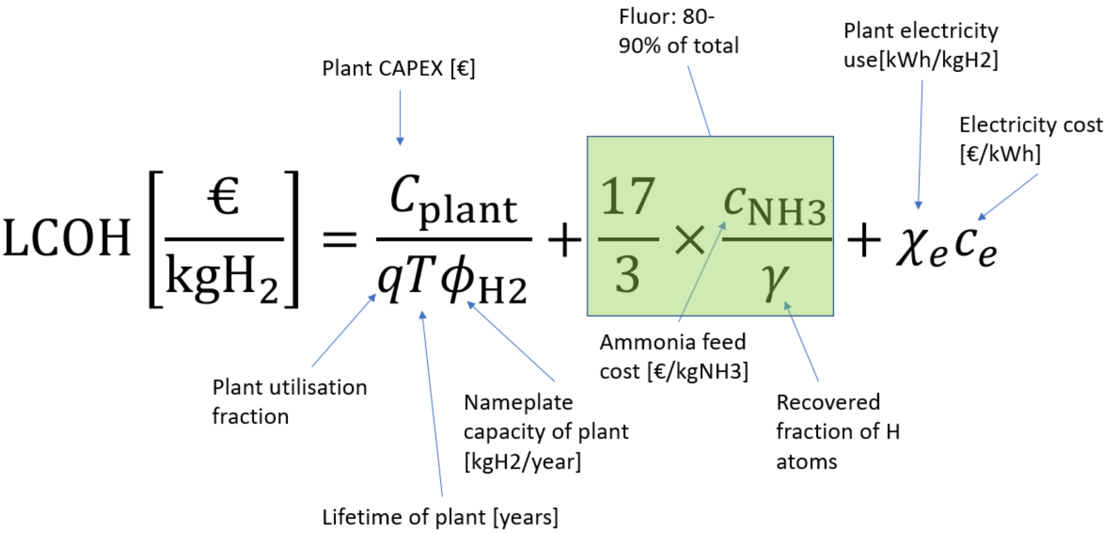

Figure 4. Equation for Levelized Cost of Hydrogen

Rewrite the CAPEX contribution as $c = C_{plant}/T\phi_{H2}$, and the marginal contribution (OPEX) as $m = \frac{17}{3} \times \frac{c_{\mathrm{NH3}}}{\gamma} + \chi_e c_e$, to get $LCOH = cq^{-1} + m$.

Now, Let's define $f = \frac{m}{c+m}$, so that $LCOH = c\left(q^{-1} + \frac{f}{1-f}\right)$.

In ref. [12] we read that for $q \approx 1$ the marginal costs (NH_3 feedstock) constitutes 80-90% of LCOH.

This implies $0.8 < f < 0.9$. A cursory analysis of the cost estimates in **Table 1** in fact leads to f even closer to one. **Fig. 5**, shows the q dependence of LCOH for a very conservative $f = 0.8$. It may be seen that running at q=0.6 only incurs a ~12% increase in LCOH. In a future project, this cost picture could be compared with the cost of H_2 storage, to determine an optimal division of flexibility between cracker and H_2 storage. A starting point could be ref. [15]

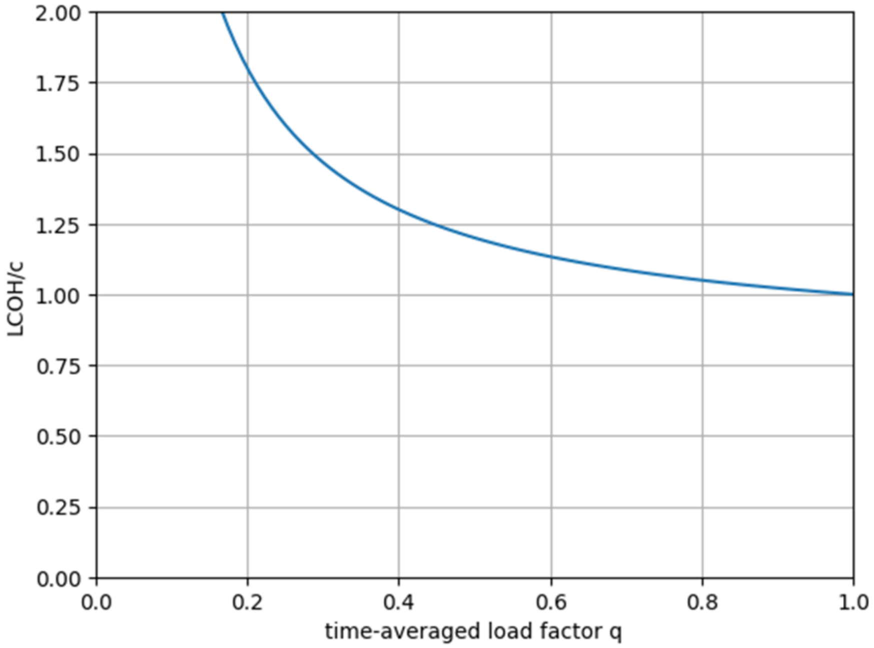

Figure 5: Levelized cost of H_2 produced with cracker plant as function of load factor q.

References

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[2] “Interview with various Technology providers”.

[3] KBR, “H2ACT (SM) : Empowering Energy Transition,” 2022.

[4] H. Green, “North of England,” https://www.h21.green/app/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf.

[5] IRENA., “Global Hydrogen Trade to Meet the 1,5C Climate Goal,” Figure 2,15, 2022.

[6] Ecuity, Engine, STFC, Siemens, “Ammonia to Green Hydrogen Project,” https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/880826/HS420_-_Ecuity_-_Ammonia_to_Green_Hydrogen.pdf.

[7] “Neglect energy requirement for separation of H2 and N2. Assume that compression of H2 from 30bara to 80bara is done fully with externally supplied electricity. Aspen+ calculation results in 0.547 MWh/t H2 for compressor and 0.44 MWh/t of cooling duty;”.

[8] “Interview with technology providers. Limiting factor in minimum turn-down ratio is the delicate control of the valves of the burners required to prevent hot spots in the catalyst tubes while maintaining overall temperature.”.

[9] “Interviews with technology providers. Statement Duiker: can ramp from minimum turn-down of 15% up to 100% in half an hour and vice versa. Statement KBR: today 0.3%/min, but with advanced controlers 5%/min should be possible.”.

[10] Interview with KBR: Start-up from cold is 1 day, cooling down of furnace is ½ day. You should avoid often cold start-ups because of material stresses.

[11] Large Scale Industrial Ammonia Cracking Plant - Flour Report for PoR, "1e6 tonnes per year of H2 production fits in 2e5-4.5e5 m2".

[12] F. 2. IRENA, “Global Hydrogen Trade to meet the 1,5C Climate Goal,” ; assume plant capacity >500 MTPD of H2, 100-500 USD/kWH2. Use 1MTPD = 1.39MW (LHV of H2 is 120 MJ/kg) and 0.91 USD/EUR, 2022.

[13] 9. IRENA - Figure 2, “Global Hydrogen Trade to Meet the 1,5C Climate Goal: Technology Review of Hydrogen Carriers,” Assuming 750 USD/tonne of NH3. storage for 7days operation of a 250 USD/kWH2 cracker [use LHV of H2]; 80% H-recovery fraction, 2022.

[14] Z. Cesaro and Matthew Ives et al., “Ammonia to Power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants,” *Elsevier,* vol. 282, no. Part A, 2021.

[15] “https://energy.nl/wp-content/uploads/h2_large-scale-underground-storage-salt-caverns_2021-12-16-093010_lnyn-9.pdf”.