AMMONIA ENERGY
ASSOCIATION

CRACKING AMMONIA — PROJECT DEFINITION

Summary

The AEA intends to publish a whitepaper that will provide an accessible and authoritative introduction to the concept of cracking ammonia in the context of a sustainable economy.

This public document will contain an overview of available and in-development technologies, describe the market applications they can address, and provide a robust literature review as a resource for further information. The whitepaper will be illustrated with industry case studies that demonstrate relevant technologies and applications, and it will contain techno-economic data that can support the integration of ammonia cracking into energy systems modelling, policy development, and investment planning.

Strategic objectives

This whitepaper fits into the Knowledge Stewardship pillar of the Ammonia Energy Association, as it fills a knowledge gap regarding ammonia decomposition technologies and applications. The academic literature mainly discusses technologies not commercially applied, while detailed information about commercial technologies is often not publicly accessible. The general understanding of the role for cracking ammonia in a sustainable economy is therefore limited, and a clearer vision of the decarbonization opportunities for cracking ammonia will create value for a wide spectrum of AEA members operating across multiple sectors.

Furthermore, this whitepaper supports the AEA's Collaboration pillar, as it will be a member-led process drawing input from AEA members via a dedicated working group, strengthening member networks and cooperation. The publication also allows the AEA to showcase the technologies and projects of its members.

Working Group establishment

The AEA is establishing a Cracking Ammonia Working Group, which will be responsible for directing the AEA staff and academic partners who will write this report. The Working Group will define the structure and content of the report, oversee the development of the report, and provide final approval of the report and the conclusions and positions it contains. Working Group participants may also wish to contribute text, images, and data, and may want to have a role in disseminating the finished report in public.

All AEA Members are entitled to participate in this working group and external experts will be invited to contribute as appropriate. The Working Group will disband upon completion of the report, estimated to be before the end of October 2022.

AMMONIA ENERGY
ASSOCIATION

Working Group schedule

All Working Group input can be provided through e-mail or via direct engagement with AEA staff, but the workplan is structured around five Working Group meetings, with the following proposed schedule:

- Meeting 1: **Kick-off and Project Definition**. Early July.
  - Before attending the meeting, members are requested to fill in a questionnaire to:
    - state any content that they want to see included or emphasized
    - indicate their knowledge on specific technologies
    - propose case studies.
  - During the meeting, we aim to:
    - amend / approve this Project Definition
    - identify missing people/organizations who should be invited to participate
    - identify data requirements and sources
    - assign any specific tasks to working group participants.
- Meeting 2: **Data sets and initial conclusions**. Early August.
  - After the first meeting, AEA staff will:
    - reach out to missing people/organizations
    - compile data and undertake initial analysis
    - draft an outline of conclusions supported by the data
    - develop a marketing and communication plan for the report launch
    - distribute these items to participants for written feedback.
  - During the meeting, we aim to:
    - identify any missing data
    - achieve consensus on the best presentation of data
    - achieve consensus on the outline of conclusions.
- Meeting 3: **First Draft**. Late August.
  - Before the meeting, AEA staff will:
    - draft a first version of the whitepaper
    - distribute the manuscript to participants for written feedback.
  - During the meeting, we aim to:
    - discuss significant feedback
    - work to achieve consensus or identify issues requiring attention
    - identify any missing content (text, data, imagery).
- Meeting 4: **Final draft and launch plan**. Late-September.
  - Before the meeting, AEA staff will:
    - draft a finished version of the whitepaper, including all data and images
    - distribute the manuscript to participants for written feedback.
  - During the meeting, we aim to:
    - discuss significant feedback
    - work to achieve consensus or identify issues requiring attention
    - approve release of the report, following final revisions, to the graphic designer
    - approve final details for marketing and communications activities.

AMMONIA ENERGY
ASSOCIATION

Project description

Ammonia decomposition technology for hydrogen production recently gained attention with various large-scale project announcements, e.g. in Rotterdam and Wilhelmshaven. Furthermore, partial ammonia cracking may support decarbonization in power generation and transportation applications.

The questions this report aims to answer include:

- What is ammonia cracking and why is it important for decarbonization?
- What is the technology readiness level of various ammonia cracking and hydrogen purification technologies? What are the available and announced technologies of AEA members?
- What are historical and future applications for ammonia decomposition technologies? How do different technologies measure up against the operational requirements of different applications?
- What are the recent developments and future announcements/expectations? How does this translate to market size?
- What are the economics of cracking ammonia? What variables are important to understand different technologies or applications for cracking ammonia?
- What recommendations does the AEA have for industry, academia, and policy-makers regarding cracking ammonia?
- Who can you contact if you want an ammonia cracker? Where can you find more information?

Proposed Charts and illustrations

- **Introduction**: Ammonia decomposition requirement for various applications. Requires input on H_2 purity requirements for various applications.
- **Technology**: Catalytic ammonia decomposition technologies. Requires input on technologies for ammonia decomposition.
- **Technology**: Large-scale ammonia decomposition system for purified hydrogen production. Requires member consultation on a typical ammonia decomposition plant layout.
- **Technology**: Catalytic membrane system for ammonia decomposition. Requires member consultation on a typical ammonia decomposition plant layout.
- **Technology**: Preferred catalysts over various temperature regimes. Requires member consultation regarding the available ammonia decomposition catalysts and their operating regimes.
- **Technology**: Common ammonia removal technologies & hydrogen purification technologies. Requires input on available technologies and attainable product specs.
- **Economics**: Total capital investment for various hydrogen capacities. Requires literature data at various ammonia decomposition plant sizes.
- **Economics**: Levelized cost of hydrogen from ammonia decomposition. Requires literature data at various ammonia decomposition plant sizes, and formulas for calculating a levelized cost of hydrogen. Requires future low carbon ammonia prices.

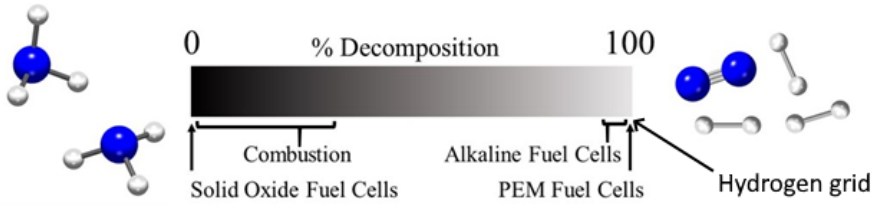
AMMONIA ENERGY
ASSOCIATION

Proposed outline of the whitepaper

1. Executive summary

2. Background

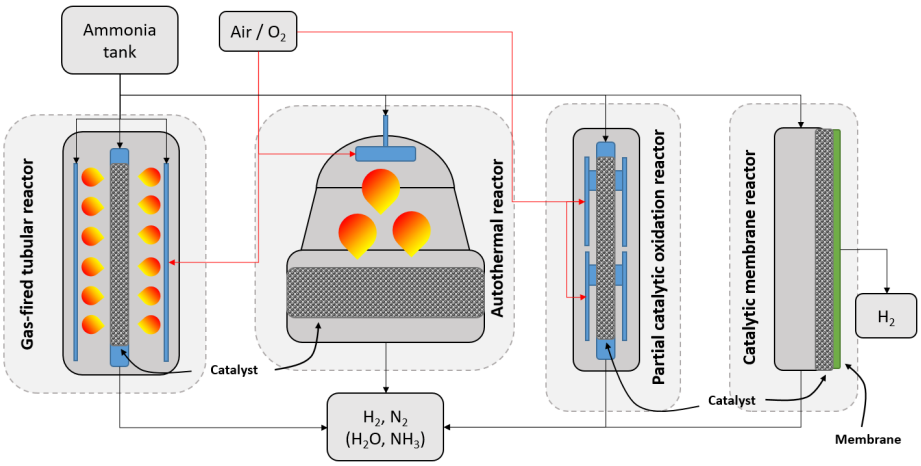
- Ammonia as fuel and hydrogen vector, a carbon-free energy commodity
- Ammonia used directly where possible, partial cracking to support combustion, cracking to pure hydrogen only when necessary
- Applications / markets:
    - ammonia for gas grid hydrogen (Europe: Rotterdam, Wilhelmshaven),
    - starting fuel for spark ignition engines or gas turbines,
    - fuel cell applications (transportation and off-grid)
- Requirements for hydrogen purification, hydrogen pressure, hydrogen recovery
- Announced projects
- Optimal applications for ammonia decomposition.



3. Ammonia decomposition technologies

Technology overview:

1. ammonia-fired tubular ammonia decomposition,
2. autothermal operation,
3. Partial catalytic oxidation reactor,
4. catalytic membrane reactor.



Commercial practice:

- small-scale crackers for metallurgy (mainly Ni catalysts without purification),
- large-scale units for heavy water production (mainly Fe-Co catalysts without purification).
- New uses, and their specific technology solutions.

Ammonia decomposition catalysts: commercial (Ni, Ru, Co-Fe, Fe)

- Lifetime of catalyst materials. Small-scale units warrant 5 years. Experience from steam methane reforming with Ni catalysts, 3 years expected at least.
- Ammonia oxidation catalysts: Pt + NOx reduction catalysts (Ni).

Separation technologies:

- NH_3 separation (condensation, washing, zeolites),
- basic principles of H_2 purification (cryogenic, PSA, membranes).
- Discuss how requirements (H_2 purity, recovery, pressure, size) determine process choice (overall H_2 yield important)

Technology readiness levels (TRL) of components and requirement for research. Parts will work, so test integrated systems, ramp up and ramp down.

4. Cost evaluation

Techno-economics for ammonia decomposition at various scales and applications

5. Case Studies

Integrated throughout the whitepaper, a series of case studies can help to illustrate the technologies and applications for ammonia cracking. Ideally, these would focus on AEA member projects and technologies, or significant announcements.

6. Conclusion, outlook, and recommendations

Conclude with main messages of the report:

- what are the available technologies and market applications?
- what are the opportunities for decarbonization?
- where are the knowledge gaps?
- where should the R&D effort focus?
- what actions can industry take?
- what are the AEA's policy recommendations?

7. Further reading / References

A further reading section will be added, with extensive references including:

1. Makepeace J (2020) Ammonia cracking: when, how, and how much? In: Ammonia Energy Conference
2. Port of Rotterdam (2020) Hydrogen Economy in Rotterdam Handout
3. Uniper (2021) Uniper Plans to Make Wilhelmshaven a Hub for Climate friendly Hydrogen. https://www.uniper.energy/news/uniper-plans-to-make-wilhelmshaven-a-hub-for-climate-friendly-hydrogen. Accessed 7 Jun 2021
4. Lamb KE, Dolan MD, Kennedy DF (2019) Ammonia for hydrogen storage; A review of catalytic ammonia decomposition and hydrogen separation and purification. Int J Hydrogen Energy 44:3580–3593. https://doi.org/10.1016/j.ijhydene.2018.12.024
5. Mukherjee S, Devaguptapu S V., Sviripa A, et al (2018) Low-temperature ammonia decomposition catalysts for hydrogen generation. Appl Catal B Environ 226:162–181. https://doi.org/10.1016/j.apcatb.2017.12.039
6. Bell TE, Torrente-Murciano L (2016) H2 Production via Ammonia Decomposition Using Non-Noble Metal Catalysts: A Review. Top Catal 59:1438–1457. https://doi.org/10.1007/s11244-016-0653-4
7. Makepeace JW, He T, Weidenthaler C, et al (2019) Reversible ammonia-based and liquid organic hydrogen carriers for high-density hydrogen storage: Recent progress. Int J Hydrogen Energy 44:7746–7767. https://doi.org/10.1016/j.ijhydene.2019.01.144