Ammonia cracking solutions

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Abstract

Ammonia (NH_3) has emerged as a promising hydrogen carrier due to it’s high energy density, zero carbon emissions and ease of transport. Ammonia cracking, the process of decomposing NH_3 into hydrogen (H_2) and (N_2) plays a crucial role in expanding ammonia based hydrogen systems. The thesis studies existing and emerging ammonia cracking technologies, including both catalytic and non-catalytic methods to evaluate their efficiency, scalability and workability for sustainable hydrogen production.

Key words: Ammonia cracking, Hydrogen carrier, Hydrogen economy

Abbreviations:

WHR – waste heat recovery
ICE – internal combustion engine
HT – heat transfer
NO – nitric oxide
NO_2 – nitrogen dioxide
N_2O – nitrous oxide (laughing gas)
CO_2 – carbon dioxide
NTP – non-thermal plasma
MWPJ – microwave plasma jet
SOFC – solid-oxide fuel cell

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1 Introduction

Ammonia (NH_3) is a colorless, pungent-smelling gas that plays a crucial role both in industrial and biological processes. It consists 1 nitrogen (N) and 3 hydrogen (H) atoms, and is one of the most widely produced chemical globally with 150MT/a in 2019 (Cholewa et al., 2022). Ammonia is primarily used in fertilizers, therefore largely contributing to the global agriculture. (Ghavam et al., 2021)

Despite its versatility, ammonia poses challenges related in it’s toxicity and environmental impact. Therefore it requires careful management and precision while in storage, transport and in use. (Fekete and Molnár, 2012)

1.1 Challenges with ammonia

Although having a lot of potential, ammonia like every other substance comes with it’s downsides. As a possible hydrogen carrier, NH_3 has the opportunity to solve the challenges of hydrogen industry. The low energy density by volume (Figure 1) , and the low level of safety in hydrogen could all be solved using NH_3 as the carrier. (Jiang and Fu, 2021)

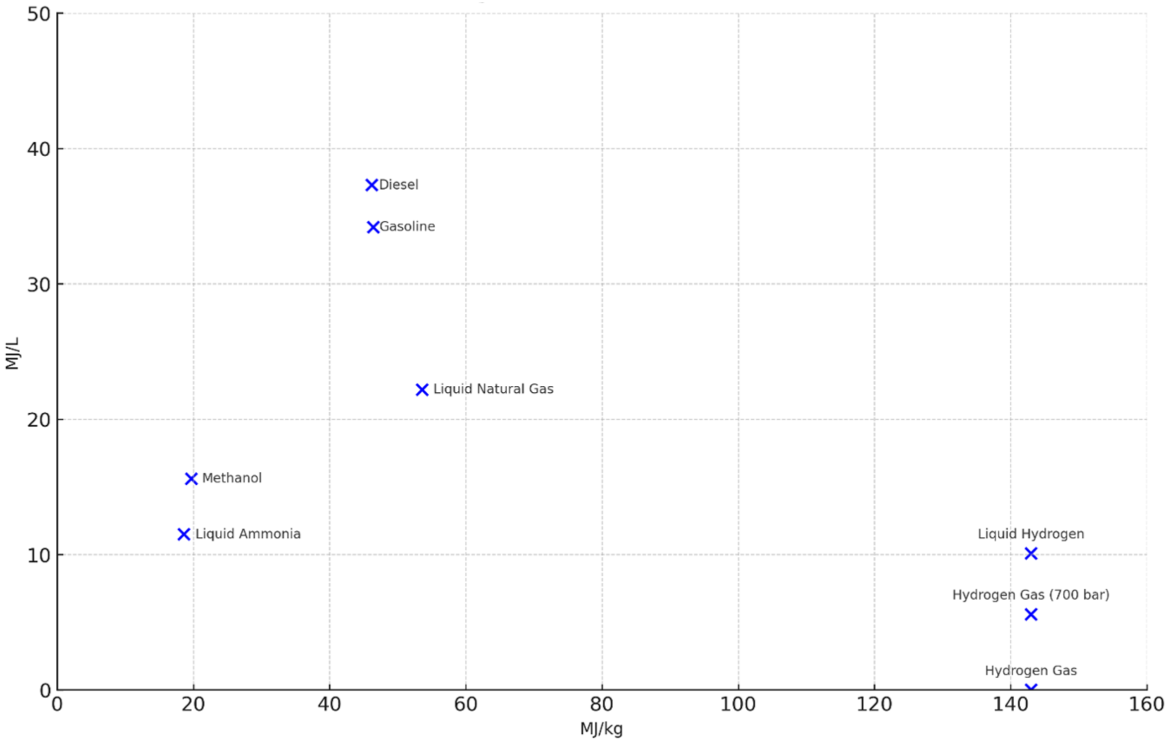


Figure 1. Different fuel energy densities. (“Energy density,” 2025) Wikipedia

Ammonia does also face challenges in the combustion side. Ammonia is a carbon-free fuel, therefore it doesn’t generate CO_2 while combusted. On the other hand, it forms nitrogen oxides on higher levels than other fuels. Main oxides (NO_x) generated by combusting ammonia are NO and NO_2. Not only by further warming the climate, these oxides also create acid rain. (Chehade and Dincer, 2021)

The production efficiency of ammonia asserts significant challenges, mainly in transitioning from conventional polluting methods to sustainable processes. Traditional ammonia synthesis mainly relies on Haber-Bosch process, which consumes significant amounts of energy, primarily from fossil fuels. The Haber-Bosch process contributes to around 3% of global CO_2 emissions (Milton et al., 2017). Transitioning to green ammonia production requires integrating renewable hydrogen from water electrolysis, which only by itself demands large amounts of energy from renewable sources.

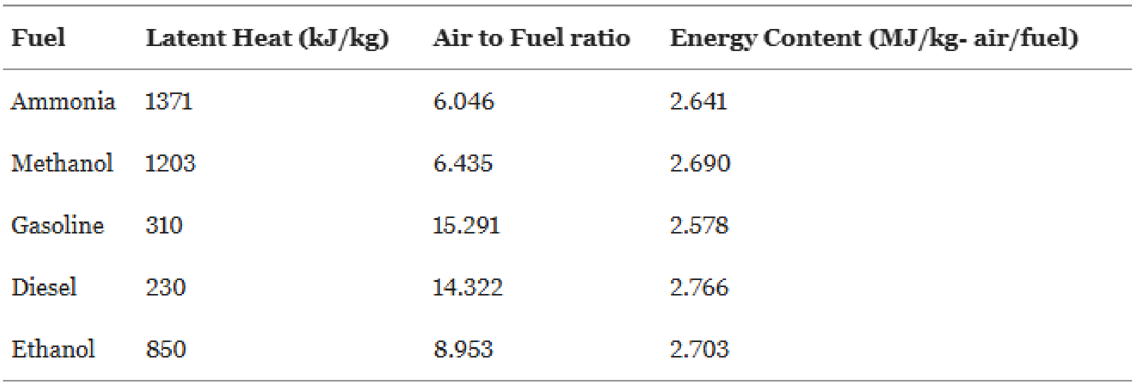
1.2 Possibilities with ammonia

Ammonia presents multiple opportunities as a sustainable fuel. It can be used as a fuel, and it also has the possibility to carry hydrogen, addressing key energy challenges. With a high volumetric energy density, ammonia enables efficient storage and transportation of hydrogen without the needed safety protocols and cautions of hydrogen. (Sun et al., 2022) This makes it an ideal candidate for fuel cells, ICE’s and gas turbines, as it can be stored in liquid form at tolerable pressures and temperatures.

One of ammonia’s key advantages is its potential to serve as a carbon-free fuel, emitting only nitrogen and water when combusted or used in fuel cells. This eliminates CO_2 emissions, making ammonia an attractive option for decarbonizing industries such as land and sea-based transportation.

Ammonia has a lower air to fuel ratio compared to traditional fuels, as shown in Table 1. This allows for combustion to happen with lower amounts of air, while still providing a competitive energy content per kilogram of air-fuel mixture.

Table 1. Different fuel properties (Chehade and Dincer, 2021)



Fuel	Latent Heat (kJ/kg)	Air to Fuel ratio	Energy Content (MJ/kg- air/fuel)
Ammonia	1371	6.046	2.641
Methanol	1203	6.435	2.690
Gasoline	310	15.291	2.578
Diesel	230	14.322	2.766
Ethanol	850	8.953	2.703

Bar chart that shows latent heat, air to fuel ratio and energy content of different fuels.

2 Ammonia synthesis

2.1 Traditional way

The Haber-Bosch process was developed in the early 20th century and it is the dominant method for ammonia synthesis (Li et al., 2020). It involves the reaction of nitrogen (N_2) and hydrogen (H_2) gases under high temperatures (400-500°C) and pressures (150-300bar) using iron-based catalysts.

$$N_2 + 3H_2 \rightarrow 2NH_3 \quad 1.$$

Nitrogen is separated from the air, while hydrogen is usually obtained from natural gas (CH_4) through steam methane reforming, making the whole process rely mainly on fossil fuels.

$$CH_4 + H_2O + heat \rightarrow CO + 3H_2 \quad 2.$$

Despite its decent efficiency large-scale production, the high energy demand (30GJ/tonne) and significant GHG emissions (2.16kgCO2-eq/kg) (Ghavam et al., 2021) released by the process emphasize the importance of finding more sustainable alternatives.

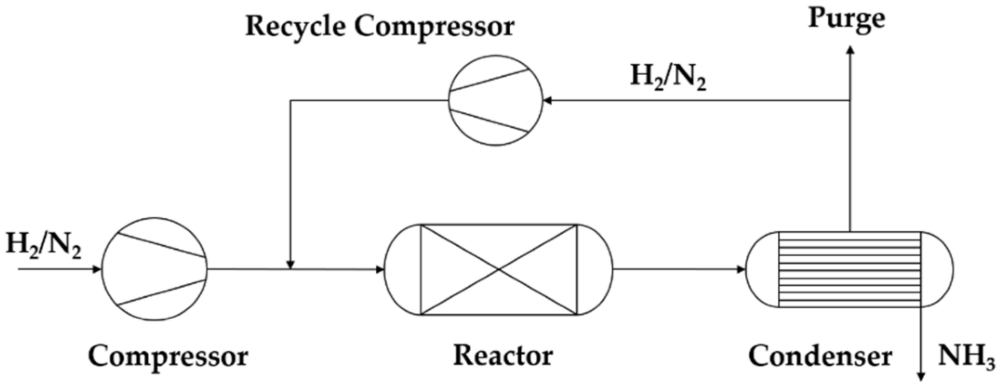


Figure 2. Haber-Bosch process (Cholewa et al., 2022)

2.2 Sustainable way

After becoming aware of human inflicted climate change, humanity has started to address the environmental concerns of their actions. This has launched a need to transfer to sustainable ammonia synthesis technologies. There are multiple ways to synthesize ammonia, but we are mainly gonna focus on renewable based Haber-Bosch.

One key strategy for making the Haber-Bosch process more efficient is the development on advanced catalysts that operate more efficiently under milder conditions. New materials for example nitrides and oxide-promoted metals have shown promise in improving reaction efficiency meanwhile reducing energy input. (Humphreys et al., 2021)

Further making the process sustainable, we can abuse the dynamic Haber-Bosch process, which allows for flexible operation using variating renewable energy sources such as wind and solar. Unlike traditional plants that require around the clock operation, this flexible model enables ammonia synthesis to align with energy availability, thus reducing carbon emissions. (Verleysen et al., 2021)

3 Ammonia cracking

3.1 Existing technologies

Ammonia cracking occurs over a catalyst surface, typically at pretty high temperatures where the ammonia undergoes adsorption, dehydrogeneration and desorption, resulting in the release of nitrogen and hydrogen gas (Figure 3).

$$2NH_3 \rightarrow N_2 + 3H_2 \qquad 3.$$

The catalyst surface enables the breaking of the chemical bonds in ammonia, leading to the release of N_2 and H_2, which can later be used for energy applications. (Asif et al., 2023)

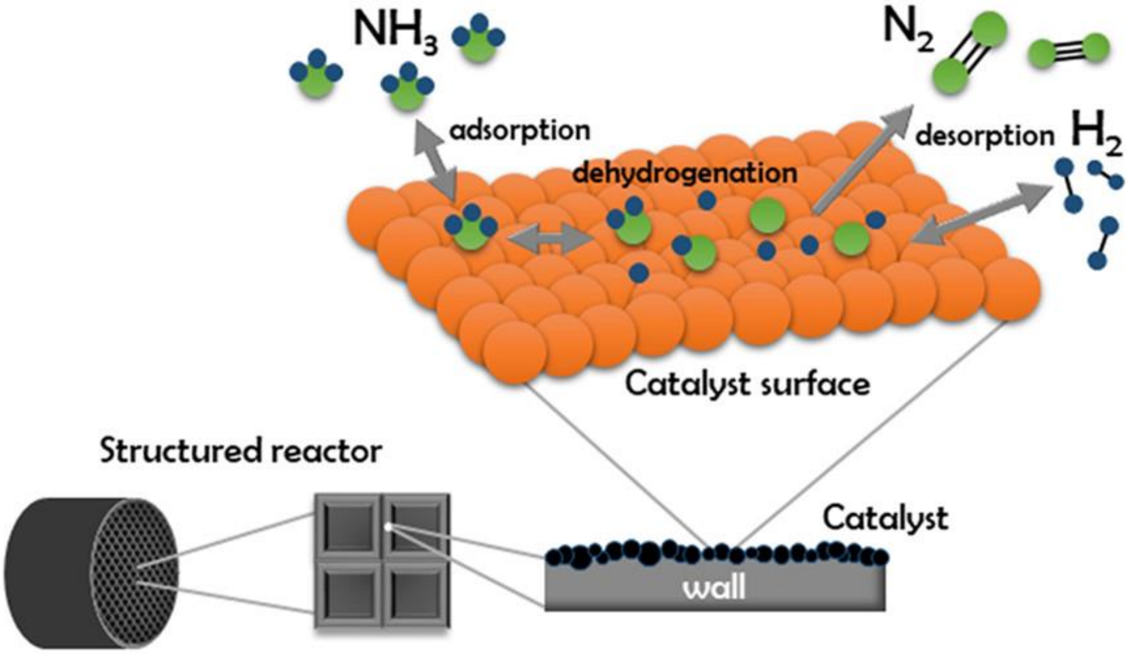


Figure 3. Ammonia decomposition over a catalyst surface. (Lucentini et al., 2021)

3.1.1 Catalytic cracking

Catalytic ammonia decomposition relies on various catalysts, including precious metals and non-precious alternatives. The efficiency of the decomposition process is influenced by factors such as catalyst composition and temperature.

1. Ruthenium-based catalysts: Ruthenium (Ru) has demonstrated high activity for ammonia decomposition, achieving near complete conversion at relatively low

temperatures (475°C) (Huang et al., 2023). However, its high price limits large-scale applications (Figure 4).

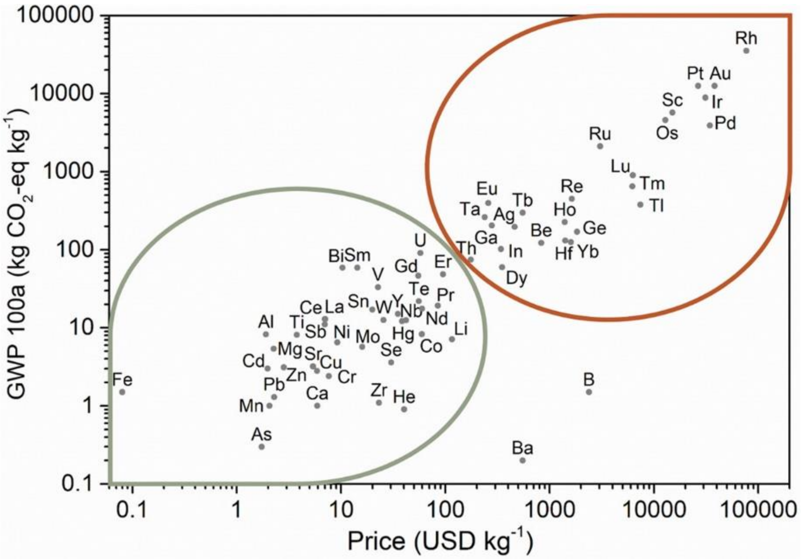


Figure 4. Prices of different catalyst materials (Lucentini et al., 2021)

2. Nickel-based catalysts: Nickel (Ni) catalysts, often supported on metal oxides offer a cost effective alternative. Ni/Al_2O_3 has recorded a 90% conversion rate at 534°C, and near 600°C is required for complete conversion (Figure 5).

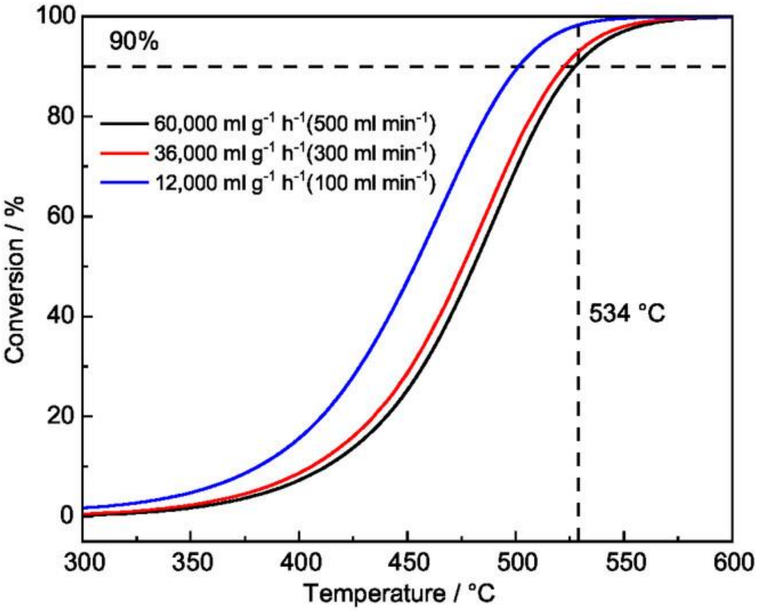


Figure 5. Ammonia conversion rate at different temperatures with Ni/Al_2O_3 catalyst (Purcel et al., 2025)

3. Metal oxide-based catalysts: Metal oxide-based catalysts, for example perovskite supported Ni catalysts have gained significant attention due to their ability to enchance reaction kinetics and thermal stability. (Xi et al., 2024) Compared to Ni-based catalysts, metal oxide supports provide stronger catalyst ability and improve long-term performance (Figure 6). Compared to Ru-based catalysts, metal oxide-based catalysts offer a better economic approach, with scalable industrial potential.

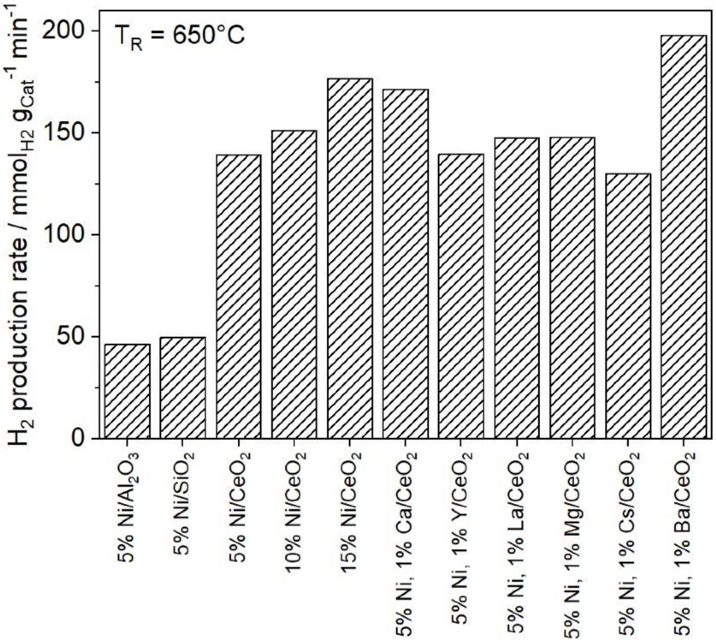


Figure 6. Different catalyst coatings for ammonia decomposition (Weissenberger et al., 2024)

3.1.2 Non-catalytic cracking

Non-catalytic cracking, also known as thermal decomposition (Zhang and Cha, 2023), relies mainly on high temperature conditions to break down ammonia (NH_3) into hydrogen (H_2) and nitrogen (N_2), without the use of catalysts. This method is attractive due to its simplicity and avoidance of catalytic materials that can be expensive, but it typically requires high temperatures nearing 700°C for the conversion to even start. (Moszczyńska et al., 2023)

1. Microwave Plasma Jet (MWPJ): Microwave plasma jet technology offers a great alternative to conventional high-temperature thermal decomposition. The MWPJ method uses high energy microwave induced plasma to break down the ammonia

quickly and efficiently. Ammonia can be fully converted when the delivered energy density exceedes 100W (Figure 7).

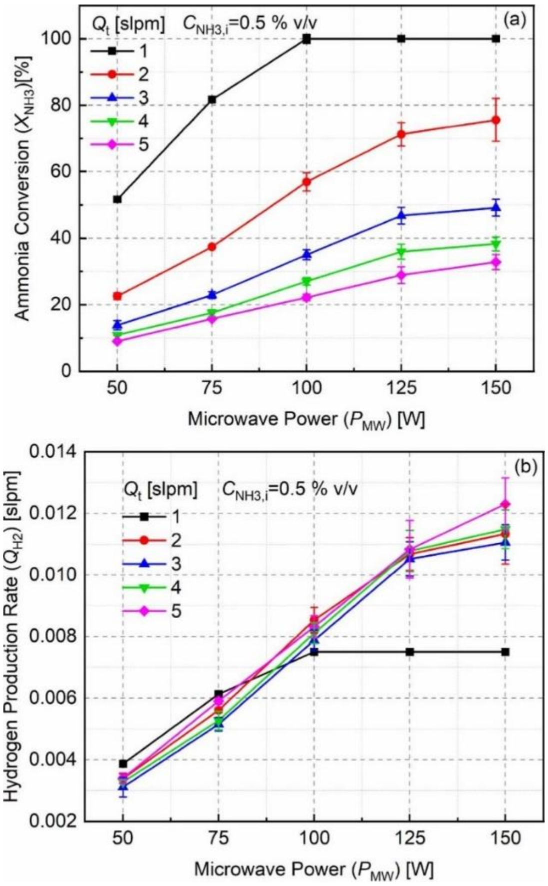


Figure 7. Ammonia conversion rates at different powers (Zhang and Cha, 2023)

The MWPJ offers great advantages compared to conventional methods suchs as as fast start-up and scalability. Conventional methods typically require a lengthy preheating period, where MWPJ can be used as an alternative or assistant. (Zhang and Cha, 2023) Since it does not require external catalysts, it can reduce the dependency on external factors and scaled to larger applications.

2. Non-Thermal Plasma (NTP): Non-thermal plasma decomposition is another rising technology that utilizes low temperature plasma reactions to break down ammonia. NTP systems function at relatively low temperatures (El-Shafie et al., 2021) and can efficiently decompose ammonia even in energy restricted conditions.

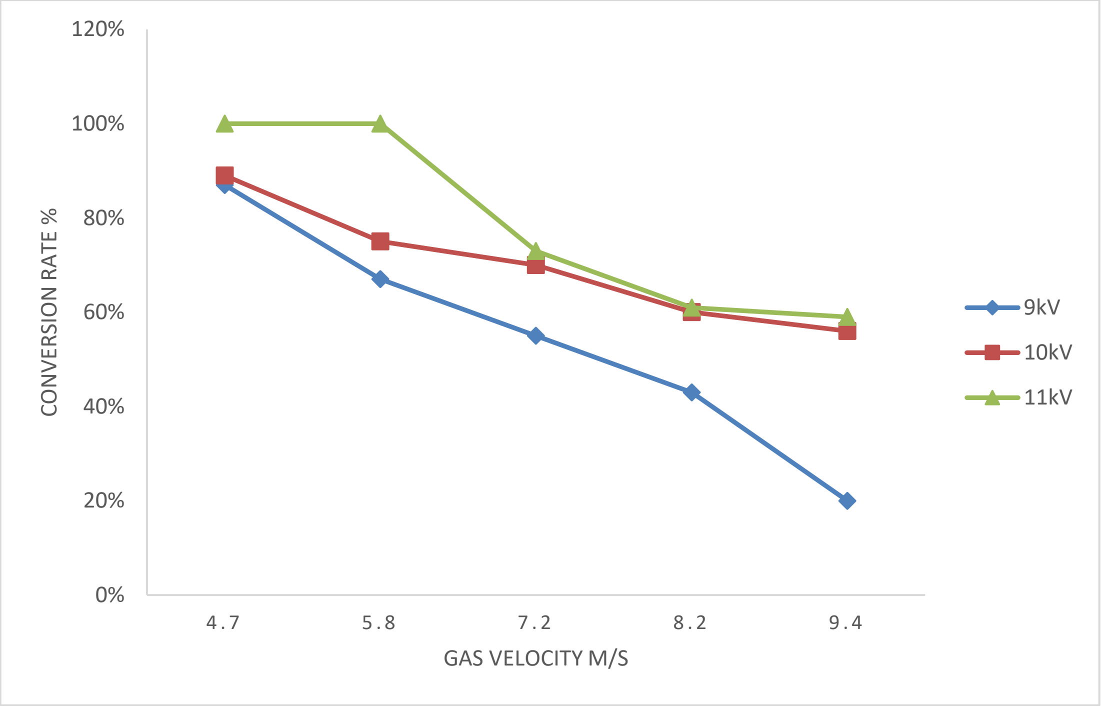


Figure 8. NTP ammonia conversion rates at different voltages
Based on "Decomposition of ammonia and hydrogen sulfide in simulated sludge drying waste gas by a novel non-thermal plasma"

NTP offers key advantages such as lower operating temperatures and zero-carbon hydrogen production. (Moszczyńska et al., 2023) Unlike conventional thermal decomposition, which requires high temperatures, NTP methods achieve significant conversion rates at lower temperatures.

When powered my renewable energy sources such as wind or solar, NTP decomposition offers a sustainable zero-carbon production for hydrogen with minimal environmental impact.

3.2 Emerging techonologies

Ammonia cracking has gained significant attention as a method for hydrogen production, particularly in the transition to sustainable energy solutions. Recent advancements in technology aim to improve the efficiency, scalability and environmental impact of ammonia decomposition.

One emergning technology focuses on green ammonia, produced using renewable energy. (Humphreys and Tao, 2024) examine sustainable synthesis methods, such as electrochemical and thermochemical processes. These advancements ease ammonia cracking as a hydrogen carrier, providing a carbon-free alternative for energy storage and transport. The highlight of their research is improvement on direct ammonia fuel cells and ammonia combustion technologies, which make ammonia a more efficient energy carrier. Furthermore by refining ammonia cracking technologies, they aim to achieve higher hydrogen recovery rates while decreasing energy input and emissions.

These emerging technologies shift humanity towards more sustainable ammonia utilization, ensuring higher energy efficiencies and lower environmental impact in hydrogen production. As research continues, advancements in catalyst development, heat management and renewable energy integration will further enhance ammonia cracking's role inside the hydrogen economy.

3.3 Applications

Ammonia cracking can be applied in multiple different fields of industry. It has a critical role in hydrogen storage and distribution. The ability to convert ammonia back into hydrogen at different points along the supply chain makes it an ideal substance for long distance hydrogen transport. This is particulary crucial for renewable hydrogen production hubs, where green ammonia is synthesized using renewable energy sources and later decomposed into hydrogen (Humphreys and Tao, 2024).

One promising application is the energy sector, where ammonia cracking is integrated with fuel cells to generate electricity. Solid oxide fuel cells (SOFC) can use cracked ammonia directly without requiring external hydrogen purification, increasing total system efficiency (Rathore et al., 2021).

As a hydrogen carrier, ammonia offers a practical alternative to compressed or liquified hydrogen due to its higher energy density (Figure 1), ease of storage and transport (Negro et al., 2023). By decomposing ammonia into high purity hydrogen and nitrogen, ammonia cracking enables a cleaner and more efficient hydrogen supply chain. The different pathaways of ammonia can be seen in Figure 9.

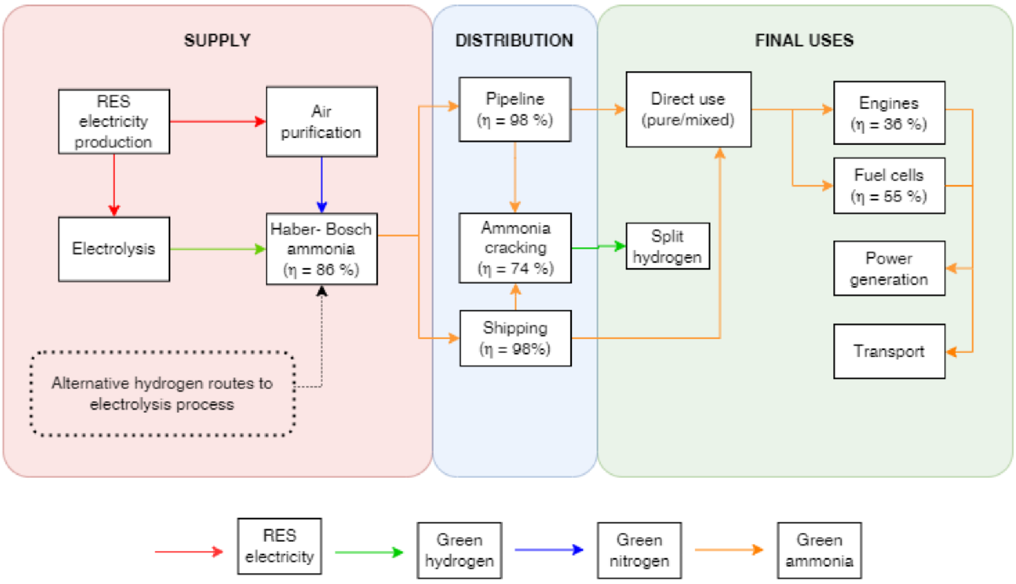


Figure 9. Different ammonia pathaways (Negro et al., 2023)

4 Challenges of ammonia cracking systems

Ammonia cracking is a key technology for hydrogen production, involving the decomposition of ammonia into hydrogen and nitrogen at high temperatures. This process is essential for using ammonia as a hydrogen carrier, enabling more efficient and easy storage and transportation of hydrogen.

Due to its endothermic nature, ammonia cracking requires significant heat input to sustain the reaction, and often utilizing the catalysts mentioned before.

4.1 Energy requirements

Ammonia cracking is an endothermic process, typically requiring high temperatures to fully decompose (Equation 4).

$$NH_{3(g)} \rightarrow \frac{1}{2}N_{2(g)} + \frac{3}{2}H_{2(g)}\ , \Delta H^0 = 45.9\ \frac{kJ}{mol} \qquad 4.$$

This demand for thermal energy presents a major challenge to the economic achievability and scalability of ammonia cracking systems. (Romano et al., 2024) emphasizes that commercial ammonia cracking reactors often rely on expensive catalysts such as Ru and Pd (Figure 4). They require significant amounts of external heat input to maintain reaction efficiency. Recent research is exploring methods to reduce operating temperatures while increasing system pressure to improve efficiency.

Another major factor influencing energy consumption is heat integration and recovery. Since ammonia cracking requires external heat energy, WHR from processes such as gas turbines or ICE’s could improve overall system efficiency. (Alboshmina, 2019) explored a HT improvement technology, which integrates ammonia pre-cracking within a combustor to utilize waste heat efficiently, reducing overall energy demand.

Research into alternative catalysts and optimized reactor desings aim to lower activation energy barriers and reduce external heating requirements. For example, efforts to develop cheaper, more generous catalysts could significantly cut down the energy input needed for ammonia decomposition (Romano et al., 2024).

4.2 Hydrogen purity and separation

One of the major challenges in ammonia cracking is achieving high purity hydrogen, especially for applications in fuel cells, industrial processes and energy storage. Since ammonia decomposition produces a mixture of H_2, N_2 and unreacted NH_3, effective separation and purification technologies are requires to meet the strict hydrogen purity standards for various applications.

Residual ammonia contamination can also have an affect on the end product. Even after cracking small amounts of unreacted ammonia may remain in the hydrogen stream. For fuel cells equipped with polymer electrolyte membrane, ISO14687-2 standards require ammonia levels below 0.1 ppm to prevent electrode degradation (Bandlamudi et al., 2025).

Several methods may be applied to separate and purify the hydrogen after ammonia cracking. Membrane separation technologies, particulary those utilizing palladium-based membranes allow for selective hydrogen permation blocking nitrogen and ammonia to achieve ultra high purity levels of 99.99% (Hayakawa et al., 2019). This comes with a cost, since palladium membranes are very expensive and therefore research is ongoing to develep cost-effective alternatives.

5 Environmental and sustainability aspects

The life cycle impact of ammonia cracking is heavily influenced by the source of ammonia production. Conventional ammonia production using the Haber-Bosch process is highly energy intensive, and contributes to significant CO_2 emissions. Advancements in green ammonia production using renewable energy powered electrolysis to generate hydrogen can dramatically decrease the carbon footprint of ammonia based hydrogen (Xue et al., 2019). Hydrogen production being very energy intensive, it also contributes to many other emissions such as NO_x, N_2O and CH_4.

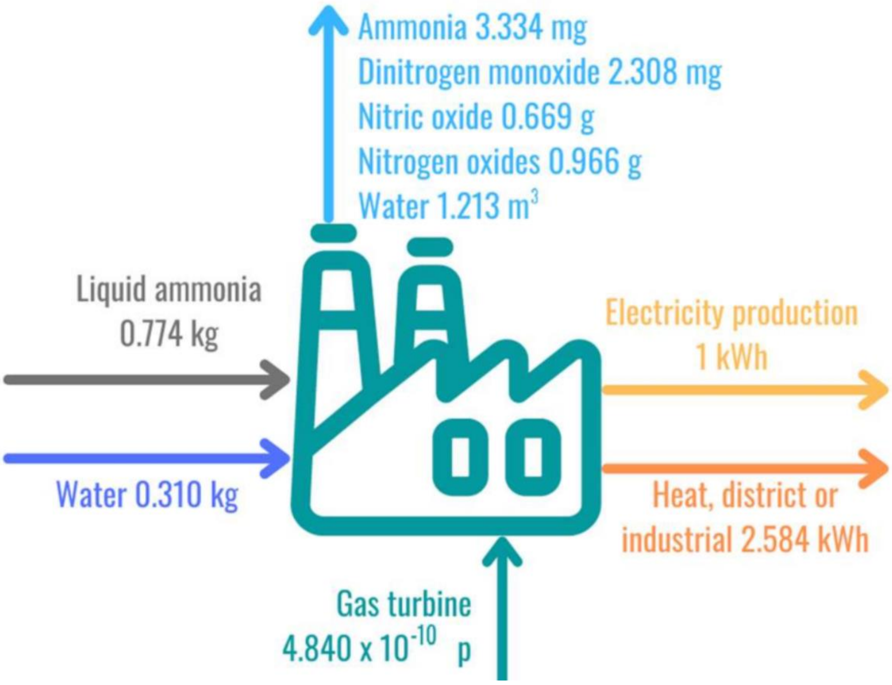


Figure 10.

Materials and energy flows of partially cracked ammonia power cycle (30 / 70 H_2 / NH_3) (Boero et al., 2021)

Life cycle assessments (LCA) further highlight that ammonia cracking based hydrogen production has lower overall carbon footprint compared to traditional fossil fuel based hydrogen generation, when green ammonia is used (Cox and Treyer, 2015). Their research shows that off grid fuel cell systems powered by cracked ammonia found that while emissions from fossil derived ammonia remain high, a switch to renewable ammonia significantly reduces environmental burdens, making the process a sustainable alternative for differenting energy applications.

6 Conclusions

Ammonia cracking presents a feasible pathaway for hydrogen exctraction, addressing the key challenges in hydrogen storage, transport and usage. This thesis has explored various ammonia decomposition technologies, including catalytic and non-catalytic methods and highlighting their efficiencies and potential for large scale applications.

Despite its advantages, ammonia decomposition faces significant challenges particularly in terms of energy efficiency, hydrogen purity and environmental impact. The high energy demands of the process highlights the need of WHR systems and improved catalyst development to enhance the conversion rates at lower temperatures. Ensuring high-purity hydrogen for fuel cell applications requires more advanced separation and purification technologies, which must be optimized for cost-effectiveness.

For ammonia cracking to play a critical role in the future hydrogen economy, further research and innovation are needed in catalyst development and renewable energy integration. The transition towards a sustainable ammonia based hydrogen infrastructure will require strict collaboration among researchers and authorities. With continued advancements, ammonia cracking has the potential to become a key implementer of a low carbon energy future, aiding the large scale deployment of hydrogen in transportation, power generation and industrial applications.

7 References

Ahmed, H.S., Yahya, Z., Ali khan, W., Faraz, A., 2024. Sustainable pathways to ammonia: a comprehensive review of green production approaches. Clean Energy 8, 60–72. https://doi.org/10.1093/ce/zkae002

Alboshmina, N., 2019. Ammonia cracking with heat transfer improvement technology (phd). Cardiff University.

Asif, M., Sidra Bibi, S., Ahmed, S., Irshad, M., Shakir Hussain, M., Zeb, H., Kashif Khan, M., Kim, J., 2023. Recent advances in green hydrogen production, storage and commercial-scale use via catalytic ammonia cracking. Chemical Engineering Journal 473, 145381. https://doi.org/10.1016/j.cej.2023.145381

Bandlamudi, George.C., Wetegrove, M., Warr, L.N., Wartmann, J., Kruth, A., 2025. Fine Gas Purification Approaches for High Purity Hydrogen Production from Ammonia. Energy Technology 13, 2301023. https://doi.org/10.1002/ente.202301023

Boero, A.J., Kardux, K., Kovaleva, M., Salas, D.A., Mooijer, J., Mashruk, S., Townsend, M., Rouwenhorst, K., Valera-Medina, A., Ramirez, A.D., 2021. Environmental Life Cycle Assessment of Ammonia-Based Electricity. Energies 14, 6721. https://doi.org/10.3390/en14206721

Chehade, G., Dincer, I., 2021. Progress in green ammonia production as potential carbon-free fuel. Fuel 299, 120845. https://doi.org/10.1016/j.fuel.2021.120845

Cholewa, T., Semmel, M., Mantei, F., Güttel, R., Salem, O., 2022. Process Intensification Strategies for Power-to-X Technologies. ChemEngineering 6, 13. https://doi.org/10.3390/chemengineering6010013

Christensen, C.H., Johannessen, T., Sørensen, R.Z., Nørskov, J.K., 2006. Towards an ammonia-mediated hydrogen economy? Catalysis Today, Frontiers in Catalysis: A Molecular View of Industrial Catalysis 111, 140–144. https://doi.org/10.1016/j.cattod.2005.10.011

Cox, B., Treyer, K., 2015. Environmental and economic assessment of a cracked ammonia fuelled alkaline fuel cell for off-grid power applications. Journal of Power Sources 275, 322–335. https://doi.org/10.1016/j.jpowsour.2014.11.023

El-Shafie, M., Kambara, S., Hayakawa, Y., 2021. Energy and exergy analysis of hydrogen production from ammonia decomposition systems using non-thermal plasma. International Journal of Hydrogen Energy, HYDROGEN ENERGY SYSTEMS 46, 29361–29375. https://doi.org/10.1016/j.ijhydene.2020.08.249

Energy density, 2025. . Wikipedia.

Fekete, V.A., Molnár, R.L., 2012. Ammonia: Structure, Biosynthesis and Functions: Structure, Biosynthesis and Functions. Nova Science Publishers, Incorporated, Hauppauge, UNITED STATES.

Ghavam, S., Vahdati, M., Wilson, I.A.G., Styring, P., 2021. Sustainable Ammonia Production Processes. Front. Energy Res. 9. https://doi.org/10.3389/fenrg.2021.580808

Hayakawa, Y., Miura, T., Shizuya, K., Wakazono, S., Tokunaga, K., Kambara, S., 2019. Hydrogen production system combined with a catalytic reactor and a plasma membrane reactor from ammonia.

International Journal of Hydrogen Energy, 9th International Conference on Hydrogen Production (ICH2P-2018) 44, 9987–9993. https://doi.org/10.1016/j.ijhydene.2018.12.141

Huang, X., Lei, K., Mi, Y., Fang, W., Li, X., 2023. Recent Progress on Hydrogen Production from Ammonia Decomposition: Technical Roadmap and Catalytic Mechanism. Molecules 28, 5245. https://doi.org/10.3390/molecules28135245

Humphreys, J., Lan, R., Tao, S., 2021. Development and Recent Progress on Ammonia Synthesis Catalysts for Haber–Bosch Process. Advanced Energy and Sustainability Research 2, 2000043. https://doi.org/10.1002/aesr.202000043

Humphreys, J., Tao, S., 2024. Advancements in Green Ammonia Production and Utilisation Technologies: Green ammonia in the transition to a sustainable energy system. Johnson Matthey Technology Review 68, 280–292. https://doi.org/10.1595/205651324X16946999404542

Jiang, L., Fu, X., 2021. An Ammonia–Hydrogen Energy Roadmap for Carbon Neutrality: Opportunity and Challenges in China. Engineering 7, 1688–1691. https://doi.org/10.1016/j.eng.2021.11.004

Li, C., Wang, T., Gong, J., 2020. Alternative Strategies Toward Sustainable Ammonia Synthesis. Trans. Tianjin Univ. 26, 67–91. https://doi.org/10.1007/s12209-020-00243-x

Lucentini, I., Garcia, X., Vendrell, X., Llorca, J., 2021. Review of the Decomposition of Ammonia to Generate Hydrogen. Ind. Eng. Chem. Res. 60, 18560–18611. https://doi.org/10.1021/acs.iecr.1c00843

Milton, R.D., Cai, R., Abdellaoui, S., Leech, D., De Lacey, A.L., Pita, M., Minteer, S.D., 2017. Bioelectrochemical Haber–Bosch Process: An Ammonia-Producing H2/N2 Fuel Cell. Angewandte Chemie International Edition 56, 2680–2683. https://doi.org/10.1002/anie.201612500

Moszczyńska, J. 1, Liu, X. 2, Wiśniewski, M. 1 1 D. of M.C., Catalysis, F. of C., Catalysis, jmoszczynska01@gmail com 2 I. for, Energy Solutions, U. of S.A., liux@unisa.ac.za, 2023. Green Hydrogen Production through Ammonia Decomposition Using Non-Thermal Plasma 14397. https://doi.org/10.3390/ijms241814397

Negro, V., Noussan, M., Chiaramonti, D., 2023. The Potential Role of Ammonia for Hydrogen Storage and Transport: A Critical Review of Challenges and Opportunities. Energies 16, 6192. https://doi.org/10.3390/en16176192

Purcel, M., Müller, A.S., Diehl, P., Kappis, K., Trunschke, A., Muhler, M., 2025. Long-Term Stability of Ammonia Decomposition over Nickel-Based Catalysts. Energy Technology 13, 2400678. https://doi.org/10.1002/ente.202400678

Rathore, S.S., Biswas, S., Fini, D., Kulkarni, A.P., Giddey, S., 2021. Direct ammonia solid-oxide fuel cells: A review of progress and prospects. International Journal of Hydrogen Energy 46, 35365–35384. https://doi.org/10.1016/j.ijhydene.2021.08.092

Romano, C., Bellotti, D., Pucci, E., Fadlun, E., Roma, M., Ghezzi, S., Manferino, G., Anfosso, C., Monacchini, C., 2024. Ammonia Cracking As Auxiliary System for Gas Turbine: Preliminary Studies. Presented at the ASME 2024 Power Conference, American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/POWER2024-137878

Sun, S., Jiang, Q., Zhao, D., Cao, T., Sha, H., Zhang, C., Song, H., Da, Z., 2022. Ammonia as hydrogen carrier: Advances in ammonia decomposition catalysts for promising hydrogen production. Renewable and Sustainable Energy Reviews 169, 112918. https://doi.org/10.1016/j.rser.2022.112918

Verleysen, K., Parente, A., Contino, F., 2021. How sensitive is a dynamic ammonia synthesis process? Global sensitivity analysis of a dynamic Haber-Bosch process (for flexible seasonal energy storage). Energy 232, 121016. https://doi.org/10.1016/j.energy.2021.121016

Wang, B., Li, T., Gong, F., Othman, M.H.D., Xiao, R., 2022. Ammonia as a green energy carrier: Electrochemical synthesis and direct ammonia fuel cell - a comprehensive review. Fuel Processing Technology 235, 107380. https://doi.org/10.1016/j.fuproc.2022.107380

Weissenberger, T., Zapf, R., Pennemann, H., Kolb, G., 2024. Catalyst Coatings for Ammonia Decomposition in Microchannels at High Temperature and Elevated Pressure for Use in Decentralized and Mobile Hydrogen Generation 104. https://doi.org/10.3390/catal14020104

Xi, S., Wu, W., Yao, W., Han, R., He, S., Wang, W., Zhang, T., Yu, L., 2024. Hydrogen Production from Ammonia Decomposition: A Mini-Review of Metal Oxide-Based Catalysts. Molecules 29, 3817. https://doi.org/10.3390/molecules29163817

Xue, M., Wang, Q., Lin, B.-L., Tsunemi, K., 2019. Assessment of Ammonia as an Energy Carrier from the Perspective of Carbon and Nitrogen Footprints. ACS Sustainable Chem. Eng. 7, 12494–12500. https://doi.org/10.1021/acssuschemeng.9b02169

Zhang, X., Cha, M.S., 2023. Ammonia cracking for hydrogen production using a microwave argon plasma jet. J. Phys. D: Appl. Phys. 57, 065203. https://doi.org/10.1088/1361-6463/ad0988