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# Power generation using Ammonia as single fuel in internal combustion engines

Fuels - Alternative & New Fuels

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## ABSTRACT

This paper presents an in-depth investigation into the potential of ammonia as a single fuel for power generation in internal combustion engines. As the global community seeks to transition away from fossil fuels, ammonia, a carbon-free fuel that can easily be derived from green hydrogen, presents a promising alternative. However, its application in internal combustion engines is challenging due to its low flame speed, high ignition energy demand, and narrow ignition limits for combustion in air.

The study begins with a comprehensive review of the properties of ammonia, highlighting its advantages such as easy storage and transportation compared with hydrogen, and its potential as a carbon-free fuel. The paper then delves into the technical challenges associated with the combustion of ammonia in spark ignited internal combustion engines, providing a detailed analysis of its combustion characteristics and the difficulties they present.

Experimental results are presented from tests conducted on a single cylinder research engine fueled by ammonia and small quantities of hydrogen to promote the combustion process. The results demonstrate the complexities of achieving stable and efficient combustion, but also reveal potential strategies for overcoming these challenges. Special attention is given to the formation of nitrous oxides in the exhaust and potential strategies in engine operation allowing for easy integration with a SCR- aftertreatment system. Besides the experimental results of the single-cylinder engine testing, the paper includes results of a study seeking to understand the impact of ammonia on engine lube oil and material compatibility.

The paper concludes with a discussion on the future prospects of ammonia-fueled engines. It suggests that while significant technical hurdles remain, the environmental benefits and the potential for integration with renewable energy systems make ammonia a compelling area for further research and development in power generation.

This study contributes to the growing body of research on alternative fuels for internal combustion engines and highlights the need for continued innovation in this field to meet global sustainability goals.

# 1 INTRODUCTION

Hydrogen can be produced via electrolysis from renewable electricity and water and can be used as an e-fuel in various applications without further chemical conversion. In addition to hydrogen, which is the simplest e-fuel, ammonia, methanol, or even long-chain hydrocarbons can be produced from hydrogen through additional chemical processing. These e-fuels also can be used in combustion engine applications as synthetic fuels, enabling a $CO_2$-neutral and, in the case of hydrogen and ammonia, a $CO_2$-free energy supply. They are a driving force in the transition from fossil fuels to renewable energy sources.

With the increasing $CO_2$ concentration in the Earth's atmosphere, the global climate is changing, and average global temperatures are rising. Currently, global warming is approximately 1.6°C above pre-industrial levels, with a rising trend. To meet the climate targets set by the Paris Agreement of 2015, which aims to limit global warming to 1.5°C, or at most 2°C, a drastic reduction in $CO_2$ emissions and a swift transition from fossil fuels to renewable, $CO_2$-neutral or, better yet, $CO_2$-free energy sources is necessary. This transformation of energy supply is a challenge that will accompany us for decades and significantly alter our daily lives. To address this challenge and facilitate the transition to a sustainable energy economy, major industrial nations have established a clear agenda for decarbonization. In addition to electrifying transportation, which contributes significantly to our $CO_2$ emissions, there is also a shift away from gas heating and an increasing transition to heat pumps for residential heating. Both measures, the energy transition and the heat transition, further increase our already growing demand for electrical energy. With the simultaneous phase-out of coal energy, a massive expansion of renewable energy sources such as wind and solar power is essential. Besides the quantitative challenge of meeting the annual demand for electrical energy through renewable generation, there is also the challenge of maintaining a balance between energy consumption and generation in our grids. However, wind and solar power are not always available. For instance, while large amounts of renewable electricity are available on a windy summer day, the yield can be much lower on a cloudy autumn day with low wind. Therefore, in addition to expanding renewable energy sources, investment in efficient energy storage systems is crucial for the successful implementation of the energy and heat transition. It should be noted that battery systems, as highly efficient storage systems, are not suitable or cost-effective for storing large amounts of energy over several days or weeks, as would be required to balance medium-term or seasonal fluctuations. However, the Power-to-X technologies offer a promising solution, where electrical energy is converted into a chemical energy carrier, such as hydrogen, for storage purposes.

As shown in Figure 1, the European Union imports about 50%-60% of its energy needs, as domestic production within the EU cannot meet the demand for energy. These energy imports are primarily based on fossil fuels such as oil, natural gas, and coal, which are mainly used in the transport, heating, and power generation sectors. It is doubtful that the European Union can meet its energy needs solely through the expansion of its renewable energy sources and the transition to more efficient consumers. Instead, it is more likely that the European Union will continue to rely on energy imports. However, these imports must be based on renewable and preferably $CO_2$-free energy sources. Cooperation with countries that can produce a significant surplus of renewable energy relative to their own needs is essential. An agreement with sun-rich countries such as Australia or those in the Middle East and North Africa for the import of electricity from photovoltaic and wind systems would be desirable, as renewable electricity can be generated in those regions with significantly lower investment costs due to the high and more consistent solar intensity. The same applies to electricity from wind power for countries in which very consistent and high wind availability allows for significantly lower investment costs for wind power generation than within the European Union. Unfortunately, countries with excellent conditions for generating electricity from wind and solar power are typically so far from the European Union that transporting electrical energy via high-voltage lines is not feasible. Here, it seems inevitable to convert the generated electrical energy into a chemical energy carrier using a Power-to-X process. In this way, existing systems such as ships or pipelines easily can transport the chemical energy carrier for power and heat generation to its destination.

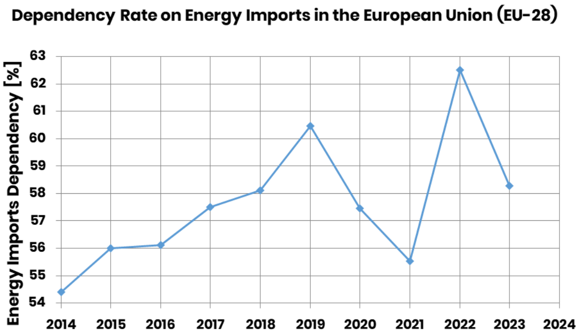


Figure 1: Dependency rate on energy imports in the EU from 2014 to 2023 [1]

## 2 E-FUELS AS A KEY TECHNOLOGY FOR DECARBONIZATION

Figure 2 illustrates the various pathways of a Power-to-X system for producing hydrogen, ammonia, methane, methanol, or long-chain hydrocarbons.

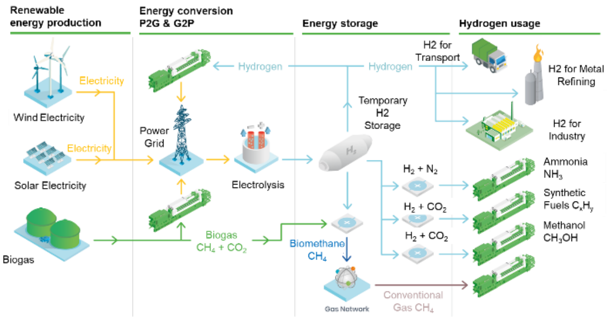


Figure 2: Overview of Power-to-X systems with focus on e-fuels production

Renewable electricity generated from wind or solar power is increasingly used not only for direct consumption by various electrical consumers in the power grid but also in transportation and residential heating using heat pumps. Additionally, electricity is used to produce hydrogen via electrolysis from water. The hydrogen thus obtained is not only the simplest element in the periodic table but also the simplest e-fuel. Hydrogen as a chemical energy carrier can be stored in a technical pressure storage system or a natural storage system such as a salt cavern or depleted natural gas field. In addition to storage as compressed gas, storage in liquid form under cryogenic conditions or chemical bonding in a metal hydride storage system also is mentioned. The loading and unloading speeds and maximum capacity depend significantly on the chosen storage system. In the context of the energy transition, natural storage systems such as salt caverns or depleted natural gas fields are of particular interest, as large quantities of hydrogen can be stored over a long period, and the storage sites often already are connected by an existing pipeline network. Researchers at INNIO Group's Jenbacher engineering center already have developed technologies to use hydrogen in innovative gas engines for stationary power generation [2]. Besides hydrogen, ammonia is another $CO_2$-free e-fuel that traditionally can be produced from hydrogen and nitrogen using the Haber-Bosch process. Ammonia is one of the most produced chemicals worldwide and is primarily used in the fertilizer industry. Accordingly, there is already a well-developed infrastructure for transporting and storing ammonia. Currently, ammonia is predominantly produced from natural gas, which is associated with corresponding $CO_2$ emissions. In addition to ammonia, hydrocarbons also can be produced from hydrogen with the addition of $CO_2$ and appropriate synthesis processes, such as the Fischer-Tropsch process. Here, simple hydrocarbons like methane and long-chain, complex hydrocarbons can be produced, which can be used in today's diesel and gas engines as well as aircraft engines without engine modifications. Accordingly, the synthetic methane produced here can be fed into the existing gas network and used in INNIO Group's Jenbacher engines without modifications. However, it should be noted that depending on the origin of the $CO_2$, the resulting synthetic fuels are at best $CO_2$-neutral if the $CO_2$ released during their combustion was obtained from biomass or directly from the atmosphere using direct air capture during fuel production. It also should be considered that each process step in the production of e-fuels is associated with costs and inefficiencies, and it should be noted that hydrogen, as the simplest e-fuel, has the lowest production costs and energy requirements, while long-chain hydrocarbons are the most energy-intensive to synthesize and often the most expensive due to the complexity of the facilities. In contrast, the energy density, specifically the energy content per unit volume, steadily increases, which plays a crucial role in transport and storage. Figure 3 shows a possible solution for future imports on renewable energy to the European Union by means of transporting ammonia as an energy carrier in large vessels. It is believed that ammonia can be synthesised easily from hydrogen and nitrogen directly at sites with very favorable conditions for renewable energy generation and subsequent shipment in bulk to selected harbors within the European Union. Ammonia then can be used directly in power plants with access to shippable waterways for power and heat generation, or it can be decomposed to hydrogen, which can, in turn, easily be transported via the anticipated hydrogen backbone and associated hydrogen pipeline network.

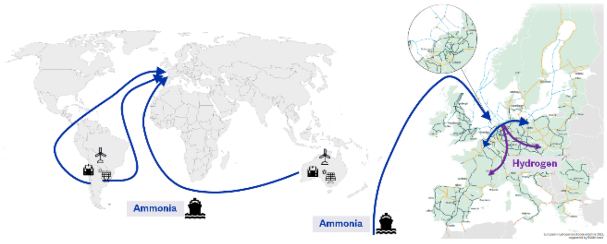
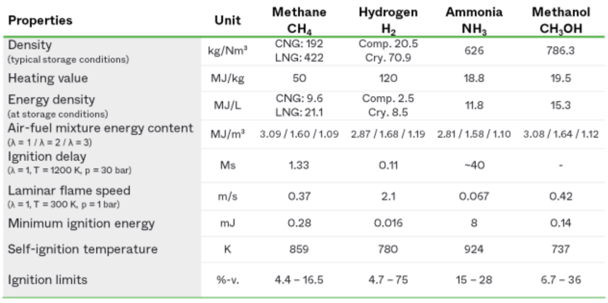


Figure 3: Energy imports to European Union via large vessels using ammonia as an energy carrier

## 2.1 Physical properties of e-fuels

For further consideration, the range of e-fuels is limited to methane, hydrogen, ammonia, and methanol. Table 1 compares the physical properties of these e-fuels and discusses them in the context of engine applications and the previously described challenges of the energy and heat transition. As can be easily seen from the data in Table 1, hydrogen has a very high gravimetric heating value, but due to its very low density, the volumetric energy density of hydrogen is very low. This poses a significant challenge for the transport of hydrogen and tank systems for mobile applications, as larger quantities of hydrogen can be stored and transported efficiently only under high pressure or cryogenic conditions in liquid form.



| Properties | Unit | Methane $CH_4$ | Hydrogen $H_2$ | Ammonia $NH_3$ | Methanol $CH_3OH$ |
|---|---|---|---|---|---|
| Density (typical storage conditions) | kg/Nm³ | CNG: 192<br>LNG: 422 | Comp. 20.5<br>Cry. 70.9 | 626 | 786.3 |
| Heating value | MJ/kg | 50 | 120 | 18.8 | 19.5 |
| Energy density (at storage conditions) | MJ/L | CNG: 9.6<br>LNG: 21.1 | Comp. 2.5<br>Cry. 8.5 | 11.8 | 15.3 |
| Air-fuel mixture energy content ($\lambda = 1$ / $\lambda = 2$ / $\lambda = 3$) | MJ/m³ | 3.09 / 1.60 / 1.09 | 2.87 / 1.68 / 1.19 | 2.81 / 1.58 / 1.10 | 3.08 / 1.64 / 1.12 |
| Ignition delay ($\lambda = 1$, T = 1200 K, p = 30 bar) | Ms | 1.33 | 0.11 | ~40 | - |
| Laminar flame speed ($\lambda = 1$, T = 300 K, p = 1 bar) | m/s | 0.37 | 2.1 | 0.067 | 0.42 |
| Minimum ignition energy | mJ | 0.28 | 0.016 | 8 | 0.14 |
| Self-ignition temperature | K | 859 | 780 | 924 | 737 |
| Ignition limits | %-v. | 4.4 – 16.5 | 4.7 – 75 | 15 – 28 | 6.7 – 36 |

Table 1: Physical properties of selected e-fuels in comparison to methane

Therefore, it is expected that hydrogen will be converted into ammonia or methanol for transport over longer distances. Ammonia and methanol are much easier to handle in this regard, as they can be easily liquefied and have a significantly higher volumetric energy density than liquefied hydrogen under typical storage conditions. Table 1 also lists the essential physical properties that are crucial for assessing engine applications. Since methane is the main component of natural gas, for which developed and optimized engine systems are available, it serves as the benchmark for evaluating the applicability of other e-fuels in an engine. Despite the significant differences in the volumetric energy content of the fuels, all fuels have an acceptable energy density for air-fuel mixtures at the typical mixing ratios for engine applications. The deviation in the energy content of the air-fuel mixture is well below 10% between the individual fuels. Significant differences are evident in the laminar flame speed. While the laminar flame speed of methanol and methane is very similar at 0.42 m/s and 0.37 m/s, respectively, hydrogen has a much higher flame speed of 2.1 m/s, and ammonia has a much lower flame speed of only 0.067 m/s. This shows that adopting existing combustion processes without adapting to the changed combustion behavior of hydrogen or ammonia is not feasible. The same is true for the minimum ignition energy. The ignition energy requirement of ammonia is significantly higher at 8 mJ than that of methane at 0.28 mJ or even hydrogen at only 0.016 mJ. The special properties of hydrogen as an easily ignitable gas also are evident when considering ignition limits. Over a very wide range from 4.7% by volume to 75% by volume, hydrogen forms ignitable mixtures in the air, while the ignition limits of ammonia are much narrower. In conclusion, it should be noted that hydrogen is a very reactive, easily ignitable fuel, while ammonia burns very slowly and is much more difficult to ignite. Methanol is most similar to methane in its physical properties.

# 3 UTILIZATION OF AMMONIA IN INTERNAL COMBUSTION ENGINES

The following section provides a more detailed examination of the use of ammonia as a $CO_2$-free fuel in large gas engines for stationary power generation.

## 3.1 General approach to ammonia combustion

As highlighted in the previous section, physical properties of ammonia are such that ignition and combustion of ammonia-air mixtures in an internal combustion engine poses significant challenges. In particular, the relatively high ignition energy requirement and low laminar flame speed pose significant challenges with respect to the use of ammonia as a fuel in a spark-ignited combustion system. To promote ignitability and accelerate fuel conversion, a combustion system using pilot injections of diesel fuel or admixing of additional fuels (i.e., hydrogen) has been investigated.

Researchers at INNIO Group’s Jenbacher engineering center and the Large Engine Competence Center chose to develop a spark-ignited combustion system that is promoted by admixing hydrogen, with the vision to derive the hydrogen from a catalytic decomposition of ammonia using a suitable catalyst and heat rejected from the engine’s combustion process. This approach is favorable for stationary power generation as customers will not have to deal with an additional fuel and respective infrastructure to operate the engine. A schematic overview of the considered system is presented in Figure 4.

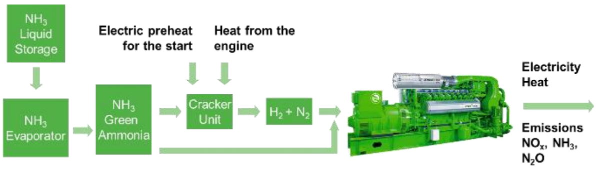


Figure 4: Schematic for combustion of ammonia in stationary power generation

## 3.2 Experimental setup and measurement results

The goal of the experimental investigation was the assessment of the impact of various hydrogen fractions in the fuel mixture on engine performance parameters and exhaust gas emissions and the definition of suitable combinations of hydrogen fractions and excess air ratios. The experiments were performed at a constant indicated mean effective pressure (IMEP) of 23 bar and engine speed 1,500 rpm.

In Figure 5, excess air ratio (EAR) variations with 2%v and 6%v hydrogen admixture to the ammonia are presented. The combustion phasing was maintained at a constant value of 6 crank angle degree after top dead center. With increasing EAR, the ignition timing (ZZP) needs to be advanced to achieve the target combustion phasing. The ignition delay time for a higher hydrogen fraction is lower, resulting in later ignition times. With constant combustion phasing, the peak cylinder pressure only showed a small increase with increasing EAR. The indicated efficiency is increasing with EAR, while there is only a small impact of the hydrogen fraction. The combustion was stable over the entire variation range. The combustion duration increases with leaner EAR and lower hydrogen content.

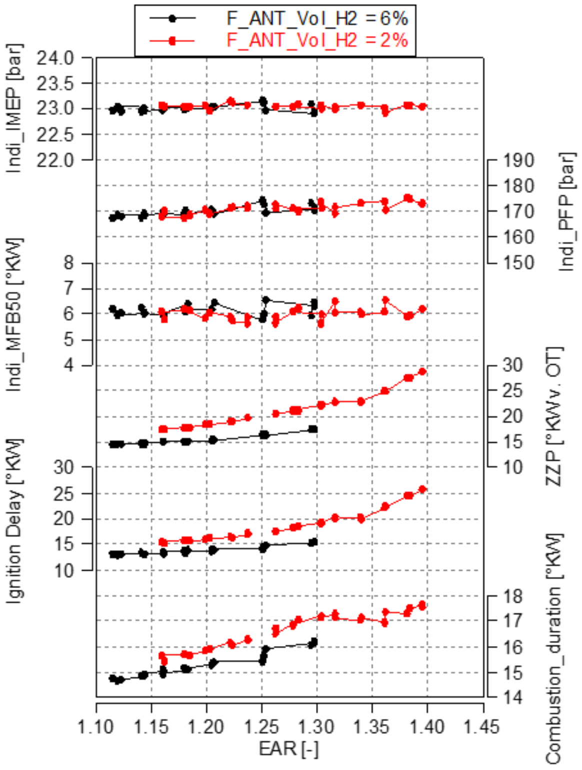


Figure 5: Selected measurement results for ammonia/hydrogen combustion at 23 bar IMEP

For ammonia combustion concepts, the most important exhaust gas emissions are $NH_3$, Nox, and $N_2O$ as well as the ratio of ammonia and NOx emission (ANR), which is crucial for efficient exhaust gas aftertreatment in an SCR catalyst. $N_2O$ emissions are critical because they have a GWP of 273 (6th AR, [4]), and even low concentrations have an impact. The NOx emissions (Figure 6) show a strong dependency on EAR with a maximum at approximately 1.25. The hydrogen fraction in the evaluated region only shows a minor impact on NOx emissions. The same trend was observed for the emission of $N_2O$, which steadily decreases with decreasing EAR. The $NH_3$ emission, however, shows a dependence on EAR as well as hydrogen fraction. With reduced EAR, the $NH_3$ emissions increase for both hydrogen fractions. The lower hydrogen fraction results in higher $NH_3$ emissions for a given EAR. This also is reflected in the ANR that is slightly higher for the lower hydrogen fraction.

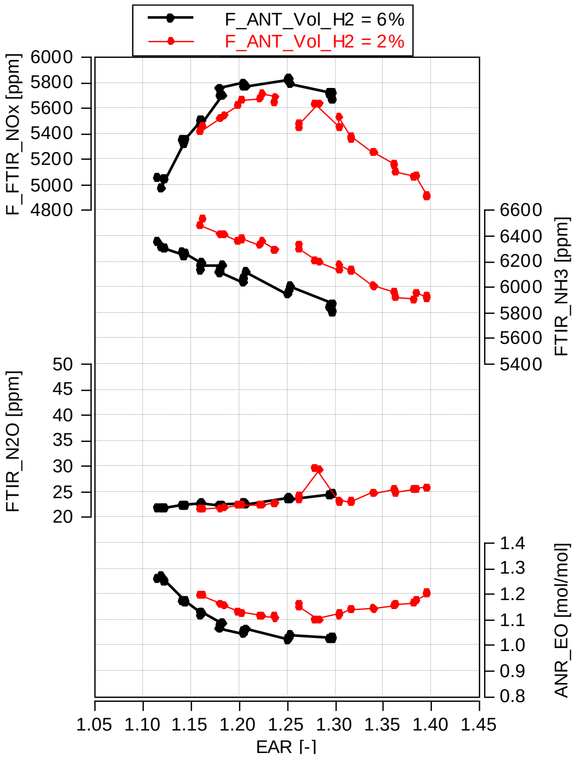


Figure 6: Selected performance parameters for ammonia/hydrogen combustion at 23 bar IMEP

The combustion results with ammonia and low hydrogen amounts show promise for realizing a viable product option.

In addition to testing at 23 bar IMEP, the ability to operate the engine in part load also has been investigated. Figure 7 shows an overview of the limits of engine operation at various loads. With decreasing engine load, an increased demand for hydrogen admixing can be observed, while at the same time the operating range with respect to EAR narrows. At full load, it was demonstrated that the combustion system does not require hydrogen as promoter.

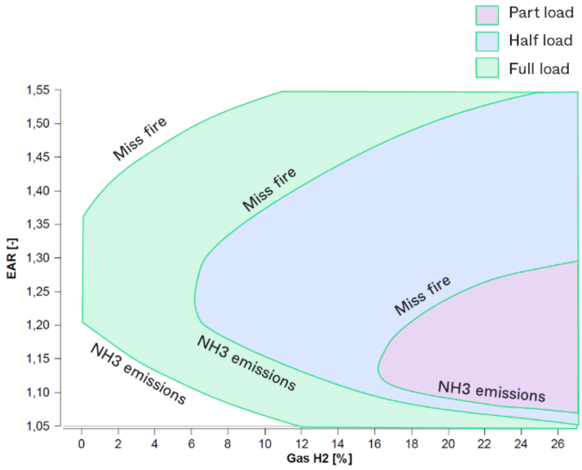


Figure 7: Limits of engine operation at various loads

It should be noted that even though the relative amount of hydrogen in the fuel is increasing at part load, the absolute amount of hydrogen that must be derived via catalytic decomposition of ammonia remains about constant due to the lower demand for ammonia at part load conditions. This aspect is very favorable from a control’s perspective, as the operating point of the catalytic cracker remains mostly unchanged, regardless of engine loading. Thus, transient requirements on the engine are not limited by the catalytic decomposition of ammonia.

## 4 PLANT LAYOUT

As part of the Campfire project, a 1 MW_el demonstrator will be installed at a test facility of the Campfire Open Innovation Lab (COIL) close to Rostock as depicted in Figure 8. The system consists of a liquid ammonia supply from a nearby storage tank, an ammonia evaporator operated by heating water, an electrically heated ammonia cracker, an $NH_3$-optimized J412 genset, an exhaust aftertreatment system, and additional safety systems, including a flare. Additionally, a hydrogen and LPG supply will be on site along with a nitrogen supply for purging the system after shutdown as illustrated in Figure 11.

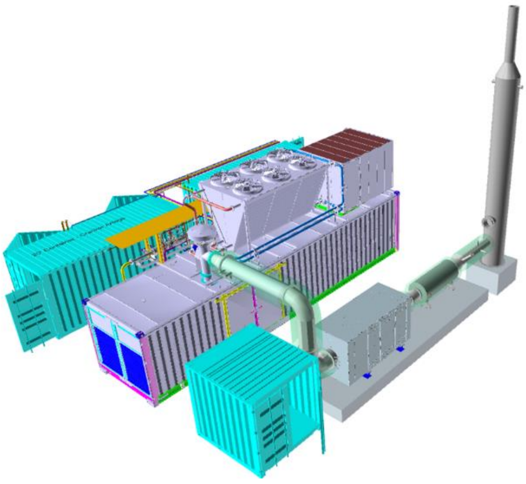


Figure 8: Overview of the test and demonstration setup of a 1 MWe genset at the Campfire Open Innovation Lab

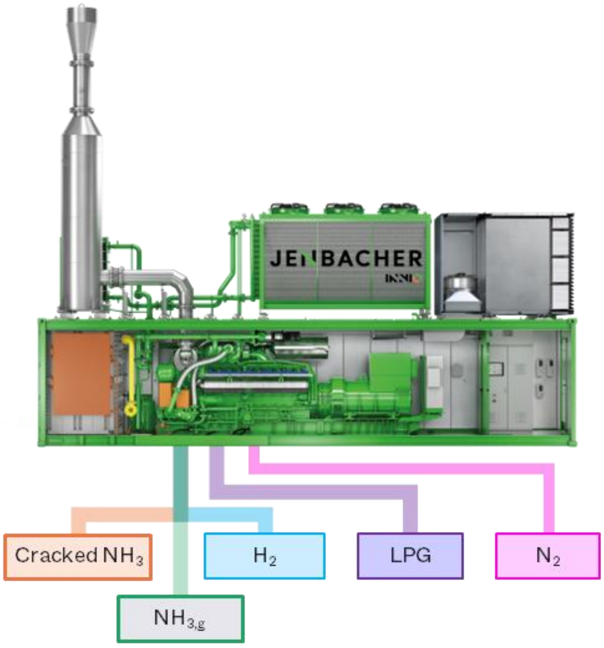


Figure 11: Jenbacher J412 container genset with $NH_3$, $H_2$, LPG, and $N_2$ supply

The genset is designed to enable high fuel flexibility for various hydrogen/$NH_3$ mixtures. Specifically for a test bench environment, LPG will be used for initial startup of the system, running checks before switching to $H_2$/$NH_3$ as the main fuel. Via the additional hydrogen supply, different $H_2$/$NH_3$ mixtures will be tested to fine-tune operating maps before coupling the $NH_3$ cracker, which will supply hydrogen directly from the gaseous $NH_3$ feed (with no external hydrogen or secondary fuel needed). The $NH_3$ cracker is sized to deliver the desired quantities of hydrogen for the entire targeted engine load range as shown in Figure 9.

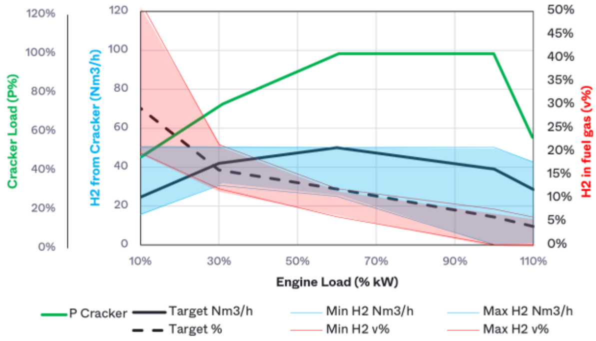


Figure 9: Hydrogen supply from the cracker over the engine load

The turbocharger matching was performed for the full load range, considering various $H_2/NH_3$ mixtures as illustrated in Figure 10. The selected turbocharger specification allows for the achievement of high efficiency and engine loads. The engine settings defined for the full load point with ammonia lead to a reduced compressor pressure ratio compared to the full load point with lean burn natural gas, thereby enabling a higher margin to the surge line and the speed limit.

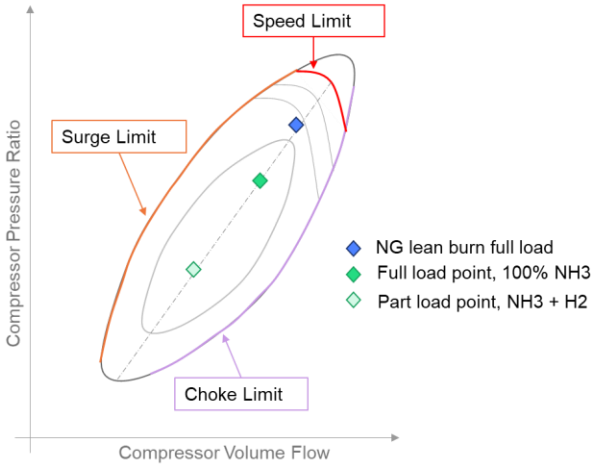


Figure 10: Turbocharger matching for $NH_3$ operation

One optimization during the tests will be to minimize the hydrogen content but maximize the engine performance while paying attention to overall emissions ($NH_3$, NOx, $N_2O$). This means providing optimal boundary conditions for the aftertreatment system to achieve very high conversion efficiency to enable low emissions at stack out over a wide operating (load) range. Further tests also will optimize the system startup performance with the target, avoiding a warmup via LPG. In other words, start up the system with $H_2/NH_3$ directly, improve startup performance and emissions via engine calibration (e.g., $H_2$ ratio, air-fuel ratio and ignition timing), and therefore avoid the requirement for a secondary fuel.

Special measurement technology, including emission measurement, additional sensors and an indication system to collect high-speed (combustion) engine data, is installed to evaluate and tune the performance of the engine and overall system.

Modifications to accommodate $NH_3$ as a fuel on a stationary genset for power and heat generation using a spark-ignited combustion system are listed below:

- Combustion system (power unit, ignition system) optimized for $NH_3$ operation
- Turbocharger to achieve high efficiency and engine loads (same as natural gas)
- Sealings (and partial material changes) on relevant assemblies to enable $NH_3$ compatibility
- Gas pressure control and gas metering systems
- Control system with additional sensors and actuators
- Container package to enable additional safety (e.g., gas sensors) and ventilation requirements

Ammonia is corrosive to brass, copper, nickel and elastomers as well as plastics. It is not critical for all other technical materials. However, there is a risk of nitric acid formation as a by-product of combustion. Therefore, not only the materials mentioned can be attacked by the ammonia combustion, but other materials and plastics can also be attacked by corrosion. Increased wear in direct contact with ammonia has not yet been observed. There is a risk that wear may be increased by tribo-corrosive mechanisms for the materials mentioned. In addition, corrosion can also occur if nitric acid is formed as a by-product of combustion.

A flare system (not shown in the 3D sketch) is used to safely combust any released ammonia gases, which are derived during testing or purging of the system. Further safety measures include an advanced gas and fire detection system.

## 5 CONCLUSIONS

In summary, innovative large engines can make a significant contribution to decarbonization and thus to the energy and heat transition. The operation with renewable hydrogen and ammonia as completely $CO_2$-free fuels is of particular interest. A significant advantage of ammonia is the effective transport over longer distances, which plays a crucial role, for example, in importing into the EU by ship. It can be liquefied much more easily than hydrogen and offers a decisive advantage here, as a significantly larger amount of energy can be transported due to the higher energy density at a given tank capacity. Additionally, ammonia offers advantages in synthesis, as no additional $CO_2$ is required, and the nitrogen demand can be easily met using atmospheric nitrogen. Thus, elaborate measures to ensure $CO_2$ neutrality by closing the $CO_2$ cycle are unnecessary. Solutions for use in large engines were presented in this article, including an outlook on a 1 MWe demonstrator constructed at the Campfire Open Innovation Lab. Particular attention was paid to increasing performance to the level of innovative natural gas engines so that no compromises are made when retrofitting existing power plants.

## 6 ACKNOWLEDGMENTS

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