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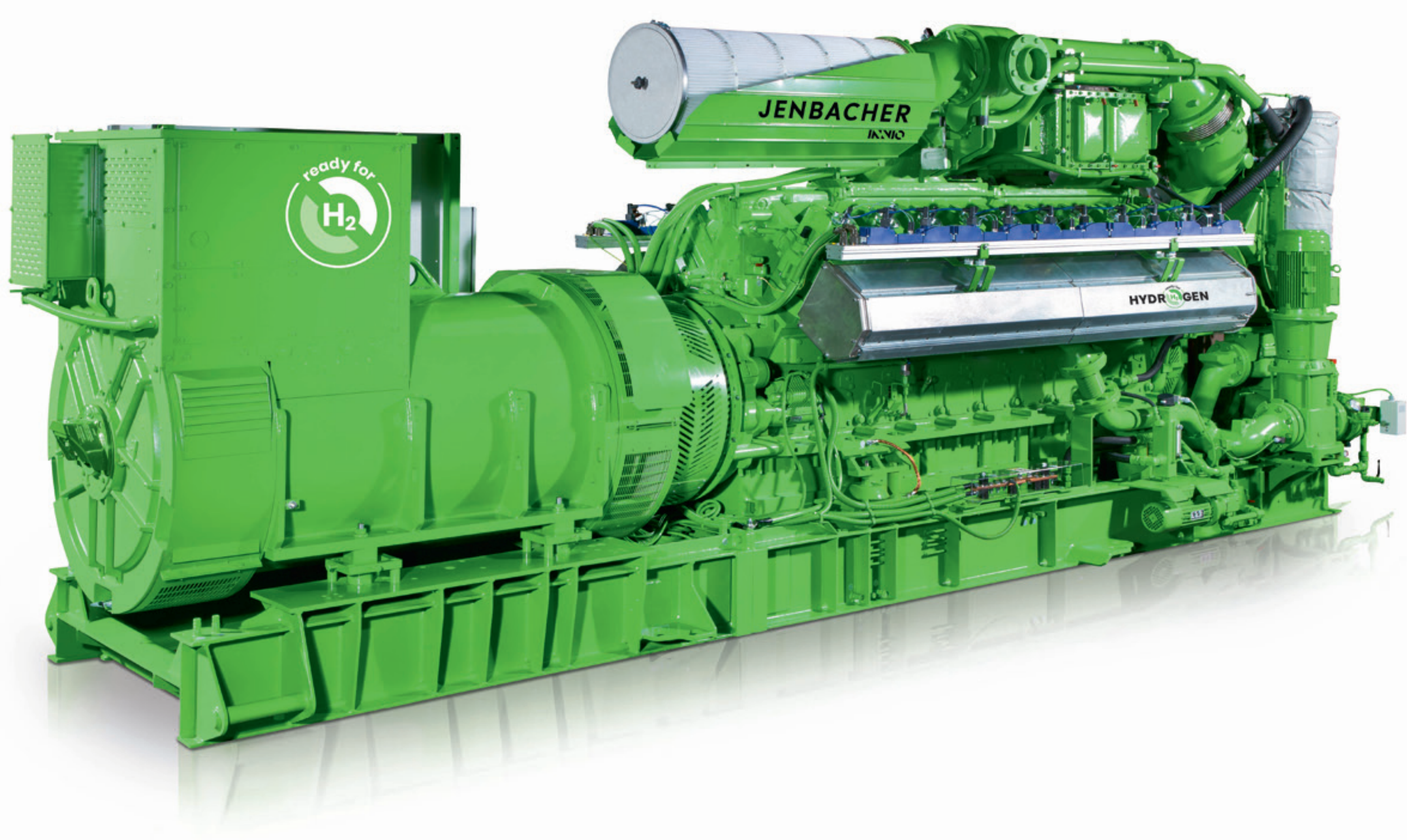
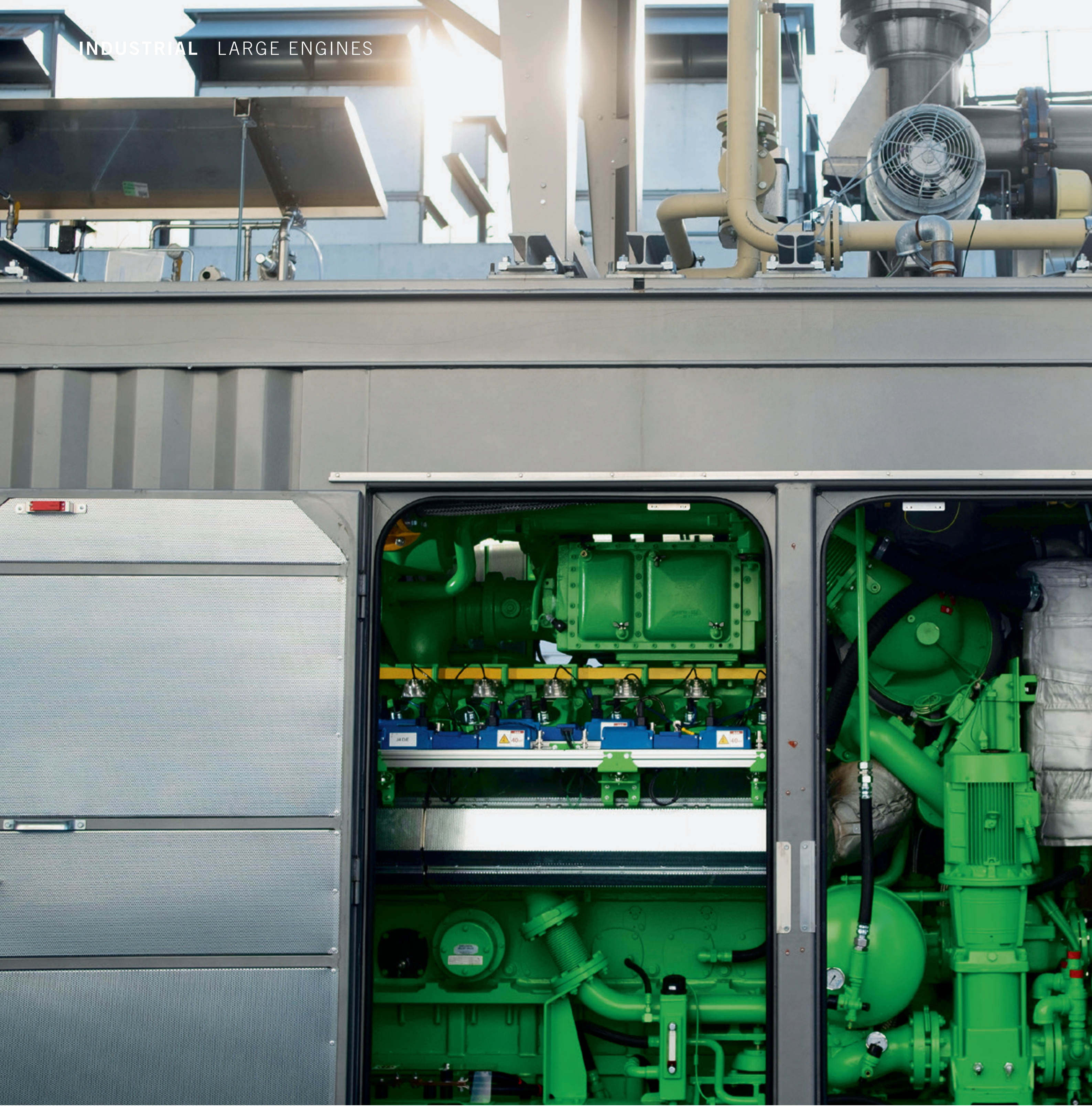


LARGE ENGINES

E-Fuels as a Key Technology for Decarbonization

JENBACHER | INNIO



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E-Fuels as a Key Technology for Decarbonization

Naturally occurring hydrogen and hydrogen produced by electrolysis from renewable electricity and water can be used as a fuel in stationary engines without any other chemical conversion. They also can be used to produce ammonia, methanol, or long-chain hydrocarbons, all of which are suitable as e-fuels. In the Innio Group's engines, they enable a carbon-neutral or in the case of using H_2 and ammonia also carbon-free energy supply and, therefore, are a driving force in the transition from fossil fuels to renewable energy sources.

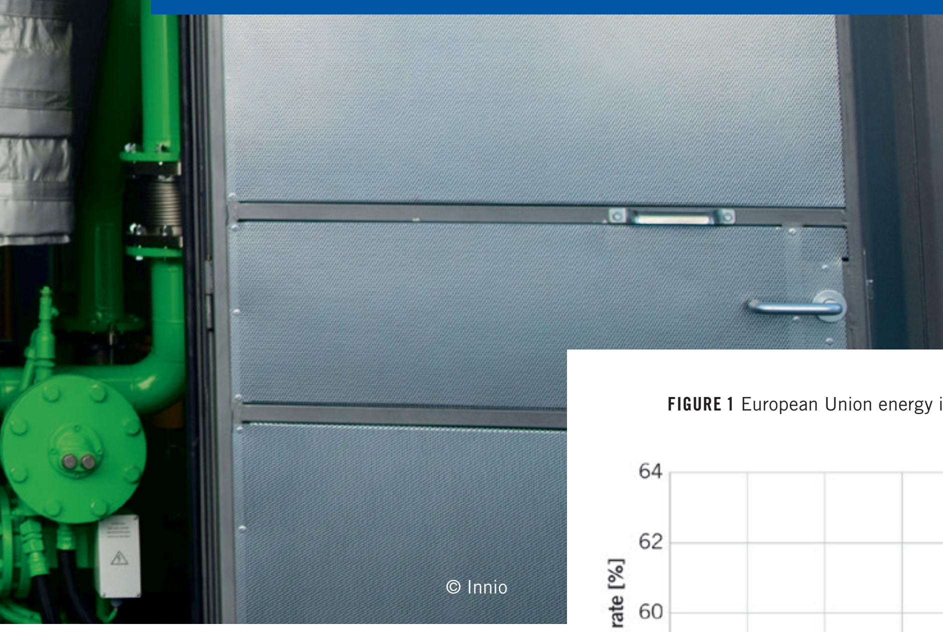
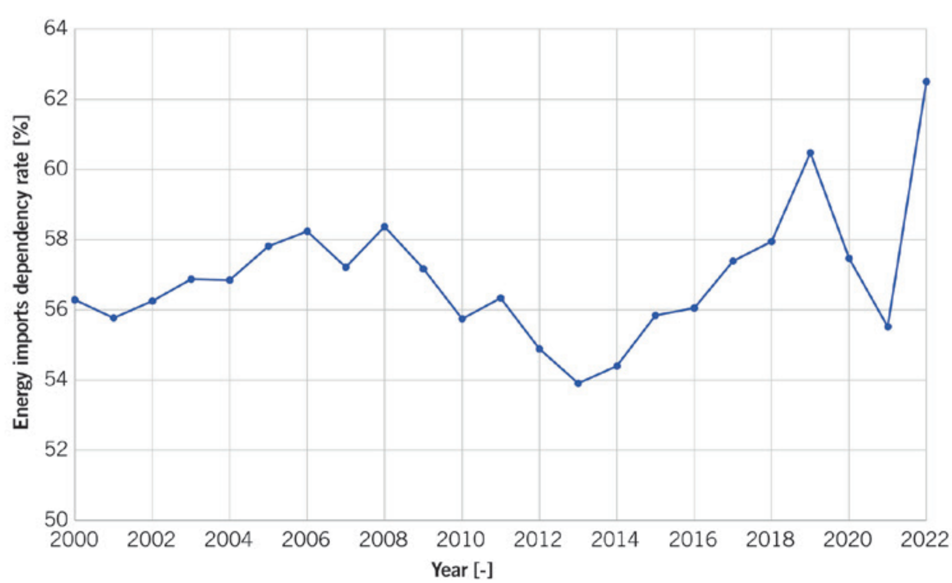


FIGURE 1 European Union energy imports (© Innio)



About 50 to 60 % of the energy required in the EU is imported [1], **FIGURE 1**. If the agreed climate action targets are to be met, more of this energy will need to come from renewable energy sources. As countries with a constant and abundant supply of sun and wind are too far away for electricity to be transported over high-voltage lines, conversion into chemical

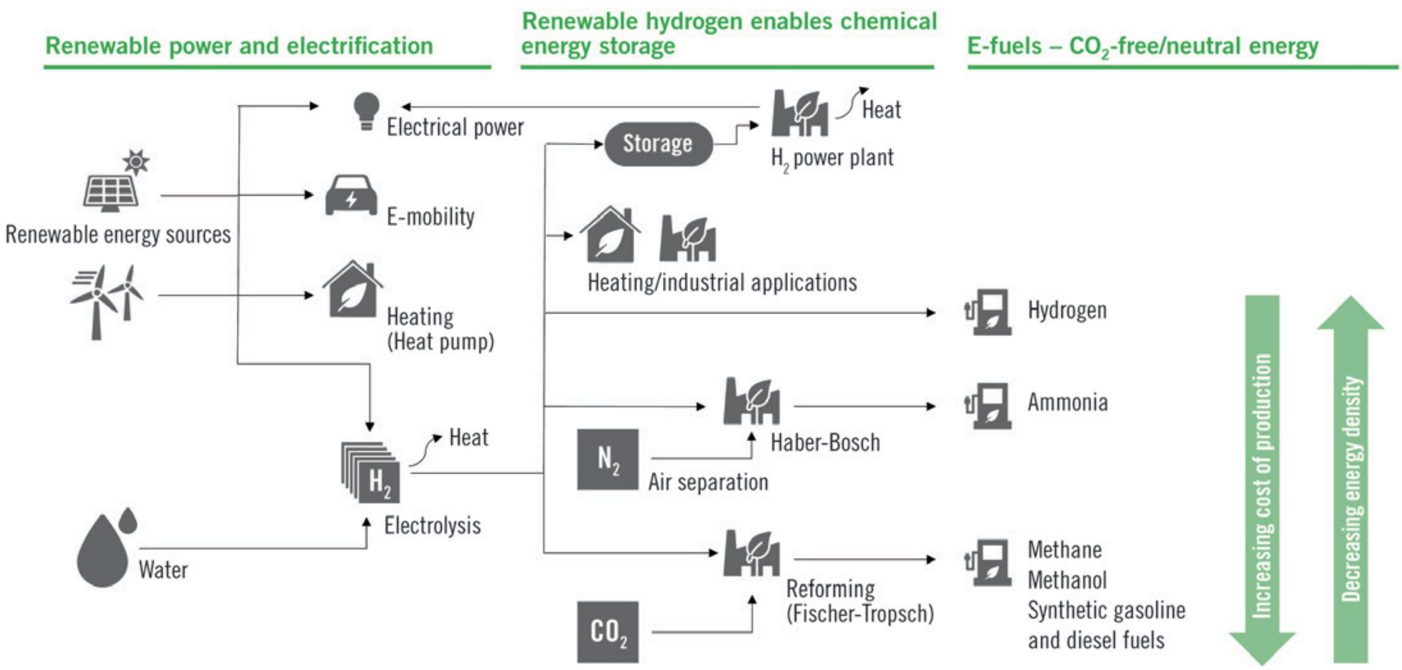


FIGURE 2 Overview of Power-to-X energy paths (© Innio)

energy sources using the Power-to-X process is unavoidable. **FIGURE 2** shows the different ways to produce hydrogen, ammonia, methane, methanol, or long-chain hydrocarbons.

THERMODYNAMIC PROPERTIES OF E-FUELS

Further analysis restricts the range of e-fuels to methane, hydrogen, ammonia, and methanol. The comparison of their physical properties shows that hydrogen has a very high gravimetric heating value, but a very low volumetric energy density, **TABLE 1**. This poses a major challenge for transport and tank systems using mobile applications, as large quantities of hydrogen can only be stored and transported effectively in liquid form under high pressure or in cryogenic conditions. For longer distances, hydrogen is converted to ammonia or methanol, which can be liquefied easily and have a significantly higher volumetric energy density than liquefied hydrogen under typical storage conditions. **TABLE 1** also shows the key physical properties for assessing the motorized use of e-fuels. Despite differences in volumetric energy content, they all have an acceptable energy density for typical air-fuel mixtures.

USE OF HYDROGEN IN ENGINES

There are different use cases for hydrogen in modern large engines: from adding it to the existing natural gas grid to 100 % hydrogen operation. **FIGURE 3** also shows a categorization based on hydrogen concentration. Category A describes engine systems that use a mixture of natural gas and maximum 25 vol% hydrogen from the grid. In category B, the mixture of hydrogen and natural gas takes place locally, and category C describes engines that run on 100 % hydrogen. The main differences in the chosen engine systems

TABLE 1 Physical properties of e-fuels (© Innio)

Properties	Unit	Methane (CH_4)	Hydrogen (H_2)	Ammonia (NH_3)	Methanol (CH_3OH)
Density (typical storage conditions)	kg/Nm³	CNG: 192/ LNG: 422	Compressed 20.54/ cryogenous 70.85	626	786.3
Heating value	MJ/kg	50	120	18.8	19.5
Energy density (typical storage conditions)	MJ/l	CNG: 9.6/ LNG: 21.1	Compressed 2.46/ cryogenous 8.5	11.78	15.33
Energy content of air-fuel-mixture ($\lambda = 1/\lambda = 2/\lambda = 3$)	MJ/m³	3.06/ 1.60/ 1.09	2.87/ 1.68/ 1.19	2.81/ 1.58/ 1.10	3.08/ 1.64/ 1.12
Ignition delay (λ = 1, T = 1200 K, p = 30 bar)	ms	1.33	0.11	~ 40	-
Laminar flame speed (λ = 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 (λ/volumetric)	-/ vol%	0.53-2.1/ 4.4-16.5	0.15-10.5/ 4.7-75	0.7-1.6/ 15-28	0.25-1.95/ 6.7-36

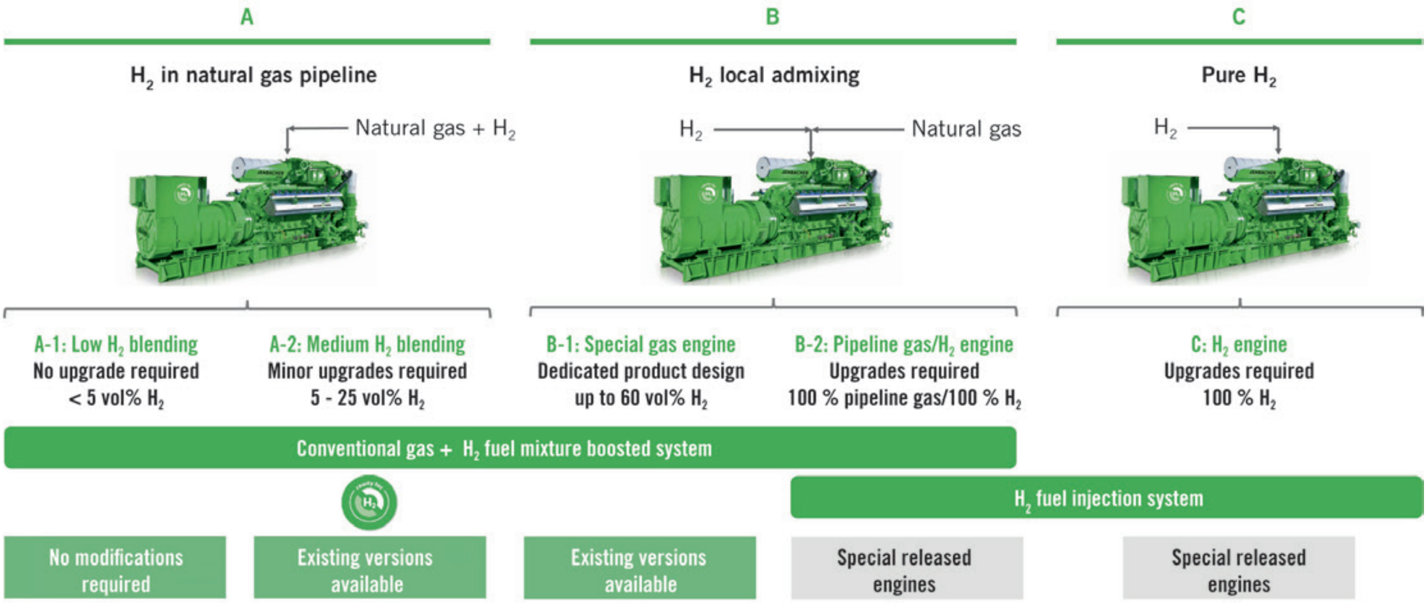


FIGURE 3 The Jenbacher hydrogen product portfolio (© Innio)

are the choice of fuel system and the hydrogen concentration.

The Innio Group's modern Jenbacher natural gas engine systems can be operated with up to 5 vol% hydrogen without any modifications, as this has only a negligible effect on the combustion properties of the natural gas, and the existing engine control system optimized for natural gas can compensate for these influences (category A-1). If the hydrogen concentration rises above 5 vol% up to a maximum of 25 vol% (category A-2), a hydrogen sensor and corresponding compensation software must be retrofitted. This can be done with all current Jenbacher engine variants, and it compensates for the faster combustion caused by the hydrogen admixture, so the engine load and emissions remain within the permissible values [2].

There are two different scenarios for the local addition of hydrogen. For admixtures with up to approximately 60 vol% hydrogen, engine systems are used that have been specially optimized to run on hydrogen-rich gases. Such Jenbacher engines already in use are running on wood and synthesis gases. The Innio Group has many years of experience in this field.

When the hydrogen admixture is to be 60 up to 100 vol%, category B-2 and C engine systems are used. They feature a dedicated hydrogen fuel system with port fuel injection technology, a combustion process optimized for hydrogen, and an advanced engine management system with cylinder pressure-based control. The main advantage of port fuel injection technology is that hydrogen is only added just before it enters the combustion chamber, which is an important safety feature. In addition, the amount of fuel can be adjusted individually for each cylinder. As the natural gas engine's conventional fuel system still can be used, this opens up the possibility of dual-fuel operation, in which hydrogen and natural gas are mixed directly in the engine. This enables operation with varying hydrogen content without any additional external fuel mixing equipment, as well as the ability to switch from 100 % hydrogen to 100 % natural gas. This means that engine operation can be guaranteed at all times, even if the availability of hydrogen fluctuates.

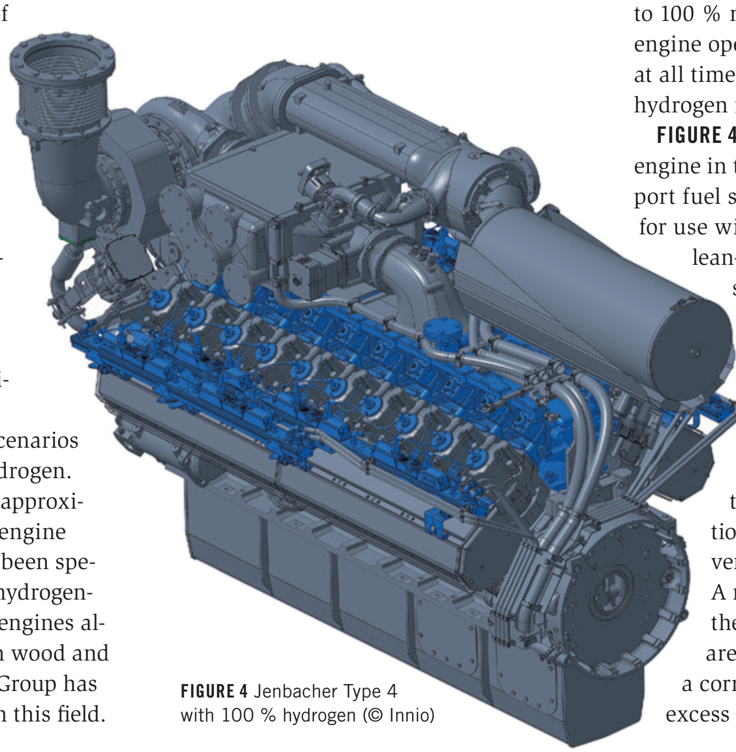


FIGURE 4 Jenbacher Type 4 with 100 % hydrogen (© Innio)

FIGURE 4 shows a Jenbacher Type 4 engine in the dual-fuel version with the port fuel system and ignition system for use with 100 % hydrogen. In the lean-burn combustion process described here, the significantly faster combustion rate and higher reactivity of hydrogen are compensated for by correspondingly higher excess air content and an adjustment of the ignition timing, so that the combustion rates approach those of conventional natural gas operation. A major advantage of this is that the engine's NO_x emissions also are reduced significantly with a correspondingly high level of excess air.

USE OF AMMONIA IN LARGE ENGINES

For the ammonia combustion process investigated here, Jenbacher engineers opted for the addition of hydrogen and the use of a spark plug for safe ignition and combustion acceleration. Catalytic ammonia cracking eliminates the need for a second fuel, simplifying the infrastructure and logistics and enabling complete decarbonization.

The concept was tested successfully in a high-speed four-stroke single-cylinder test engine regarding the influence of the air-fuel ratio and different hydrogen concentrations and ignition times. With the technology concept described, indicated mean pressures of up to 25 bar could be achieved with a minimum admixture of 2 up to 6 vol% hydrogen. **FIGURE 5** shows the main results at an indicated mean pressure of 23 bar. Increasing the hydrogen content at constant excess air generally results in a shorter ignition delay and faster conversion of the air-ammonia mixture in the combustion chamber. While the hydrogen concentration only has a minor influence on the NO_x emissions, the excess air has a major influence.

The observed results are very promising, as the selected concept was able to demonstrate stable engine operation with high power density at a very low hydrogen content in the fuel. The observed ammonia and NO_x emissions can be addressed using a commercially available SCR system [3].

INVESTMENT SECURITY AND CERTIFICATION

In October 2023, the Jenbacher hydrogen engine concept for Series 4 and 6 running on 100 % hydrogen was audited and certified by TÜV Süd on the basis of the "H_2-Readiness of Gas Engine Power Plants" guide. The awarded certificate takes into account the current state of technology regarding the use of hydrogen and its effects on an engine power plant's main components. In addition to new installations, it also covers the concept developed by the Innio Group for retrofitting large engines to run on 100 % hydrogen.

This certification corroborates the Innio Group's claim to offer its customers engine systems that already are equipped to run on hydrogen. All Jenbacher types can be purchased or retrofitted to run on 25 vol% hydrogen. They also subsequently can be retrofitted to run on 100 % hydrogen at a later date. This provides crucial investment security, especially in view of current supply uncertainties during the hydrogen ramp-up.

SUMMARY

Modern large engines can make a significant contribution to decarbonization – especially if they run on green hydrogen and ammonia as completely carbon-free fuels.

Hydrogen has excellent combustion properties and can be used in modern engine systems both blended with natural gas and in pure form. The expan-

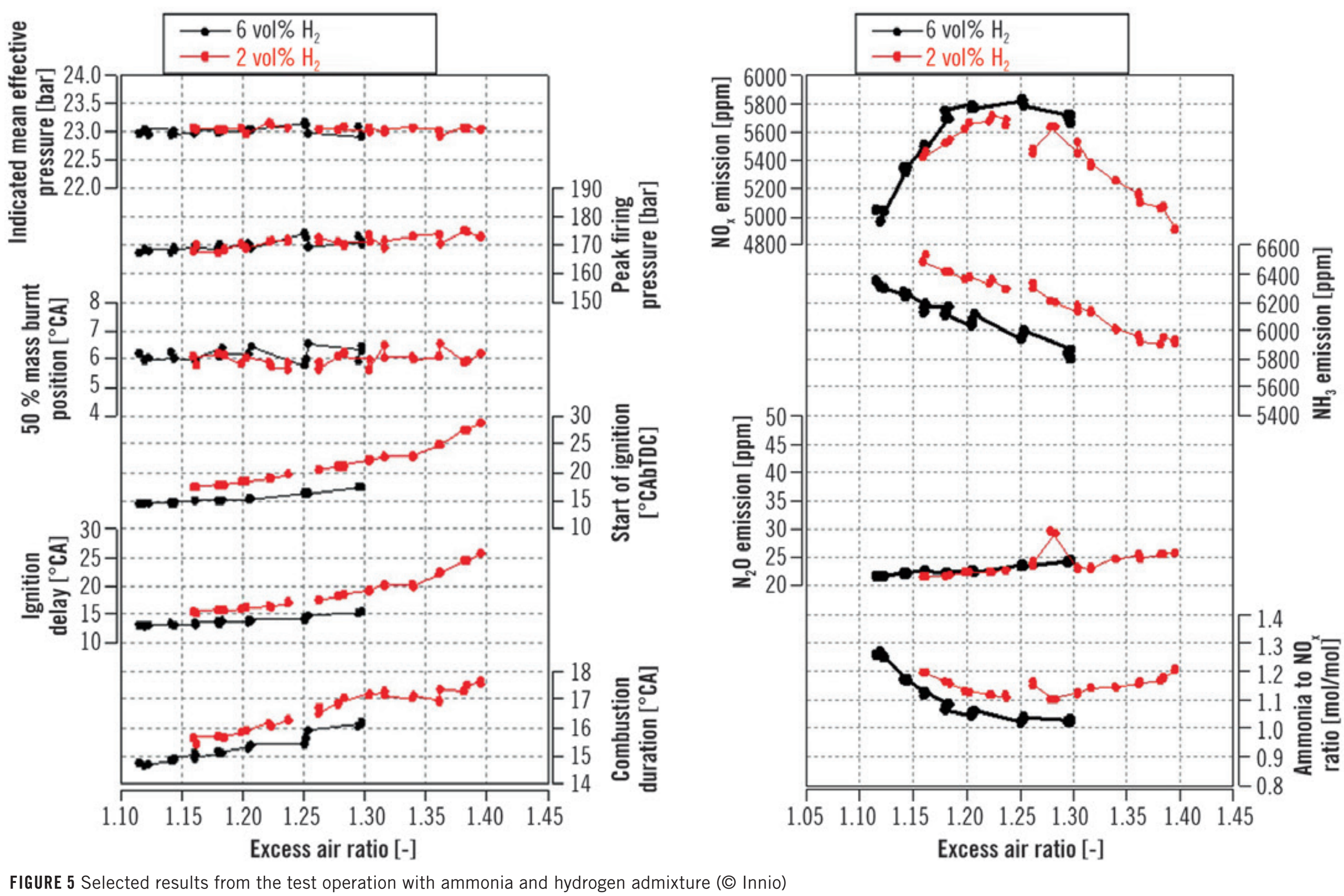


FIGURE 5 Selected results from the test operation with ammonia and hydrogen admixture (© Innio)

sion of the European hydrogen grid and the repurposing of existing natural gas grids will enable the distribution of hydrogen on a large scale. Intercontinental transport of natural gas now increasingly is taking place in liquid form as LNG, but this transport is much more complicated and expensive for hydrogen. Ammonia, on the other hand, is much easier to liquefy, making it ideal for longer distances and larger volumes. It also has the advantage of not requiring CO_2 for its synthesis.

The Innio Group already has developed solutions for the use of hydrogen and ammonia in large engines and offers an engine system for the use of 100 % hydrogen with the Jenbacher Type 4. A first concept for the use of ammonia without the need for an additional ignition fuel has been demonstrated successfully on a research engine and will be further improved in the next few years. Beginning in 2025, the Innio Group plans to introduce additional solutions for the use of 100 % hydrogen with larger engines with several MW of power. The goal also is to bring the specific power density of hydrogen engines as close as possible to that of modern natural gas engines so that no major compromises must be made when an existing power plant is retrofitted from natural gas to hydrogen operation at a later date.

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