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The role of gas engines in a future energy market with sustainable fuels

Fuels - Alternative & New Fuels

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ABSTRACT

The world and its climate are changing faster than ever before. The European Commission has made the European Green Deal with its “Fit for 55” package a top political priority to align with the Paris agreement limiting global warming to 1.5°C. To put the European Union on a balanced, realistic and prudent path to becoming climate neutral by 2050, the Commission has agreed to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Basically, all scenarios predict a massive reduction in engine operation with fossil fuels by 2050 and an increase of alternative sustainable fuels.

Due to the volatility of renewable energy sources such as wind and solar, fast backup power supply and energy storage is a key challenge. On the one hand, a short-term solution is needed to balance fluctuations within a day. On the other hand, seasonal supply fluctuations require storage of several TWh over a half-year period.

Energy storage with batteries is a viable option for only a few hours. Seasonal storage of a carbon-free fuel must follow the H2 route. Hydrogen can be stored directly, in “hydrogen carriers” or in synthetic fuels. Gas engines for biogas or green synthetic methane (SNG) are already developed, and existing products can be used. For other synthetic fuels such as methanol or ammonia, development is required to modify existing gas engine technology

The basic requirements for gas engines will change. Some years ago gas engines where operated up to 8000 h per year and with about 10 oph/start. With all the renewable energies in the electric grid, the requirements are changing. Gas engines operated with carbon free or carbon neutral fuels in a peaking or backup mode will support the grid.

This paper will address the changes in engine operation from the fuel supply to the operating profile. And in specific how INNIO is addressing these changes in the engine and controls architecture. With a special focus on fast start up and grid stabilization.

1 INTRODUCTION

The world and its climate are changing faster than ever before. With CO2 in the atmosphere already passing the 400 ppm mark, CO2 pollution must be lowered to limit rising atmospheric temperatures from global warming. The European Commission has made the European Green Deal with its “Fit for 55” package a top political priority to align with the Paris agreement limiting global warming to 1.5°C. It is the European Union’s aim to transform into a fair and prosperous society with a modern, resource-efficient and competitive economy, while leaving no one behind. The climate ambitions of the Commission were reinforced in 2019 with the Green Deal Communication 1, which set an objective of net zero greenhouse gas emissions by 2050. To put the European Union on a balanced, realistic, and prudent path to becoming climate neutral by 2050, the Commission also has agreed to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Those ambitious targets have been enshrined in European Climate Law. With the “Fit for 55” package, the Commission has presented the legislative tools, including 13 legislative proposals to deliver on the approved targets in the European Climate Law.

Europe is aiming for carbon neutrality by 2050, but the energy transition is not just an EU initiative. Countries inside the EU and globally are setting targets to reach carbon neutrality even before 2050. This global transition is centered on the transformation from a largely fossil-based to a low or carbon-neutral energy system. This implies strong growth of the well-known renewable energy sources (RES) such as volatile wind & solar PV.

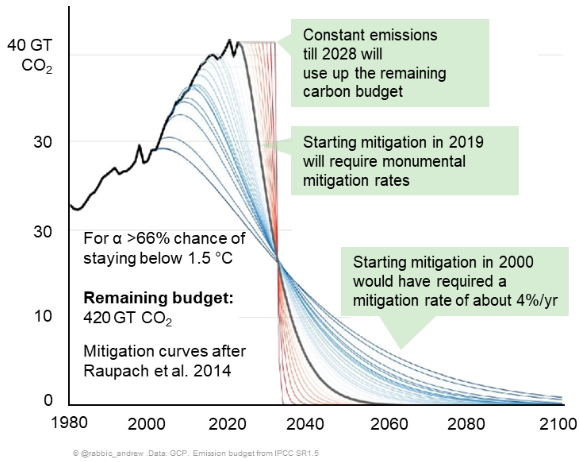

Figure 1. CO2 mitigation curves 1.5 °C target [1]

As CO2 stays for a longer time in the atmosphere, a remaining CO2 budget can be calculated to reach the 1.5°C target. Figure 1 shows the annual CO2 emissions and scenarios to reach the 1.5 °C target.

If the world had begun working to reduce GHG emissions in 2000, a “moderate” GHG reduction by about 4% would have been required. Year over year, the required reduction rate increased, and if we keep emissions on the level of 2019, we will have used up the remaining budget by 2028.

We must either reduce emissions to zero by 2028 or introduce technologies to remove CO2 from the atmosphere. One trend is toward electrification. With electric propulsion for passenger cars and trucks, electrification is supporting a new sector of energy consumers that—until now—was dominated by fuels. And with a strong growth forecast for heat pumps, electrification also is growing in the heating sector. However, there is a big challenge with the imbalance of volatile RES supply and electricity demand, which cannot be fixed with demand side management and large battery energy storage alone.

Energy storage is one of the big challenges of the energy transition. Multiple technologies exist that can manage the storage of relatively small amounts of energy over a short period of time, but technologies with large storage capacities that can store energy over a long period of time and provide seasonal storage also are required (Figure 2). Currently, the production of green hydrogen from RES is the most promising solution for large (TWh capacity) and seasonal renewable energy storage. Energy stored directly as hydrogen or as hydrogen-based fuels, such as synthetic methane, green methanol, ammonia, or other synthetic fuels, are the options on the table.

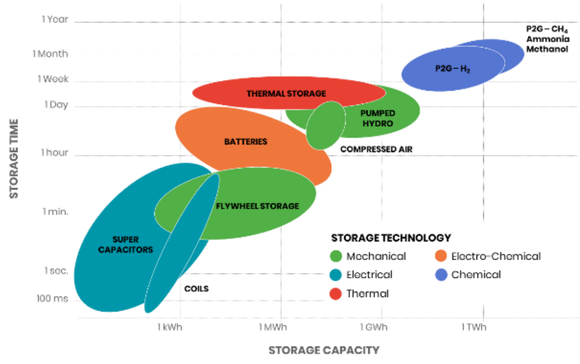

Figure 2. Energy storage options capacity vs. duration

Maintaining a stable and steady energy supply that is mainly based on volatile RES requires a flexible and dispatchable backup solution. Battery energy storage solutions will be available but can serve only relatively small capacities and merely provide hourly storage. Backup solutions based on fuels can provide large energy storage for longer periods of time. Such fuels, which will become 100%

renewable fuels over time, can be used for centralized and distributed power generation in the transportation sector, the heating sector, and industry in all kinds of established and mature technologies, such as combined heat and power (CHP). For power generation, we call solutions based on renewable fuels dispatchable renewable energy sources (dRES) because they are available when needed and run on renewable fuels—the backbone of the volatile renewables wind and solar PV.

2 THE CHALLENGE

To reach net zero with GHG emissions requires a change in the power generation products. If we have a closer look at the CO2 intensity in g/kWh of different electric power production technologies (Figure 3), we see options to reduce GHG emissions.

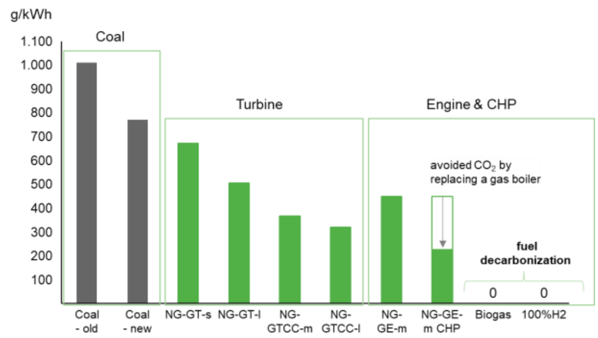

Figure 3. CO2 intensity of different technologies

Using fuels with higher hydrogen content lead to lower CO2 emissions. And with the same fuel, operations with higher efficiency are more beneficial. CHP plants, which are in the range of up to95% overall efficiency, are the preferred option in power production.

A switch from an old coal-fired power plant to a modern CHP large engine power plant can reduce the GHG emissions by more than70%, if electric power and heat are used. But to step down to 0 g/kWh GHG emissions, a change in fuel is needed. Net zero can be reached with carbon-neutral fuels like biogas or green methanol or a switch to carbon-free fuels like green hydrogen or green ammonia. The production of these carbon-free fuels must come from renewable energy sources.

Table 1 lists some key combustion parameters that show the differences of the target fuels hydrogen (H2), ammonia, and methanol when compared to methane. Methane is the reference fuel and is representing natural gas. While other Fischer-Tropsch fuels are possible, the focus of this paper is spark-ignited engine operation.

Table 1. Parameter of different fuels

		Methane	H_2	Ammonia	Methanol
CH_4	Vol-%	100	0	0	0
H_2	Vol-%	0	100	0	0
NH_3	Vol-%	0	0	100	0
CH_30H	Vol-%	0	0	0	100
LHV	kJ/Nm³	35,784	10,800	13,665	
LHV	kJ/kg	50,013	120,000	18,720	19,900
Auto-ign. temperature	°C	595	585	657	439
Min. ignition energy	mJ	0.29	0.017	8	0.14
MN I Octan number	-	100 / 130	0 / -	- / 130	- / 119
Lam. Flame speed	cm/s	38	350	7	36
Density	kg/Nm³	0.66	0.08	0.73	786

Specifically, the minimum ignition energy and the laminar flame speed should be mentioned. These parameters are extremely different for hydrogen and ammonia, and only methanol is comparable to methane. The parameters study concludes that:

- Hydrogen has a very low minimum ignition energy, which will lead to an increased risk of preignition. For safe operation, the air/fuel ratio must be on the very lean side to reduce the laminar flame speed of the mixture.

- Hydrogen will burn very fast, which will lead to a high air/fuel ratio demand to keep the combustion stable with enough knock margin.

- Ammonia is hard to ignite and has a slow flame propagation, leading to combustion systems with a combustion “enhancer.” Additionally, it will need to be determined whether to feed the ammonia into the engine as gas or liquid, which is the way it usually is stored. The vapor pressure of ammonia is 8.57 bar at 20°C, and the boiling temperature is -33.3°C at ambient pressure.

- Methanol is similar to natural gas except that it is present in liquid form and must be evaporated. The challenge is to avoid the intensive cooling of the mixture if it is injected as a liquid in the engine.

2.1 A hydrogen blend in the natural gas grid

The blending of hydrogen into the existing natural gas grid has been discussed. Gas transmission grids should be capable of at least 5% volume of hydrogen blends. For gas distribution grids, 10, 20 or even 25% volume of hydrogen blending is under investigation. Although some tests of the gas pipeline infrastructure show good results with a hydrogen content of up to 20% volume, some end consumers have difficulties with the changing gas properties.

While LNG imports from different suppliers around the globe already result in changing gas properties beyond current limits, hydrogen blending leads to additional challenges. Blending 20% volume of hydrogen can change the Wobbe Index by 5% to 6% but reduces the methane number by 10 to 15 points. Blending hydrogen to natural gas also brings gas billing challenges because the Lower Heating Value changes significantly. Especially when the hydrogen blending is not constant, varying for example between 0 and 20% volume, the heating value changes by about 15%. Engines with an adapted controls strategy can handle the discussed amounts of hydrogen in the gas grid.

Figure 4 shows decarbonization results with hydrogen blending. As the blending is always referenced in volume percentage and hydrogen has a very low density (~1/8 from natural gas), the impact on CO2 emission reduction is low. Natural gas blended with 20% volume hydrogen will lead to a CO2 reduction of only 7%. A significant CO2 reduction in the order of 50% requires about 80% volume H2 blending, and with this amount we can step straight to a 100% hydrogen version.

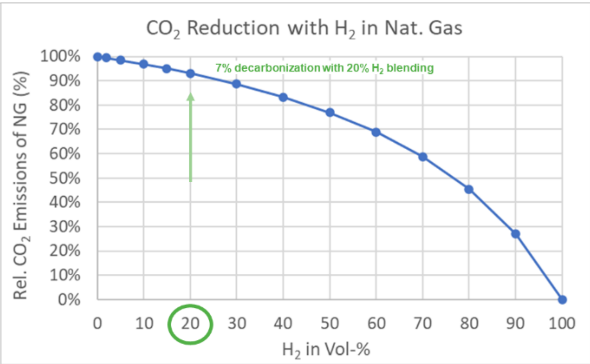

Figure 4. CO2 reduction with H2 in natural gas

2.2 Future engine requirements

Large engines are the backbone to stabilize the electrical grid in the future. Most likely, engines will not be operated with natural gas. Engines will be operated with e-fuels, such as hydrogen, ammonia, or methanol, and engine manufacturers need to develop products that can be used with these fuels to avoid “stranded assets.” Retrofit kits are mandatory if these engines will be used the new e-fuels.

3 THE SOLUTION

Driven by the fuel properties, different combustion concepts must be developed. INNIO’s development work takes place in close cooperation with the LEC GmbH, a university-related R&D company in Graz, Austria. Development is done in the standard way, with simulation-supported engine component testing and single cylinder and multi cylinder engine tests.

One challenge with e-fuels is the infrastructure. The fuel supply and handling are different when compared to natural gas. Therefore, the infrastructure needs to be set up properly for multi fuel applications.

3.1 H2 combustion

3.1.1 H2 testing infrastructure

Today, hydrogen testing is a challenge with multi cylinder engine test runs. Because a hydrogen pipeline infrastructure typically is not available, hydrogen must be shipped with trailers. Such trailers only have a capacity of about 400 kg hydrogen (see Figure 5). As a rule of thumb, an engine with 1 MW electric power output consumes about 75 kg of hydrogen per hour.

Figure 5. Hydrogen trailer for engine testing

With this hydrogen consumption, a 1 MW engine requires a new trailer every day. The logistical effort and all the additional traffic are acceptable for a short test duration, but not for a sustainable H2 engine development procedure. In the long term, a hydrogen pipeline connection to the H2 engine test center is needed.

The fuel supply is one topic, and the stringent safety requirements and material compatibility is the other. Hydrogen, and specifically ammonia, needs special measures to ensure safe and reliable engine operation.

3.1.2 Combustion development

Combustion development was accomplished with three main targets driven by requirements from the field:

1. In the simulation of hydrogen blending to the natural gas pipeline, 0 – 25% volume of hydrogen should be considered.

2. Hydrogen should be admixed locally, from 0 to up to 100%, which is typical with a not stable

hydrogen supply. For example, natural gas could be the main fuel, with hydrogen admixed as available, or hydrogen could be the main fuel, with natural gas as the back-up fuel.

3. If no operation with natural gas is foreseen, the engine could operate on 100% hydrogen.

3.1.3 0 – 25% hydrogen blending

The engines need to tolerate up to 25% volume of hydrogen blended into the natural gas supply. As shown in Figure 6, engine settings are blocked and the combustion with 25% volume is accelerated.

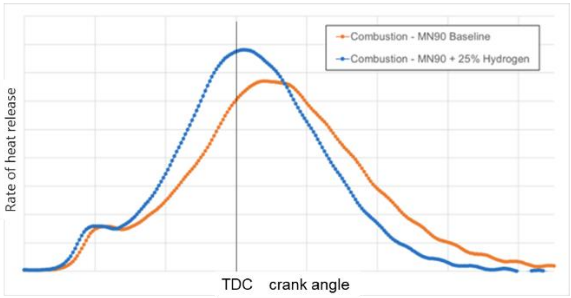

Figure 6. Heat release rate for natural gas vs. hydrogen combustion

This will lead the engine to exceed the NOx limits, depending on the NOx controls reserve at 100% natural gas operation (Figure 7), at some volume percentage ratio. With an active H2 controls system it is possible to keep the NOx emissions constant with different hydrogen volume percentage levels.

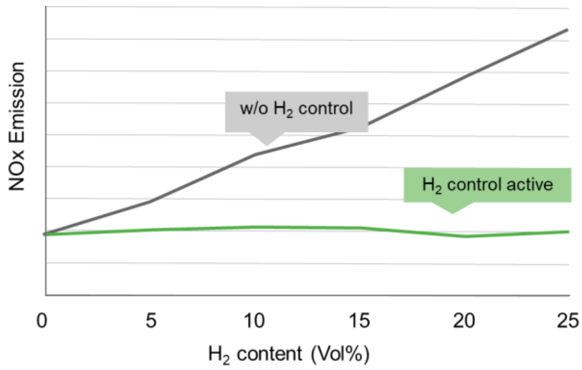

Figure 7. NOx emission with/without active H2 control

3.1.4 0 – 100% hydrogen admixing

A 100% dual fuel engine can be developed in two ways: an optimized engine for operation on natural gas that also is capable of operation with 100% hydrogen, but with compromises, or a dedicated hydrogen engine, with compromises when operated on natural gas.

The consequences on a dedicated natural gas engine are shown in Figure 8. The engine was optimized for the highest efficiency in natural gas operation, and it was tested to see what would happen if just the fuel was changed. Although engine operators request no changes in the engine, only the fuel, and with no other adjustments, this does not work. Remember that natural gas has a methane number of 100 and hydrogen of 0.

Both the natural gas operation in blue and the hydrogen operation in green are operated with the same hardware, with an optimized combustion regime with the same power rating. In hydrogen mode, the engine operation must be much leaner than in natural gas operation. Lambda was increased from 1.6 to 3.3. On the top of Figure 8, the cylinder pressure plot (labeled as 1) demonstrates that there is a much higher boost pressure demand with hydrogen operation to reach the same power output. This also leads to an increased peak firing pressure (PFP, labeled as 2). The engine structure must be designed for these high PFP values.

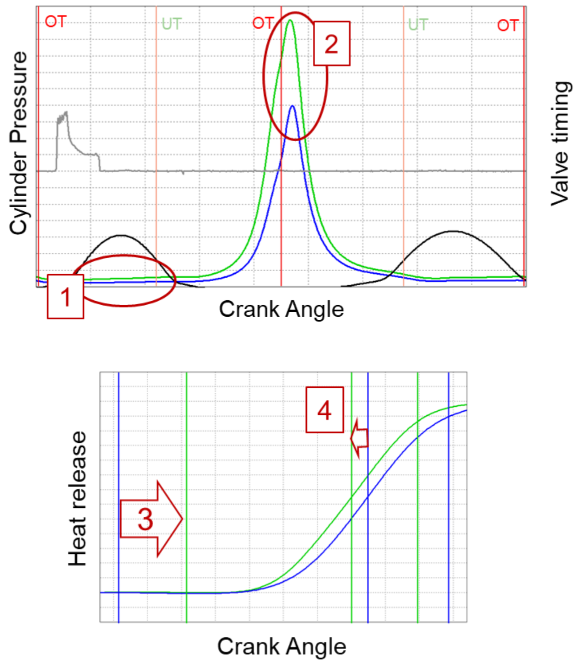

Figure 8. Combustion performance NG (blue)/H2 (green)

On the bottom of Figure 8, the heat release plotting shows the impact of the low ignition energy and high flame speed. The ignition timing (labeled 3 and 4) is the MFB50% point. With hydrogen, the Lambda is much higher, but even with retarded ignition timing the MFB50% point is earlier than in natural gas operation. The ignition delay of the hydrogen mixture is much shorter, and with the high air/fuel ratio the laminar flame speed is still higher.

The comparison was done at a lower engine load. If load is increased, abnormal combustion events can happen. Such an event is plotted in Figure 9. The cylinder pressure is plotted vs. the crank angle. A standard hydrogen combustion cycle is depicted in green, and an abnormal combustion event is shown in red. In the area labeled as 5 just before the intake valve is closing (black line), a backfire occurred. There is a pressure rise visible close to bottom dead center (BTC), and as all the charge is combusted there is only a compression and expansion in the cylinder but no combustion pressure rise at top dead center (TDC).

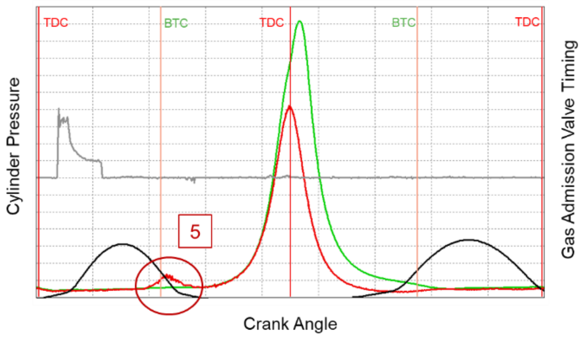

Figure 9. Abnormal combustion phenomena

The challenge is the high required boost pressure. In Figure 10, the consequences are shown. Compared to the 21 bar in natural gas operation, a 100% hydrogen engine has almost the same boost pressure requirements at 12 bar BMEP. Just to take a dedicated natural gas engine and change the fuel is not enough. The engine needs must be optimized for hydrogen combustion.

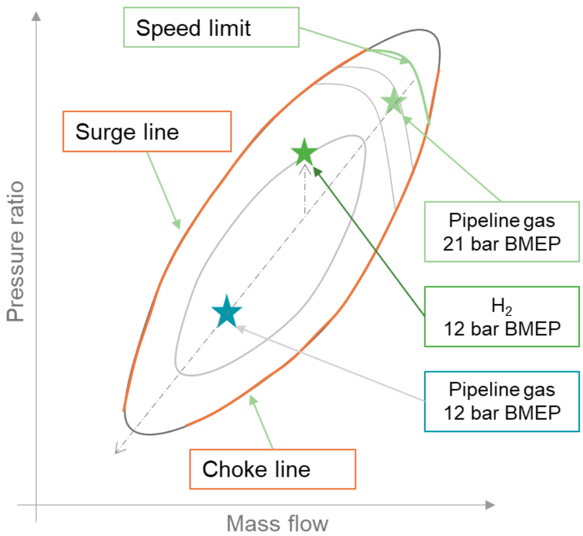

Figure 10. Compressor map example

3.1.5 Hydrogen engine

A 100% dual fuel engine, able to be operated on 100% natural gas or 100% hydrogen and all mixtures between, can be developed. The 1st 0 to 100% hydrogen capable engine is shown in Figure 11. This hydrogen kit is designed as a retrofit option to upgrade existing natural gas engines to hydrogen operation. The engine was tested successfully in 2020 and is under operation at a customer site.

Figure 11. INNIO's Jenbacher hydrogen engine

3.2 NH3 combustion

Due to the physical and chemical properties of ammonia, typical natural gas combustion concepts must be adjusted for a practical application in the internal combustion engine. The biggest differences in the fundamental properties of ammonia compared to other fuels typically used in internal combustion engines lie in the high minimum ignition energy and the low laminar flame speed. To alleviate this difficulty, a promoting agent to improve the combustion properties of ammonia can be employed. Besides using pure hydrogen, it was proposed to use an ammonia dissociation system to provide hydrogen as an ignition and combustion promoter for spark ignition engines.

Figure 12. Ammonia combustion concepts

Together with the LEC, we are investigating various fuel admission and ignition concepts for ammonia combustion on single cylinder research engines. The spark ignition concepts use external mixture formations of ammonia and air and employ hydrogen in various quantities as an ignition promoter. The hydrogen is combined with the ammonia-air mixture in the intake manifold. Two spark ignition concepts are being considered. While the first uses a direct ignition concept, the second uses a prechamber ignition concept in which hydrogen and/or ammonia also are supplied directly into the prechamber to enhance the ignition conditions at the spark plug location (Figure 12).

3.2.1 NH3 Testing Infrastructure

The test bed infrastructure at the LEC was expanded to provide the flexibility to investigate different ammonia combustion concepts and to fulfill all safety requirements. The ammonia supply for the engine test cells is provided by a mobile container in which up to 2,000 kg of ammonia can be stored in liquid form. A temperature-controlled vaporizer unit ensures a constant supply of gaseous ammonia to the engine test cell. A temperature-controlled catalytic exhaust gas aftertreatment system ensures that no increased pollutant concentrations are emitted. Advanced sensorics for ammonia and nitrogen oxides are installed for pre- and post-catalyst monitoring, and detailed exhaust gas specification is performed via FTIR measurements. The fuel supply infrastructure that is depicted in Figure 13 provides the flexibility to use various fuels and fuel mixtures and enables the use of scavenged prechamber concepts as well as open chamber concepts. The fueling infrastructure includes a natural gas supply and allows a smooth transition from natural gas to ammonia operation. Hydrogen and nitrogen in adjustable quantities can be added to the natural gas or the ammonia upstream of the fuel-air mixing unit.

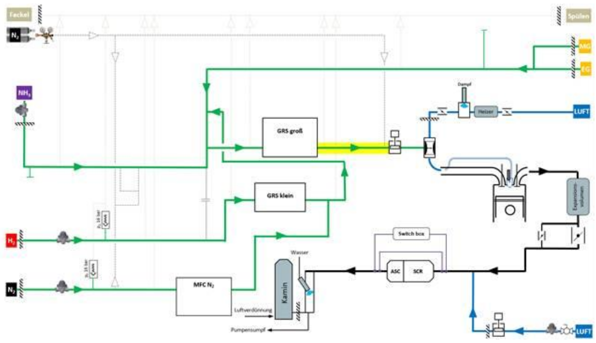

Figure 13. Test infrastructure for ammonia engine operation

3.2.2 Experimental test setup

The experimental investigations were carried out on a high-speed four-stroke single cylinder research engine (SCE) derived from INNIO's Jenbacher Type 4 series. The compression ratio (CR) was chosen in the range of typical large engine applications with low flashpoint fuels. Table 2 shows further information about the engine.

Table 2. SCE Type 4 technical data

Rated speed	1,500 rpm
Displacement	≈ 3 dm^3
Valve timing	Miller valve timing
Number of intake and exhaust valves	2/2
Charge air	Provided by external compressors with up to 10 bar boost pressure
Hydrogen supply	Central mixture formation
Ammonia supply	Central mixture formation
Ignition system	Modified high-voltage capacitor discharge

3.2.3 Measurement results

The goal of the experimental investigation was to assess 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 of 1,500 rpm.

In Figure 14, excess air ratio (EAR) variations are presented with 2% volume and 6% volume hydrogen admixture to the ammonia. 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 combustion performance parameters are presented in Figure 15. The indicated efficiency is increasing with EAR, while there is only a small impact of the hydrogen fraction. Combustion stability could be maintained over the entire variation range, as indicated by the coefficient of variation of the IMEP and the peak cylinder pressure.

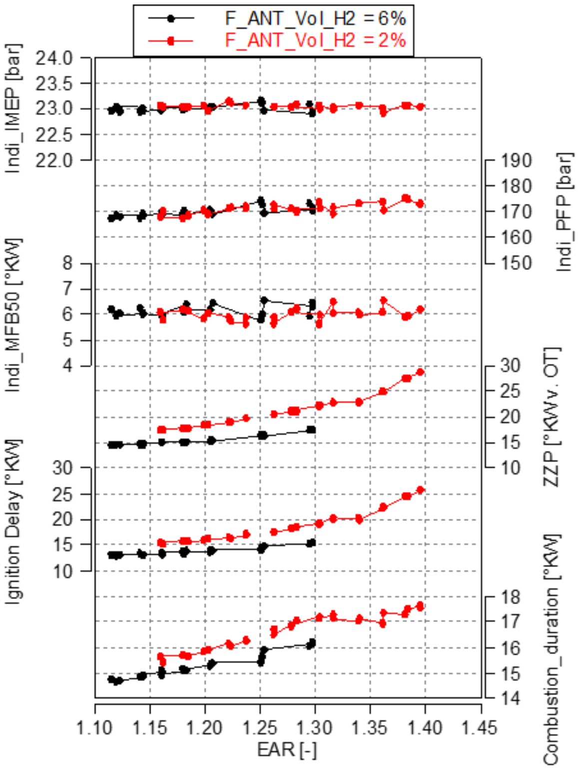

Figure 14. Selected measurement results for ammonia/hydrogen combustion @ 23 bar IMEP

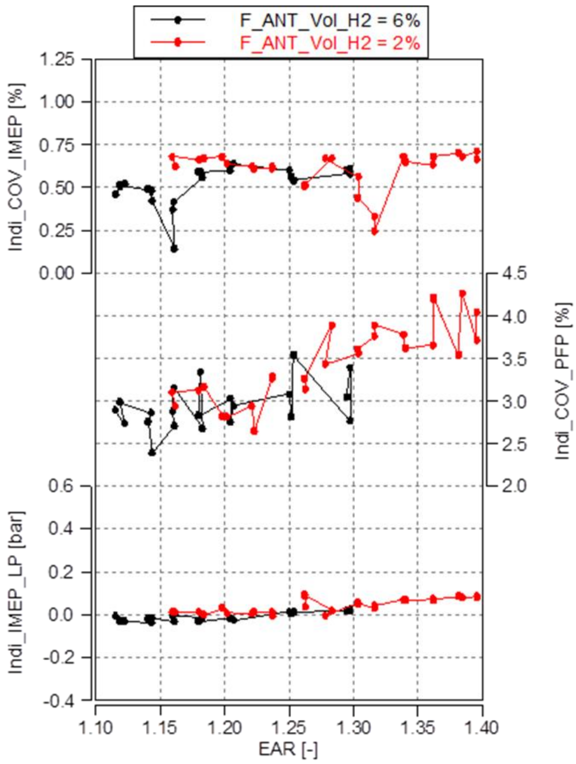

Figure 15. Selected performance parameters for ammonia/hydrogen combustion @ 23 bar IMEP

For ammonia combustion concepts, the most important exhaust gas emissions are NH3, NOX and N2O, as well as the ratio of ammonia and NOX emission (ANR), which is crucial for efficient exhaust gas aftertreatment in an SCR catalyst. N2O emissions are critical because they have a GWP of about 300 (100 year), and even low concentrations have an impact. The engine-out NOx emissions (Figure 16) show a strong dependency on EAR with a maximum at approximately 1.25. The hydrogen fraction only shows a minor impact on the NOx emissions. The same trend was observed for the emission of N2O, which steadily decreases with decreasing EAR. The NH3 emission, however, shows a dependence on EAR as well as hydrogen fraction. With reduced EAR, the NH3 emissions increase for both hydrogen fractions. The lower hydrogen fraction results in higher NH3 emissions for a given EAR. This is also reflected in the ANR that is slightly higher for the lower hydrogen fraction.

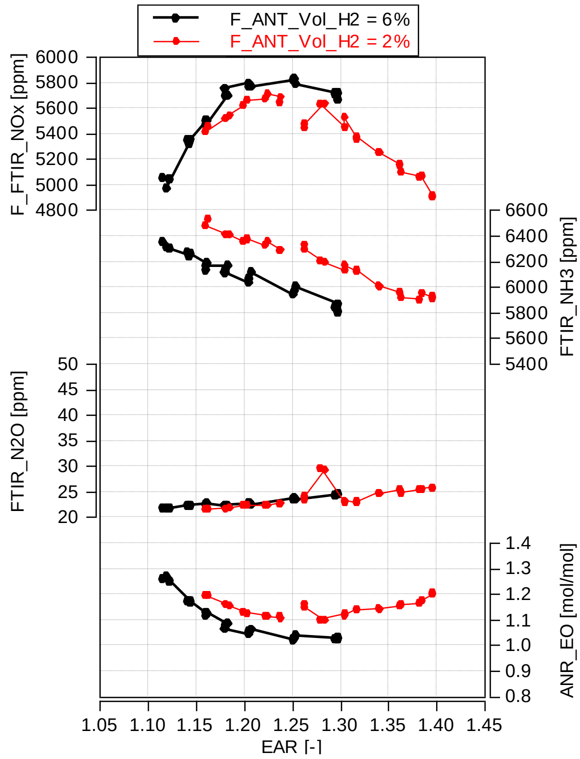

Figure 16. Selected engine-out emissions for ammonia/hydrogen combustion @ 23 bar IMEP

The combustion results with ammonia and low hydrogen amounts are promising. As the engine performed well with low hydrogen amounts, a spot check was done to see if ammonia also could be combusted without hydrogen enrichment. The results are plotted in Figure 17. The rate of heat release is shown for natural gas operation (red), ammonia with 5% hydrogen (blue), and 100% ammonia (black). The air/fuel ration was changed to stable engine operation. But with rich mixtures, the rate of heat release can be comparable to natural gas operation. Although the NOx emissions were much higher, with ammonia as a fuel, an SCR catalyst already is needed.

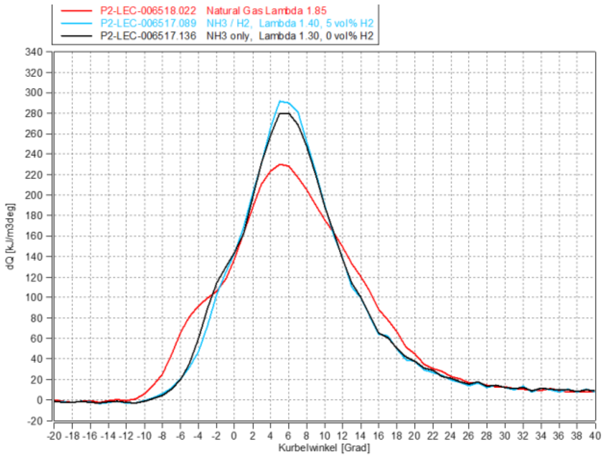

Figure 17. Rate of heat release with different fuel types

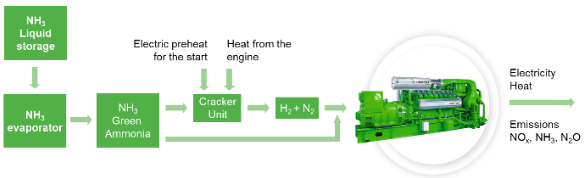

Figure 18. NH3 supply and cracker for a large engine

In Figure 18, the fuel treatment concept is shown. Ammonia will be stored in liquid form, under pressure or cooled. Out of the storage tank, the ammonia needs to be evaporated, and a portion will be cracked into hydrogen and nitrogen. This part of the stream will be mixed with the main ammonia stream and fed into the engine. As ammonia is a strong NOx promotor, an SCR catalyst as exhaust gas aftertreatment system is required. Ammonia also forms laughing gas (N2O), and measures are required here as well to reduce N2O.

3.3 Methanol combustion

The physical and chemical properties of methanol, and especially the high methane number, lead to favorable conditions for spark-ignition combustion concepts. For methanol, different combustion concepts are feasible with open chamber configurations or with prechamber concepts.

3.3.1 Experimental test setup

The LEC conducted experimental investigations on a high-speed four-stroke engine derived from INNIO’s Jenbacher Type 6 engine. The cylinder head was equipped with a port fuel injector for liquid methanol. The technical specifications of the engine are summarized in Table 3.

Table 3. SCE Type 6 technical data

Rated speed	1500 rpm
Displacement	≈ 6 dm3
Valve timing	Miller valve timing with early IVC
Number of intake and exhaust valves	2/2
Charge air	Provided by external compressors with up to 10 bar boost pressure
Methanol supply	Port fuel injection (commercial gasoline DI injector)
Ignition system	Modified high-voltage capacitor discharge

3.3.2 Measurements results

The goal of the methanol investigation with an open chamber configuration was the determination of suitable operating windows with regard to combustion phasing and excess air ratio. The major limitation for this investigation was the methanol mass that could be injected with the available injectors that were designed for automotive applications. This limitation is reflected in the small operating window that could be achieved (Figure 19).

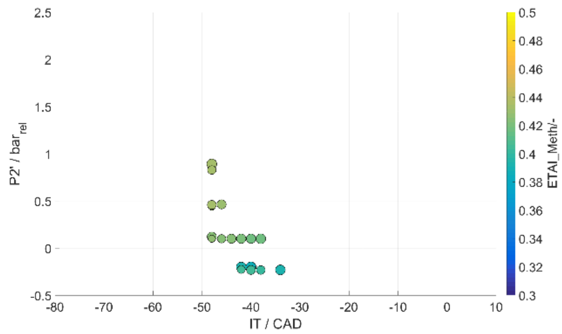

Figure 19. Operating window for methanol fuel combustion concept

In this open chamber configuration with lean mixtures, the ignition delay time was significantly longer than for typical natural gas applications, resulting in very early ignition timing. This trend was even more pronounced with higher EAR. In addition to the long ignition delay time, a high cyclic variability also was observed. The combustion variability was assessed for a medium load operating condition by using scatter plots displaying MFB5% vs. MFB5%, MFB50% and MFB90% (Figure 20). Average values of 60 consecutive combustion cycles are shown. Ignition delay time decreases with lower EAR and later IT, while burn duration also decreases with lower EAR but increases with later IT.

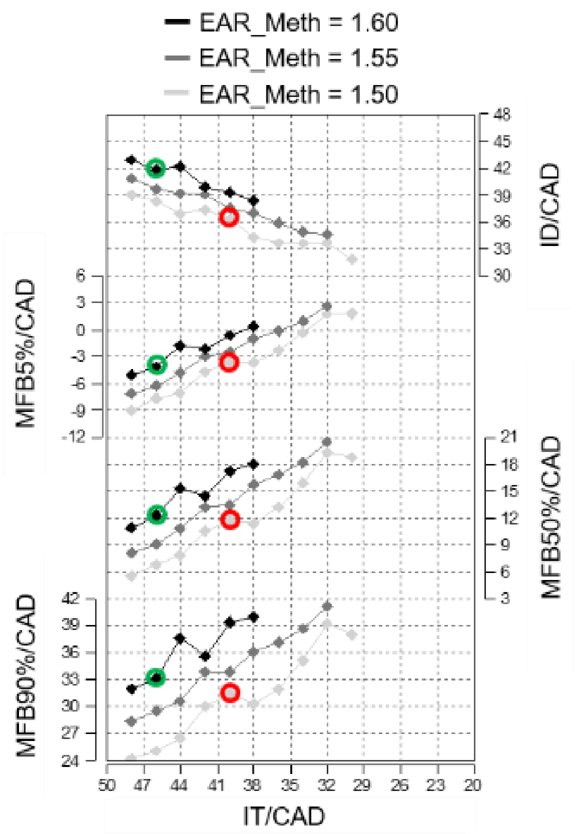

Figure 20. Combustion variability for methanol operation in an open chamber configuration

In Figure 21, analyses of two single operating points with similar MFB50% are shown: EAR = 1.50 at the top and EAR = 1.60 at the bottom, marked in the left plot with a red and a green circle, respectively. No significant difference regarding combustion fluctuations exists, meaning similar spread of MFB5%, MFB50% and MFB90%.

Significant improvement potential for methanol combustion will be investigated at the LEC. Besides improved injector technology with larger flow rates, the focus will be on injector layout and ignition concepts, including prechamber configurations.

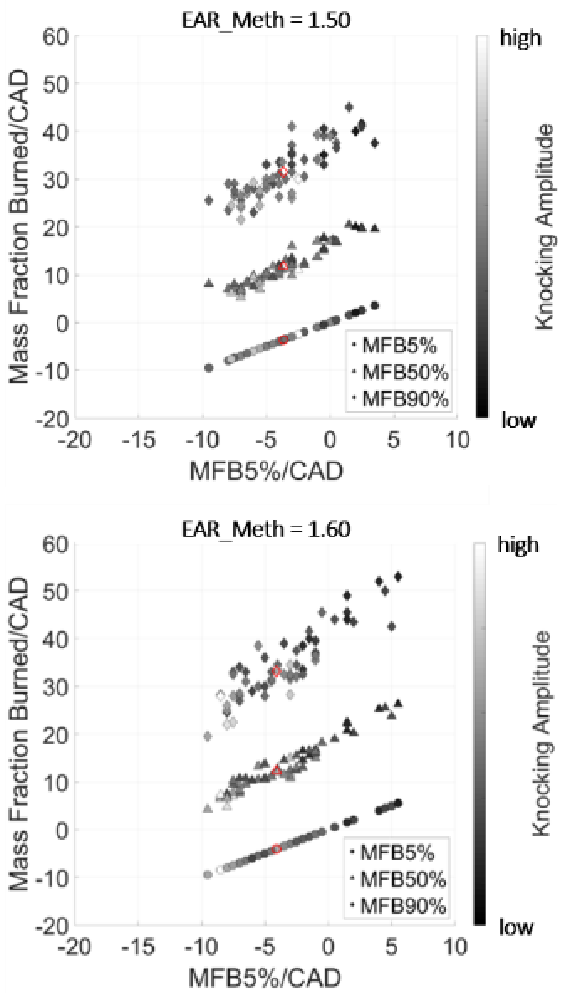

Figure 21. Combustion variability for methanol operation in an open chamber configuration

4 FUTURE CHALLENGES

Decarbonization leads to electrification in a number of ways. Many industrial and end consumer applications that use fuels today can be converted to electricity-based application. Electric vehicles and heat pumps for producing low grade heat are two areas of strong growth where a great deal of fuel can be replaced by renewable electric power. The remaining fossil-based fuel applications are under pressure and need to be replaced by carbon-neutral or carbon-free fuels. However, a silver bullet for a dominating carbon-neutral or carbon-free fuel is not yet seen.

Hydrogen and hydrogen-derived fuels such as ammonia (NH3), methanol (CH3 OH), synthetic gas (CH4), or any kind of e-fuels are being considered as replacements to fossil fuels. Supply chain and the use or re-use of existing infrastructure are the most critical elements for a conversion to these green fuels.

On the other side are the technologies that are required for a decarbonized energy system. While for some sectors and applications such as electric vehicles, short distance marine, or airplane applications, the technology of engines can be replaced completely, other applications like long-haul road transportation, long-haul shipping, and long-distance air transportation rely on fuel-based technologies. In these cases, the fuel needs to change and become sustainable and carbon neutral or carbon free.

4.1 Renewable power challenges

Large engines will play a major role in a future reliable power generation market. The renewable power generation portfolio will grow significantly, mainly due to wind and solar additions, but the volatility will be high and availability low. Therefore, conventional dispatchable technologies ensuring a stable electricity grid will definitely be required for the foreseeable future. Figure 22 shows a scenario plotted where large engines for stationary power generation can be used. Energy production is dominated by RES like wind, PV, hydro, or biogas, but the energy also needs to be stored for the times with high demand and low wind and sun. As electricity cannot be stored easily, it must be converted and stored chemically. Electricity is converted to hydrogen and stored directly as hydrogen or processed to hydrogen carriers such as ammonia or methanol. All of these fuels will play a role in future energy scenarios, and large engines must be capable of handling all of them. To avoid stranded investments, retrofit kits for existing fleet engines must be developed, ideally with limited performance changes.

4.2 Alternative technologies

Fuel cells are the most promising and most popular alternative technology to replace engines or turbines. Although many different fuel cell types and technologies exist, fuel cells typically are linked to hydrogen and often are seen as the only technology for hydrogen fuel. In reality, more established and mature technologies like engines or turbines have better fuel flexibility and also can operate on hydrogen, achieve higher reliability, and be produced at lower cost and with more sustainable raw materials.

It is very important that all stake holders in the energy transition stand up for technology openness and allow fair competition in a liberal market environment.

5 CONCLUSIONS

More and more it turns out that the main challenge meeting climate goals is how fast we can be successful with the energy transition. The use of existing supply chains and infrastructure or re-use of existing infrastructure with low modifications will be key to a fast transition. Also, the utilization of existing technologies or the modification of existing technologies for the use of green fuels is becoming increasingly important. Therefore, in a future energy marketplace, large engines will play an important role. The existing large engine technology is an excellent starting point for modification to hydrogen or other green fuel use all at low cost, with low risk, and in a relatively short time.

This paper has shown that all three green fuels can be used in large engines. Hydrogen operation is well advanced, but higher power density needs to

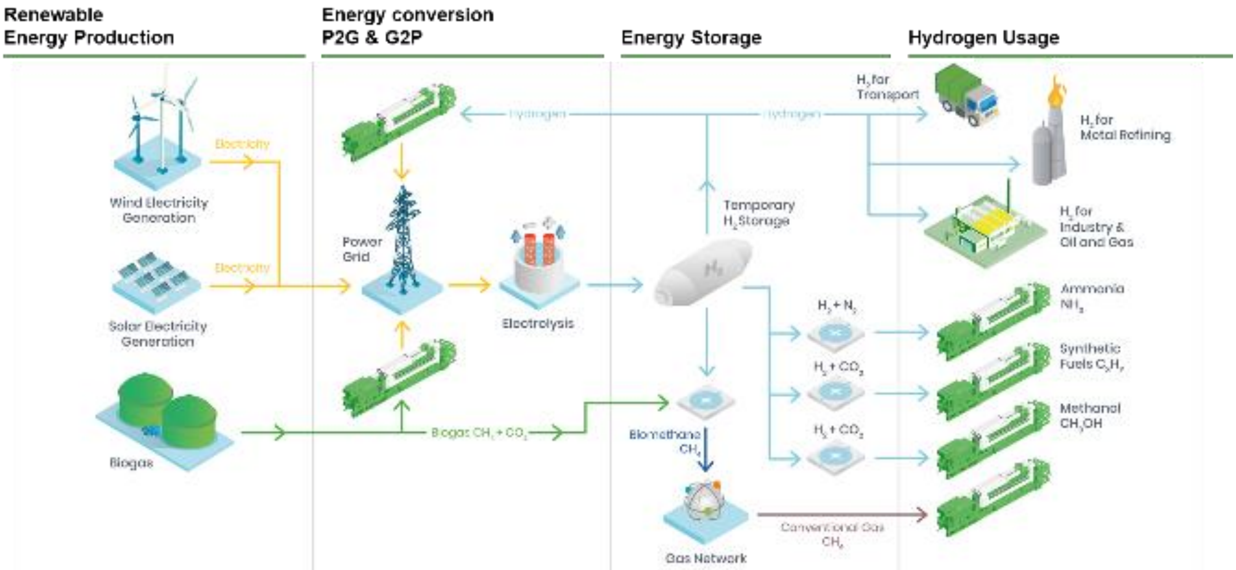

Figure 22. Green product portfolio

be reached. Ammonia is theoretically possible and demonstrated on single cylinder research engines. Methanol is also possible. The engine operation with all of these new fuels is not as mature as with natural gas operations yet, but it is possible with continuing development.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

ANR ammonia NOx ratio

BMEP break mean effective pressure

BTC bottom dead center

CHP combined heat and power

CR compression ratio

dRES dispatchable renewable energy sources

EAR excess air ratio

FTIR Fourier-transform infrared spectroscope

GHG greenhouse gas

GWP global warming potential

IMEP indicated mean effective pressure

IVC intake valve close

MFB mass fraction burned

PFP peak firing pressure

PV photovoltaic

RES renewable energy sources

SCR selective catalytic reaction

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