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GHG and methane slip reduction: the role of hydrogen blending into natural gas

Emission Reduction Technologies - Engine Measures & Combustion Development

Stefania Ischia, Wärtsilä

Kaj Portin, Wartsila
Diego Delneri, Wartsila
Miguel Prat, Wartsila

ABSTRACT

Hydrogen blending into natural gas is being explored as a promising option for the shipping industry to reduce carbon emissions and mitigate unburnt methane. By incorporating hydrogen into natural gas combustion, the industry can take significant steps towards achieving its greenhouse gas reduction goals.

When utilizing both hydrogen and natural gas as fuel, one of the main concerns is safety. Both hydrogen and natural gas are gaseous fuels, and any leaks can pose safety risks. Especially hydrogen, being highly flammable, poses a higher risk of fire and explosion compared with natural gas. Unknown sources of ignition should be identified and proper safety systems including leak detection and fire suppression measures should be used. According to the paper, a safe implementation of hydrogen blending into natural gas will be outlined.

Ensuring compatibility of the fuel system and engine components to prevent leaks and corrosion with both fuels is key. The combustion characteristics of natural gas and hydrogen differ, requiring adjustments to the fuel-air mixture and ignition timing to optimise the combustion. To minimize environmental impact, the unburnt methane from the natural gas combustion will be reduced.

This article examines the engine performance and safety of the hydrogen blending into natural gas concept. It also addresses the challenges and benefits using hydrogen and natural gas for combustion engines. This article aims to demonstrate the secure and efficient implementation of hydrogen blending into natural gas, emphasizing its potential to drive the shipping industry towards a decarbonized future.

1 INTRUDUCTION

In the transition process from fossil fuels to sustainable fuels, a fundamental role can be played by energy carriers, including hydrogen. Hydrogen is a molecule that, not containing carbon atoms, allows the reduction of carbon dioxide (CO_2) and methane (CH_4) emissions, respectively a combustion product and a combustion residue of internal combustion engines and therefore promotes the reduction of gases most responsible for the greenhouse effect.

Hydrogen-powered internal combustion engines (ICE) represent a viable path to comply with future European Union (EU) and International Maritime Organization (IMO) regulations, which will include not only CO_2 but also CH_4 end N_2O emissions limits. [1]

The aim is to start the transition towards zero carbon emissions through the progressive introduction of increasing quantities of hydrogen blends in natural gas, using current technologies and making only the changes strictly necessary to comply with safety principles required by Class Societies for Marine applications and by Internal guidelines which include Standards and Technical Reports for Power Plant applications. [2] [3] [4]

Natural gas, for the shipping industry (in the power plant market it is already widely used), is the starting point to reduce greenhouse gas emissions (GHG) and greenhouse gas emissions intensity (GHG intensity) in the coming years. [5]

In the long term, sustainable methane (bio- or e-) could be introduced. Synthetic fuels will be an essential part of decarbonisation. [6]

Methane slip remains a problem that can be solved with different strategies. [7] One of these, is the introduction of hydrogen blends which allow to extend the life of ICE contributing to further reduce both CH_4 and CO_2 emissions.

This article shows the main challenges related to combustion control, the minimum sufficient modifications to be made to the systems and the actions in terms of engine settings required to enable the introduction of hydrogen as a fuel in spark gas port injection engines optimized for natural gas operation. A different approach must be followed in case of hydrogen blending below 25% by volume or above such threshold due to the different classification of the gas and therefore the different rules that must be applied.

The information presented is based on test campaigns conducted with hydrogen blending at Wärtsilä facilities, as well as the experience and measures adopted to ensure the safety of test cells, systems, and personnel.

2 LEAN BURN COMBUSTION ENGINES AND LIMITATION WITH HYDROGEN BLENDING

2.1 Lean burn combustion engines

The lean burn combustion principle, suitable for both marine genset and power plant engines, represents a straightforward and expedient technology to introduce to the market in the medium term to reduce at the same time nitrogen oxides (NO_x), nitrous oxide (N_2O), particulate matter (PM), sulphur oxide (SO_x) and carbon dioxide (CO_2) emissions compared to conventional diesel combustion. Additionally, spark ignited (SI) engines can be used in combination with dual fuel (DF) engines. Both SI and DF technologies allow the use of natural gas and hydrogen blending. [8]

Hydrogen blending is therefore a valid and feasible option to reduce the methane slip, especially in the most unfavorable engine operating area, in gas mode, at part and low loads.

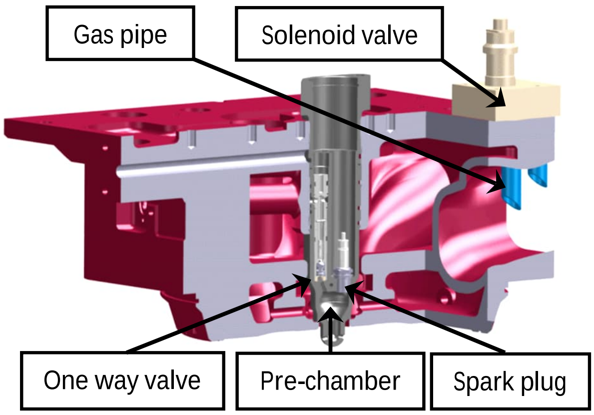

Figure 1. Spark Ignited Gas (SI) technology.

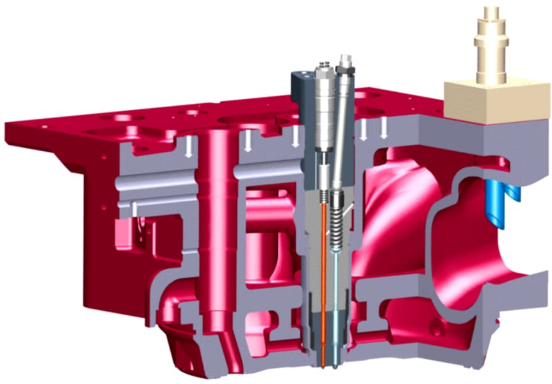

Figure 2. Dual Fuel (DF) technology.

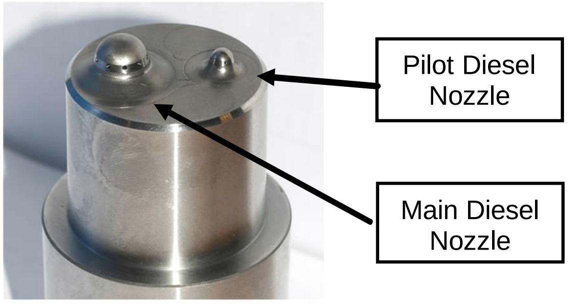

Figure 3. Dual Fuel (DF) nozzle.

The use of hydrogen blending can be introduced in parallel with other engine technologies with the aim to maximise the green house gas reduction.

Methane slip can be further mitigated by means of engine tuning and advanced control software, engine component design optimization, after-treatment devices and system solutions which include system dimensioning, configurations and connected technologies. [9]

2.2 Limitations

The tests were performed for exploratory purposes to evaluate the ability of spark ignition engines with standard hardware and settings, optimized for natural gas, to operate with increasing hydrogen blending ratios as the load decreases. The settings were then fine-tuned specifically for load and hydrogen content.

Gas engine combustion is a compromise of several parameters, targets and limits. The aim of this study was to achieve the maximum hydrogen content at defined engine loads by fine-tuning the combustion control settings. No additional margins, usually adopted to allow the engine to operate in extreme ambient conditions and or at high altitude, have been considered. Only the standard limits imposed to prevent damage to engine components were applied.

The information collected will be used in the future to better develop our products and enable engines to operate safely with hydrogen blends above 25%-vol.

2.3 Main challenges using hydrogen as fuel in ICE

The introduction of hydrogen as a fuel in internal combustion engines presents both advantages and disadvantages. The specific physical, chemical, and operational properties of hydrogen require careful consideration.

Using hydrogen as a fuel in internal combustion engines is attractive for several reasons, including:

- Mature engine manufacturing processes.
- Fuel flexibility of internal combustion engines.
- Low fuel purity requirements compared to fuel cells.

However, challenges related to hydrogen production, storage and distribution remain.

In terms of engine technology, there are technical challenges to successfully burn hydrogen in conventional systems with minimal design changes.

The main challenges in using hydrogen as main fuel in ICEs are: [10]

1. Low energy per unit volume: Due to the low density of hydrogen gas, high-pressure storage tanks are required to store sufficient energy.

2. Wide flammability range: Hydrogen has an equivalence ratio in air from 0.1 to 7.1 and an extremely low minimum ignition energy, which is an order of magnitude lower than those of fossil-fuel–air mixtures at stoichiometric ratios. These features can cause combustion control problems, such as pre-ignition and detonation, as they expose the engine to uncontrolled ignition due to hot spots and hot gases acting as ignition sources. On the other hand, the wide flammability limits of hydrogen extend the stable combustion regime to leaner mixtures compared to natural gas.

3. High laminar flame speed (LFS): Hydrogen has a remarkably high laminar flame speed across a wide range of equivalence ratios (from 1.0 to 3.5). High laminar flame speed, among other effects, raises cylinder pressure, increases NOx emissions and closes the exhaust wastegate Higher nitrogen oxides emissions compared to other fuels are attributed to the higher flame temperature and speed. However, flame temperature and flame speed are highly dependent on the equivalence ratio. To reduce and control the development of the combustion flame, an equivalence ratio value in air below 0.5 is required, which reduces nitrogen oxides emissions and distances pre-ignition.

4. Very low quenching distance: Hydrogen flames move closer to the cylinder wall before extinguishing than other fuels. They ignite rapidly and are relatively short-lived. This significantly impacts combustion in the gaps between the cylinder and piston and increases the evaporation of the lubricant. Low quenching gap values promote more complete combustion but may increase the tendency for backfire since the flame can get past a nearly closed intake valve compared to traditional fuels.

5. High diffusivity: Hydrogen's high diffusivity promotes the homogenization of the mixture but makes it difficult to stratify the mixture.

Table 1. List of the main properties of hydrogen.[11]

Properties	Hydrogen
Limits of flammability in air, (vol.%)	4–75
Stoichiometric composition in air, (vol.%)	29.53
Minimum energy for ignition in air, (mJ)	0.02
Auto ignition temperature, (K)	858
Flame temperature in air, (K)	2318
Burning velocity in NTP * air, (cm/s)	325
Quenching gap in NTP air, (cm)	0.064
Normalized flame emissivity	1.0
Equivalent ration flammability limit in NTP air	0.1–7.1
Methane number	0

* NTP (normal temp. and press.).

In conclusion, while hydrogen offers several benefits as a fuel for internal combustion engines, addressing these technical challenges is crucial for its successful implementation.

2.4 Impact of hydrogen used as fuel in ICE

Due to the above-mentioned properties, hydrogen-fueled engines with lambda characteristics of natural gas may experience anomalous combustion phenomena. These phenomena include spontaneous ignition during the intake stroke (backfire), premature uncontrolled ignition (pre-ignition), and autoignition of the end-gas region or excessive flame rates (knock). [12]

During our tests, several pre-ignition, advanced, and fast combustion cycles were observed when operating the engine with hydrogen blends at constant settings optimized for natural gas (Lambda 2.0). The limiting factors for these phenomena depend on the engine load and the hydrogen blending ratio.

The main combustion issues encountered during the test campaign at different load ranges with settings optimized for natural gas operation are illustrated in the charts below.

At high load, engines fueled with hydrogen blends are generally limited by firing pressures, reduced flow through the exhaust waste gate as hydrogen content increases and knocking.

These findings highlight the challenges and considerations necessary for optimizing hydrogen-fueled internal combustion engines, particularly in terms of managing combustion development.

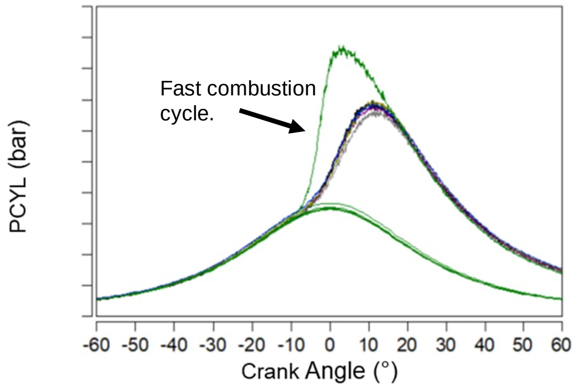

Figure 4. Fast combustion cycle detected in one cylinder among six at 75% load, 58%-vol H_2.

The combustion is faster and starts slightly earlier compared to natural gas as depicted in Figure 5.

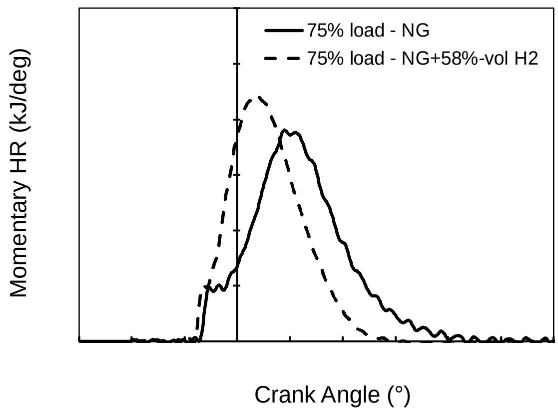

Figure 5. Momentary Heat Release at 75% load, 58%-vol H_2.

At part load, increasing the hydrogen content, the limiting factors are fast and advanced combustion cycles due to the reduced ignition delay. Knocking and pre-ignition events occur operating the engine with performance settings optimized for natural gas as shown in Figure 6.

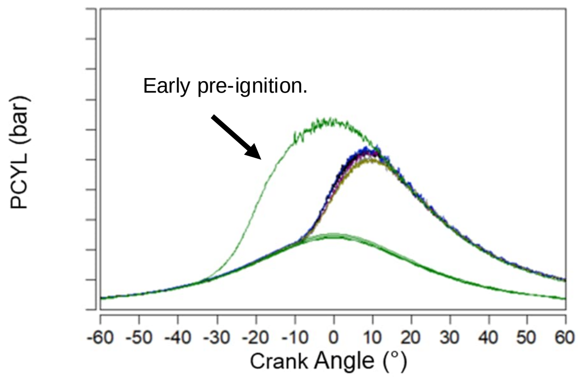

Figure 6. Early pre-ignition cycle detected in one cylinder among six at 50% load 70%-H_2.

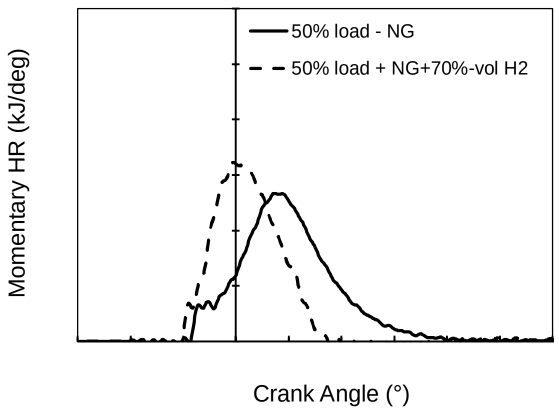

Figure 7. Momentary Heat Release at 50% load, 70%-vol H_2. HR (50% position) moves toward TDC.

Dedicated settings can solve these issues (pre-ignition and fast combustion cycles); however, the combustion process remains faster and more advanced compared to natural gas.

At low loads, the limiting factors are extremely fast and advanced combustion cycles, with the main combustion process occurring before Top Dead Center (TDC) near the end of the compression stroke.

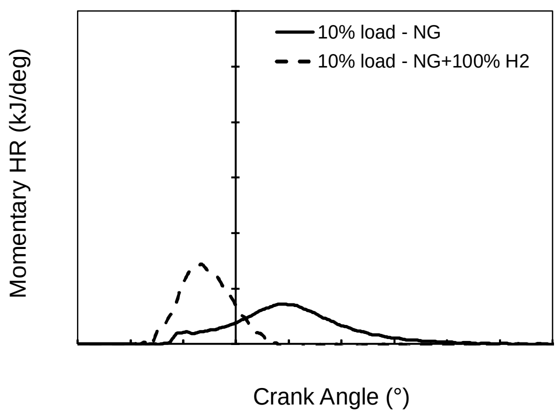

Figure 8. Momentary Heat Release at 10% load – 100%-H_2. The start of combustion with H_2 is advanced due to the lower ignition delay.

With extreme hydrogen content, it is not possible to retard the start of combustion by adjusting spark ignition timing. Auto-ignition in some cylinders may cause instability and lead to engine shutdown.

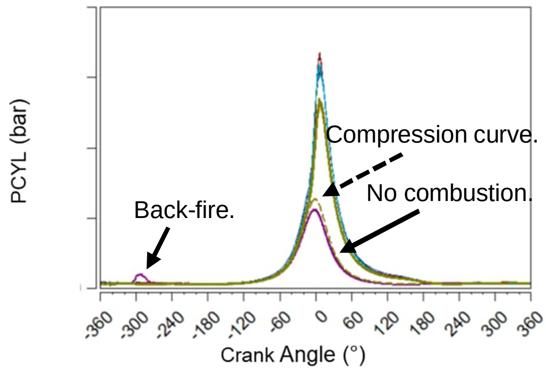

Figure 9. Back-fire detected at 10% load, 100%-H_2. Backfire events appeared changing spark ignition timing or spark voltage level.

Suppressing phenomena such as knocking, pre-ignition, backfire, and extreme firing pressures is mandatory to ensure proper engine durability but is quite challenging when operating the engine with high percentages of hydrogen.

Defining a maximum power output, combined with settings specifically tuned for each hydrogen content helps to avoid these unwanted phenomena.

Engine design is also of considerable importance: zero overlap valve timing, crossflow cylinder head, and reduced crevices on the top land and cylinder head are crucial to mitigate backfire issues and generally support minimizing abnormal combustion phenomena. Lowering the compression ratio (CR) and using an upsized turbocharger could also help, but these measures heavily affect the performance and heat rate of engine operation with natural gas and were therefore not considered in this study.

3 CLASSIFICATION OF GASSES

Natural gas is still classified as methane as long as hydrogen content is under 25 % by volume, therefore the safety measures adopted for natural gas continue to be valid with hydrogen percentages up to 25% by volume.

When the hydrogen content exceeds 25% by volume, the classification changes from class IIA (valid for natural gas) to IIC (valid for hydrogen), and the safety measures become more stringent. This classification is based on IEC 60079-20.

Due to the different classification of hydrogen blending, with a threshold of 25% by volume of hydrogen, the test campaign was divided into two phases: a first phase with hydrogen up to 25% by volume blending and a second phase with hydrogen up to 100% by volume. The hardware remained the same in both phases; only modifications were made before starting the second test campaign to comply with the more stringent safety regulations required for a hydrogen content over 25% by volume.

This paper will focus on the engine behavior and the necessary settings modifications to operate a spark gas engine at part and low loads with hydrogen blends above 25% by volume.

4 EXPERIMENTAL SETUP

In this study, a dedicated test facility was used to experimentally investigate the effects of hydrogen blending on the performance and exhaust gas emissions of a spark gas engine. Figure 10. illustrates the detailed schematic of the gas plant layout.

As depicted in Figure 10, the experimental setup comprises a spark gas engine, a hydrogen storage area, a gas mixing unit where natural gas and hydrogen are mixed according to the load and the required hydrogen blending ratio, a gas ramp with multiple functions, including the control of the gas feed pressure before the engine, and various measurement and safety devices, which are not directly visible in the picture but will be explained in more detail in the subsequent subsections.

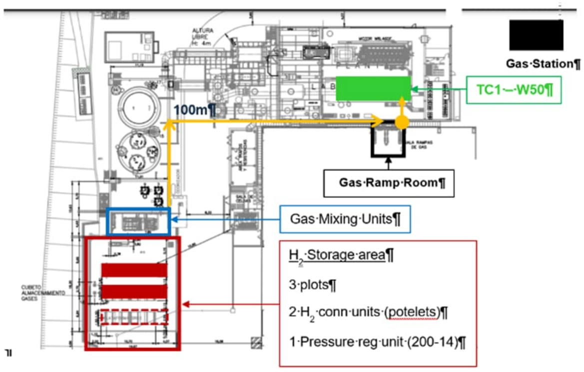

Figure 10. Experimental setup.

4.1 Hydrogen storage area

All the units included in this area are not owned by Wärtsilä and are designed for a maximum capacity of 820 m^3/h of hydrogen:

- Hydrogen Supply. Hydrogen is supplied via 2+1 trailers with a volume of 4000 m^3, maximum load of 415 kg and maximum pressure of 200 kg/cm^2.

- Hydrogen Connection Unit. It is important to avoid any contact between hydrogen and oxygen to eliminate the risk of a possible explosion. This unit includes a nitrogen purging system, so the operator can flush the lines and the flexible hose between the trailer and the unit when this is changed. The hydrogen pressure remaining in the trailers is continuously monitored in this unit. Additionally, there is an automatic shut-off valve in case of any emergency.

- Pressure Regulating Unit. There are two parallel lines with two pressure regulators on each line. The first pressure regulator decreases the pressure to 30 bar and the second one to 14 bar. If more than 50 kg/h of hydrogen is required, both lines are working in parallel to avoid big pressure drops.

4.2 Gas mixing unit

The gas mixing unit is designed to blend different gases and consists of two main components:

- Natural Gas Mixer: This component allows the mixing of natural gas with other gases such as propane and nitrogen. The purpose is to adjust the methane number or the lower heating value (LHV) of the gas. This process is essential for testing engine performance with various gas qualities.

- Hydrogen Mixer: This component blends hydrogen with the gas output from the natural gas mixer.

Both mixers are equipped with various sizes of lines, regulators, and flow meters, enabling a wide range of mixing ratios.

For hydrogen, the flow rate is determined by the blending ratio, engine load, and engine size. To accommodate different engine loads and blending ratios, the system includes two parallel lines, each with two pressure regulators and one flow meter. The flow limitations for each line are as follows:

- Low flow line: 3-35 kg/h
- High flow line: 20-200 kg/h

The calculation of these limits is based on:

- Operation Range of the Regulators: Due to the size of the internal parts of the valve, there is a minimum controllable flow determined by the minimum opening of the valve. The valve operates properly within a range of 10% to 90%.

Table 2. High flow line limits (example).

Variable name	Unit	Min	Normal	Max
Mass flow rate	(kg/h)	20.0	165.0	190.0
Inlet pressure	(barg)	13.5	13.5	13.5
Outlet pressure	(barg)	12.0	12.0	12.0
Inlet temperature	deg C	20.0	20.0	20.0
Specific heat ratio	(-)	1.400	1.400	1.400
Dynamic viscosity	(cP)	0.100	0.100	0.100
Sizing coefficient	(-)	0.578	4.746	5.484
Open	(%)	12.0	68.0	72.0

- Operation Range of the Flow Meter: The size of the flow meter is crucial for measuring flow with proper accuracy. The accuracy decreases exponentially at lower flows. Additionally, the speed of hydrogen through the flow meter must be less than 0.3 times the sonic velocity of the gas at higher flows. For hydrogen, this means the speed through the flow meter cannot exceed 395 m/s.

Table 3. Flow meter capacity range (example).

Flow rate	Mass flow accuracy	Pressure drops	Velocity
(kg/hr)	(+/- % of rate)	(bar)	(m/s)
200.000	0.250	1.202	375.049
166.000	0.250	0.836	311.291
132.000	0.250	0.536	247.533
81.000	0.250	0.209	151.895
64.000	0.301	0.133	120.016
47.000	0.411	0.074	88.137
30.000	0.643	0.032	56.257

Safety Measures: Two shutoff valves are included in the hydrogen mixer to close the hydrogen supply in case of any emergency.

4.3 Hydrogen blending control

Bermeo receives natural gas (NG) directly from the Spanish gas pipeline system. Most of the gas is coming from the North of Afrika. The lower heating value (LHV) of this natural gas (NG) can change between 49.0-49.8 MJ/kg.

Hydrogen (H_2) is delivered to Bermeo by truck, with the hydrogen pressurized in bottles. The LHV of hydrogen is 119.82 MJ/kg.

By knowing the LHV of both NG and H_2, it is possible to calculate the LHV for various blending ratios.

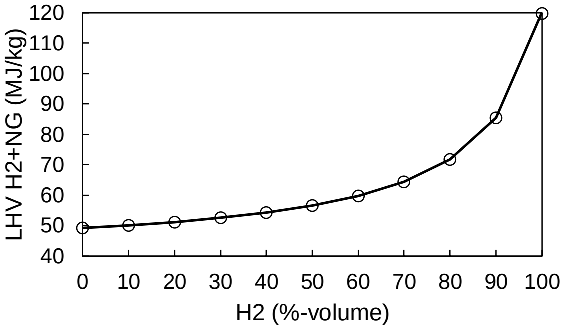

Figure 11. LHV of NG+H_2 versus H_2 blending ratio

The table below illustrates the correlation between the hydrogen blending ratio (percentage by volume) and the lower heating value of the natural gas-hydrogen mixture.

Table 4. LHV of NG+H_2 versus H_2 blending ratio.

LHV of NG+H_2	H_2 content
49.13	0.00%
50.04	10.00%
51.14	20.00%
52.51	30.00%
54.25	40.00%
56.55	50.00%
59.70	60.00%
64.31	70.00%
71.70	80.00%
85.42	90.00%
119.82	100.00%

When the engine operator selects the hydrogen percentage to blend into the natural gas via the Human Machine Interface (HMI), the Programmable Logic Controller (PLC) calculates the required H_2 and NG flow rates using the following formulas:

$$SP\_FLOW_{H2} = \frac{FLOW_{ENG_T} \times (LHV_{NG} - LHV_{MIX})}{LHV_{NG} - LHV_{H2}}$$

$$\mathrm{SP\_FLOW_{NG}} = FLOW_{ENG_T} - \mathrm{SP\_FLOW_{H2}}$$

$FLOW_{ENGT}$ is the actual gas flow of the engine, measured by a mass flow meter on the gas ramp.

LHV_{MIX} is the calculated value of the LHV of NG + H_2.

SP_FLOW_{H2} is the set point of the hydrogen flow regulator.

$\mathrm{SP\_FLOW_{NG}}$ is the set point of the natural gas flow regulator.

4.4 Gas analysis instruments

Four different instruments are used to calculate the gas quality. Gas quality is commonly described by its lower heating value, stoichiometric air/fuel ratio, density, methane number, and the mass fraction of carbon, hydrogen, oxygen and nitrogen.

- Continuous Gas Analyser: Installed close to the gas ramp, this device continuously monitors gas quality. It measures all gas components except hydrogen.
- Hydrogen Sensor: Also installed near the gas ramp, this sensor continuously monitors the hydrogen content in the gas.
- Gas Chromatograph: Positioned close to the gas ramp, this device offers the highest

accuracy for determining gas quality. Despite its precision, it necessitates manual sampling, which precludes its use as a safety device Instead, it is primarily used for official gas analysis during performance measurements.

- Gas mixing station flow meters. The hydrogen percentage in the gas is calculated using the measured NG and H_2 flow, and the NG and H_2 density.

$$H_2(\%) = \frac{Flow_{H2}/Dens_{H2}}{\left(\frac{Flow_{NG}}{Dens_{NG}}\right) + \left(\frac{Flow_{H2}}{Dens_{H2}}\right)} \mathbf{x100}$$

5 SAFETY

5.1 General Safety risks

The use of hydrogen, due to its chemical-physical properties, requires attention in the design of plants, control systems and the selection of materials and components. [13]

Below are the risks that must be managed when using hydrogen as fuel in ICE.

Hydrogen is a highly flammable gas with very low ignition energy. The risk of hydrogen explosion must be minimized and mitigated by implementing proper measures and protocols. Depending on the flammable conditions, pressure, and concentration of hydrogen, a mixture exposed to ignition sources may combust by either deflagration (subsonic combustion) or detonation (supersonic combustion, not possible in open air).

Hydrogen gas systems must be properly designed to prevent deflagration from propagating through the piping and containment systems. This can be achieved by using appropriate safety devices. Best practices to mitigate the risks of deflagrations and detonations include eliminating the possibility of dangerous concentrations of hydrogen through proper gas management, pipe purging, and ventilation.

Contained areas are particularly susceptible to fire hazards if hydrogen leaks inside. Primary safety measures for handling and using hydrogen include proper ventilation, hydrogen gas detection, and appropriately rated electrical equipment in hazardous areas and enclosed spaces where hydrogen may leak and accumulate to flammable levels.

Gas leak sensors are positioned at various points along the double gas feed pipes to detect any leakages. This safety measure is now standard for all gas engines.

Based on Lower Explosive Limit (LEL) measurements, it was possible to determine the maximum hydrogen blending ratio with LEL below the limit. The results indicate that LEL levels exceed the explosive limit when operating with hydrogen concentrations above 75% H2 %-vol.

Although the LEL level remains constant at hydrogen concentrations between 0% H_2 %-vol and 25% H_2 %-vol, the data shows a progressive increase in LEL levels when the hydrogen concentration exceeds 25% H_2 %-vol.

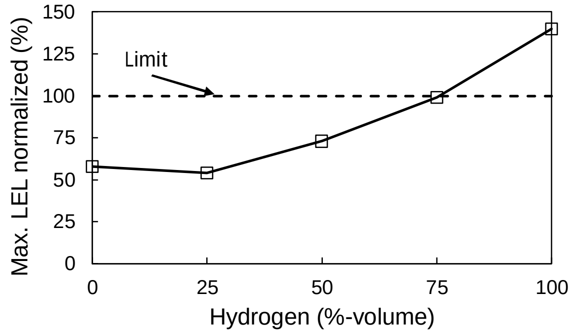

Figure 12. Maximum LEL level (%) measured in the crankcase (normalized at 65°C temperature and according to the gas composition) versus hydrogen content (%-vol).

It has been confirmed by measurements that the LEL level measured in the cylinder head cover is less critical than the one measured in the crankcase in all cases.

Further countermeasures, such as an additional crankcase ventilation, must be applied to meet the LEL requirements.

If the hydrogen flow is contaminated by solid particulates, electrostatic charges may develop which can cause sparks and ignition of flammable concentrations of hydrogen. All hydrogen handling equipment must be protected from electric charge to avoid hydrogen ignition.

Hydrogen is odourless and colourless. Hydrogen flames are invisible and can be very difficult to detect. When ignited, the generated radiant heat of such fire is only one tenth of an equivalent hydrocarbon fire.

Due to the very small molecular size of hydrogen, the gas is capable of dispersion through materials, including penetrating into the walls of containment systems. Hydrogen should be stored in appropriate materials that minimize permeation and hydrogen embrittlement.

Certain metallic materials and equipment exposed to hydrogen gas can suffer from hydrogen embrittlement. These can include tank interior surfaces, weldments, pipes, valves, fuel nozzles, and pressure relief valves or pipes.

The practices used to avoid hydrogen embrittlement include utilizing proper metallic material with appropriate thickness, surface treatments and coatings/films to protect the surface from hydrogen contact.

5.2 Safety systems – H2 > 25%-vol

This section outlines the primary actions required to operate with hydrogen content exceeding 25%-vol within the engine room. The standard requirements for natural gas are applicable for hydrogen content up to 25%-vol.

5.2.1 General requirements

Before any operation involving hydrogen blending above 25%-vol, the following steps are mandatory:

- Conduct an extensive Risk Analysis (HAZOP).
- Develop an Emergency Response Plan (ERP).

A comprehensive and detailed documentation, including the following documents, must be prepared:

- Piping and Instrumentation Diagram (P&IDs).
- Explosive Atmospheres zone mapping (ATEX).
- Procedures for operation, maintenance. venting, inerting, and purging.
- Hydrogen-specific training.

These measures are essential to ensure safe and efficient operations when handling hydrogen content above the specified threshold.

5.2.2 Leak detection - Component - Material

Preventing leaks is crucial for maintaining operational efficiency and safety. Below are detailed actions to avoid leaks:

- Minimize the number of flanges and devices inside the engine rooms.
- Gather the equipment with the highest risk of leaks in closed and ventilated rooms with gas detection. Gas ramps, flow meters, selection valves must be installed in a separate room outside the engine room.
- Use of materials, flanges, gaskets, valves and devices suitable for hydrogen.
- Detection system: Detectors must be installed in every place where leaks may occur.
- When the engine is stopped, all the gas from the pipes is vented out from the engine room.

5.2.3 Explosion - Fire detection

Actions to avoid explosions or fire:

- Use ATEX IIC H_2 certified electrical devices.
- Install proper earthing in new facilities.
- Install video cameras / thermal cameras.
- Personal Protection Equipment.

5.2.4 Automation

The plant and the gas mixing station are controlled by safety PLCs. These are designed to force the process to a known state before safely shutting down the machine when a safety condition is triggered.

These are the safety conditions that are implemented on both safety PLCs:

- Emergency push buttons.
- Fire detection system.
- Gas leakage detection system.

Additionally, the gas mixing station has other critical signals implemented on the safety modules:

- Gas flow meters: These are the key devices of the gas mixing station for controlling the blending ratio and for safety.
- Hydrogen quantity sensor: This is only used for safety purposes.
- Hydrogen pressure sensor after the pressure regulation unit: This sensor detects the failures of the pressure regulation unit.

The engine and the gas mixing station shut down when a critical signal, such as the emergency push buttons, gas detection system, or the fire detection system, is triggered.

Additionally, if a critical signal to control the hydrogen blending ratio is triggered, such as hydrogen flow meters or hydrogen content sensors, the hydrogen shutoff valves will close, and the engine will be transferred to natural gas.

6 ENGINE SETUP

The test engine is a single stage turbocharged air cooled 6-cylinder 4-stroke spark gas port injection engine located in the Wärtsilä laboratory facility in Bermeo, Spain. It is equipped with electronic prechambers and G-shape spark plugs. Notably, no exhaust gas recirculation (EGR) or exhaust aftertreatment device was used.

Hydrogen and natural gas are mixed upstream of the engine and then delivered with the requested blending ratio to the engine though a double wall gas pipe. The same gas line is used for the main and pre-combustion chambers, meaning that the same mixture of natural gas and hydrogen is supplied to both the main chamber and the prechamber at low pressure. Gas pressure is defined as a delta to the charge air. The mixture is then injected through the main gas valves located in the intake port and into the prechamber via a one-way valve.

Nominal power of the engine is 6270kW at 500 r/min.

Table 5. Main engine characteristics.

Items	Specification
Compression ratio	11.5:1
Bore × Stroke	500 mm x 580 mm
Engine speed	500 rpm
Maximum power output	1045 kW/cyl
BMEP	22020 mbar
Valve overlap	~ 0 deg
Cylinder head	Crossflow

Engine emissions are measured by using standard laboratory equipment the Horiba MEXA-7100® emissions bench including total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), nitrogen oxides (NO_x).

6.1 Engine Controls

The control and safety systems present on gas engines have been extended to operate the engine on hydrogen blends. Standard alarm settings have been maintained.

Signals monitored during testing include knock, IMEP used to identify misfires or weak combustion cycles, raw firing pressures, main fuel injection (MFI) duration (this is an indicator of cylinder balance and engine stability during steady-state operation together with exhaust gas temperatures measured downstream of the combustion chamber).

In cylinder pressures (300 combustion cycles acquired in each cylinder) were acquired with AVL® and post-processed using Concerto® to better understand and compare the combustion progress using different settings and hydrogen blending ratios.

Lower Explosive Limit (LEL), the gas concentration in the crankcase and cylinder head cover, was monitored and acquired during the entire test campaign as a safety measure.

7 EXPERIMENTAL PROCEDURE

The target of the test was to operate the engine with the highest hydrogen share at defined engine loads.

The engine's capability to operate with increasing amounts of hydrogen quantities as the load decreases has been investigated with the current engine design stage optimized to operate at TA Luft NOx emission level, equal to 500 mg/Nm3 at 15% O2, dry or 1.16 g/kWh. IMO Tier III limit for this engine equals 2.6 g/kWh. It is important to note that no hardware modifications were made throughout the testing campaign.

The performance and emissions of the test engine were recorded under steady-state conditions using natural gas with a minimum methane number of 80. The engine was run at 500 r/min and tested at four different loads: 10%, 25%, 50%, and 75%.

Table 6. Reference natural gas used for MN80.

Gas composition		
Methane	mol-%	91.0
Ethane	mol-%	8.5
Propane	mol-%	0.5

7.1 Test matrix

At defined engine loads, tests were performed by increasing the hydrogen content while maintaining natural gas optimized settings, as detailed in Table 7 (TP1). The hydrogen content was set just below the threshold that would trigger an automatic engine shutdown for safety reasons.

In the second phase, the settings were specifically tuned for each test point reported in the Table 7 (TP2). The parameters were adjusted one step at a time and the performance results with the best combination of settings (fine-tuned lambda, MFI timing, MFI duration and spark injection timing) are illustrated in the Chapter 8.

Table 7. Test points.

-	TP 1 NG settings	TP2 New settings
Load (%)	$H_2/(H_2+NG)$ (%-vol)	$H_2/(H_2+NG)$ (%-vol)
75	58	58
50	70	70
25	<u>70</u>	<u>90</u>
10	100	100

8 RESULTS

8.1 Hydrogen blending ratio below 25%-vol

The engines in Wärtsilä portfolio are currently able to operate at full load with hydrogen blending up to 3%-vol with standard hardware and settings.

Engine operation with hydrogen blending up to 25%-vol is feasible on SI engines by adjusting the lambda to maintain a constant NO_x emission level, delaying the start of combustion to maintain the 50% heat release in an optimum position and reducing the power output to ensure adequate margin from firing pressure design limit. The same operating conditions as a standard natural gas engine are guaranteed. Performance settings offsets are automatically applied by automation based on hydrogen ratio and load. Total hydrocarbons (THC) with 25%-vol hydrogen blend (it corresponds to 3.7%-mass and 9%-energy) are reduced by approximately -12.5% and CO_2 emissions by approximately -9%.

Engine operation with hydrogen blends up to 25%-vol has been extended to all spark ignition engines in the Wärtsilä portfolio for energy production by applying the above-mentioned actions and more sophisticated combustion control features.

8.2 Hydrogen blending ratio above 25%-vol

Percentages of hydrogen blending exceeding 25%-vol, as previously mentioned, require the upgrade of the plant and the safety system and a general retuning of all the main settings in addition to the lambda and spark ignition timing.

Without any hardware modifications and only by fine-tuning the performance settings the engine can operate at the tested load-hydrogen points depicted in the Figure 13 and Figure 14 without anomalous combustion events.

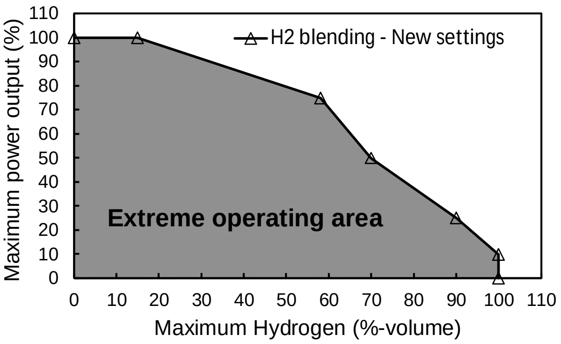

Figure 13. Tested Loads (%) versus H_2 (%-vol).

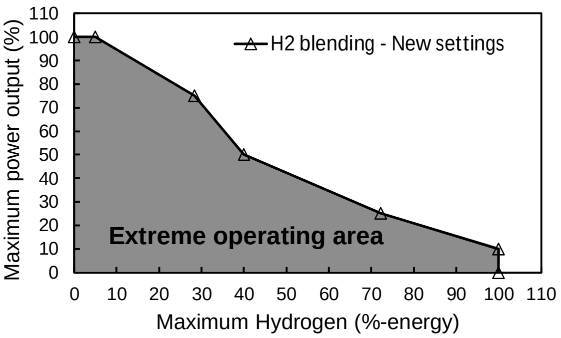

Figure 14. Tested Loads (%) versus H_2 (%-energy).

The experimental results are presented by using the behavior of the engine powered by natural gas as reference (dotted lines in the charts).

Sensitivity to key performance parameters due to hydrogen blending was investigated at the indicated test points, initially using the same settings optimized for natural gas engine operation for direct comparison and then with new performance settings. tuned specifically for each load-hydrogen test point.

As mentioned, specific physical and chemical hydrogen properties cause faster and advanced combustion compared to natural gas, resulting in higher firing pressures and NOx emission levels.

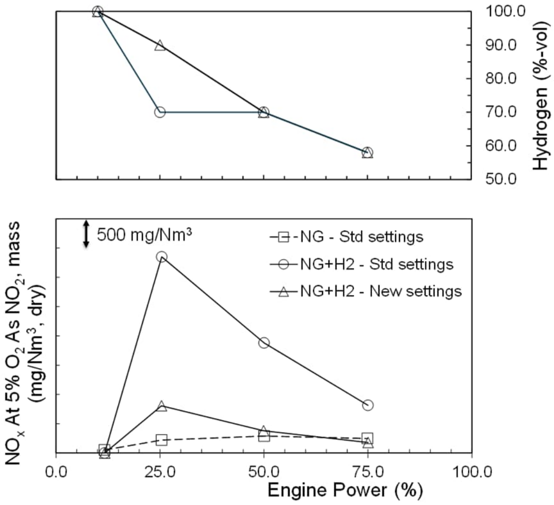

Figure 15. Impact on NOx emissions.

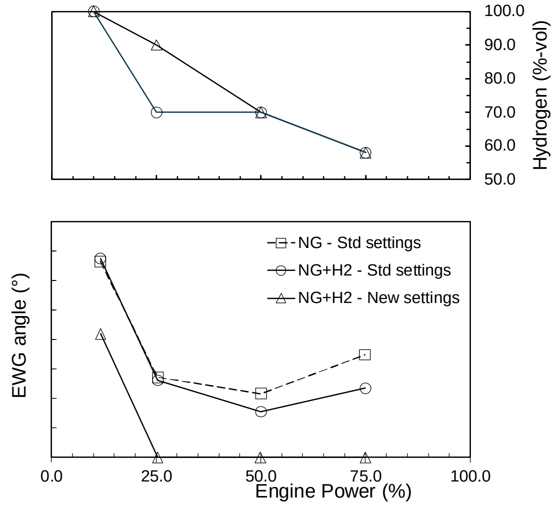

Figure 16. Lambda tuning Impact on EWG angle.

Leaner mixtures (higher lambda in the range 2.4÷3.4) together with delayed gas ignition timing (to avoid overlapping of gas injection and exhaust valve opening) and shorter gas injection duration (it improves the air-gas mixture and reduce the permanence of the gas within the intake port) clearly help to reduce the number of pre-ignition events. Leaner mixtures also eliminate the knock issue and lower the NOx emissions.

By increasing the lambda, it was possible to bring NOx emissions below TA-Luft level except at 25% load with 90%-vol hydrogen, where it was possible to lower NOx level below IMO Tier III (Exhaust wastegate fully closed).

At 10% load, the engine runs on a lean mixture already in gas mode, no further benefit increasing the lambda up to the EWG closure. A small lambda increase was sufficient to prevent pre-ignition and backfire. Engine shutdown happened with closed EWG after backfire and dead cycles events and by reducing the receiver temperature below the nominal due to unfavorable thermodynamic conditions in the combustion chamber (CC).

The combustion duration with hydrogen blending is not significantly affected by tuned performance settings. It remains shorter compared to natural gas despite the similar NOx emission level.

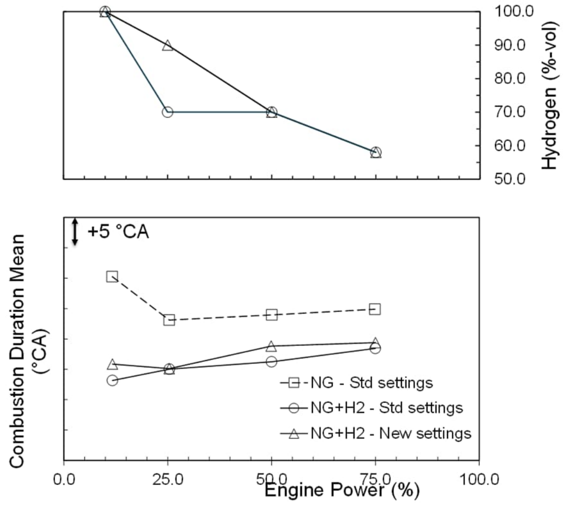

Table 17. Impact on Combustion duration.

The impact on firing pressures raises with load despite the lower hydrogen content. No chance to mitigate the firing pressure level by tuned performance settings. They only improve the firing pressure distribution.

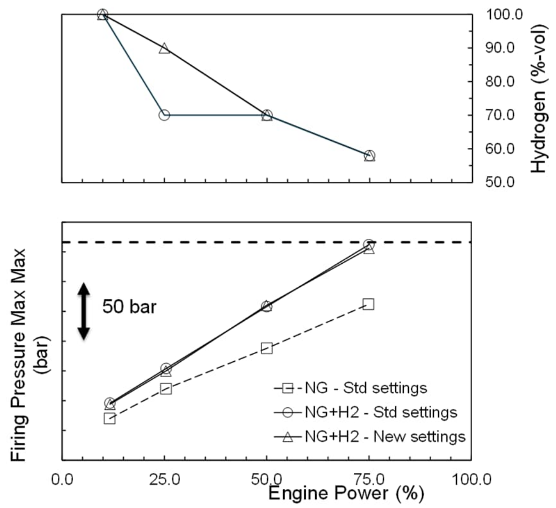

Figure 18. Impact on Firing pressure.

No remarkable impact on temperature before turbine by adding hydrogen at constant settings. As expected, the temperature before engine lowers when increasing the lambda.

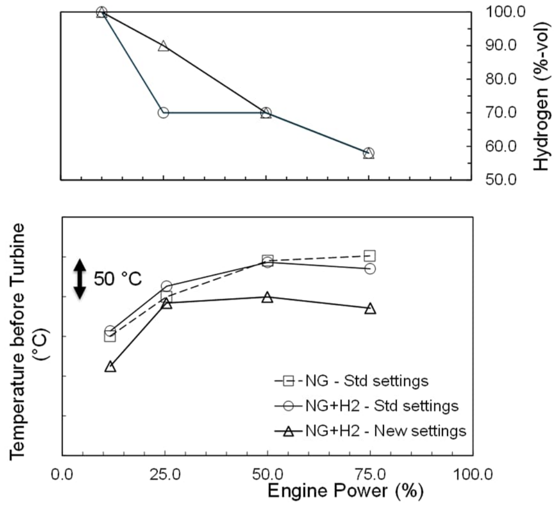

Figure 19. Impact on Temperature before turbine.

The engine efficiency is generally higher compared to natural gas and it is not penalized by leaner mixture.

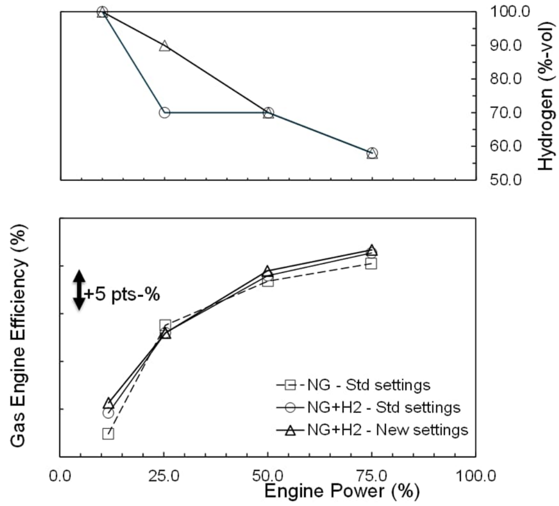

Figure 20. Impact on engine efficiency.

Total hydrocarbon emissions are remarkably reduced when introducing hydrogen.

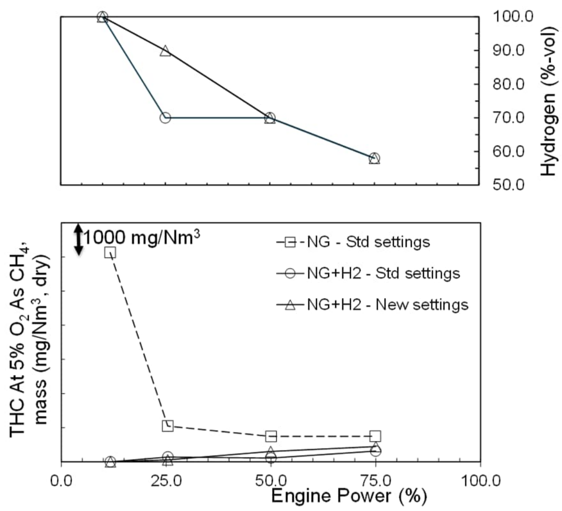

Figure 21. Impact on THC emissions.

It is well known that the methane slip worsens at lower loads (at tested loads the CH_4 emissions are approximately -14% lower compared to THC emissions) due to the leaner conditions in the combustion chamber and the not completed combustion. Methane slip depends also on engine design, on the position of the main gas admission valve, on valve timing and on gas admission timing. All these aspects can be optimized to eliminate the component that direct escape from the exhaust valve during the intake phase. Crevices in the combustion chamber should be also reduced to avoid that trapped unburned gasses flows through the exhaust valve.

CO_2 equivalent is commonly used to evaluate the reduction of carbon dioxide (CO_2) and methane slip (CH_4) obtained thanks to the introduction of hydrogen. CO_2 and CH_4 are expressed as CO_2 equivalent. N_2O is not considered in this study.

CO_2 equivalent is calculated according to the formula [13]:

$$CO_2eq\ (g/kWh) = CO_2\ (g/kWh) + CH_4\ (g/kWh) * GWP_{CH_4}$$

Intergovernmental Panel on Climate Change (IPCC) sets the Global Warming Potential (GWP) values relative to CO_2.

Table 8. Global warming potential (GWP) 100 years factor.

GWP100 factors	AR04 (2007)	AR05 (2014)	AR06 (2020)
CO_2	1	1	1
CH_4	25.0	28.0	27.0

The use of the latest values is recommended.

The proper characteristic of hydrogen, a quenching distance one order of magnitude lower than methane and the lower ignition energy coupled to a wider flammability range favor a more complete and efficient combustion even at low loads and therefore a lower CO_2 equivalent. The largest contribution to the CO_2 equivalent reduction is due to the partial replacement of a carbon-based fuel with a carbon-free fuel.

The total CO_2 equivalent reduction is the sum of the three contributions reported in the Table 9.

Table 9. CO_{2eq} reduction divided in sub-factors.

	CO_2 equivalent reduction due to:		
Load (%)	H_2 vs C (%)	Methan slip (%)	Efficiency (%)
75.0	-28.3	-1.4	-2.0
50.0	-40.0	-2.0	-1.7
25.0	-72.2	-2.6	-1.3
10.0	-100.0	-	-

The total CO_2 equivalent reduction, expressed as a percentage, is illustrated in Figure 22.

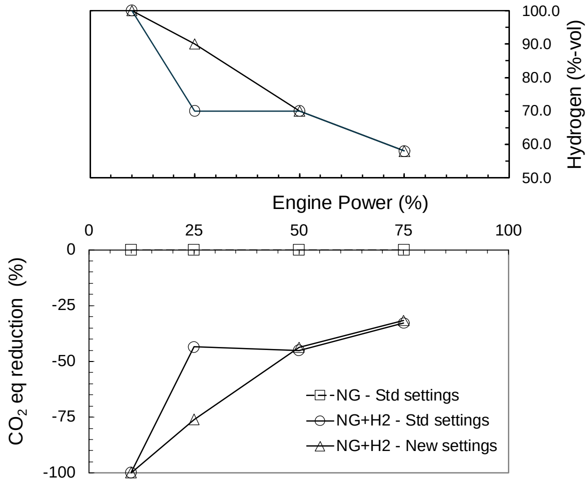

Figure 22. Impact on CO_2 and CH_4. as CO_2 eq.

9 CONCLUSIONS

The contribution of a reliable technology like the IC engine can be significant thanks to its capability to operate with different fuel types. It can support the transition from fossil to renewable fuels including hydrogen. Hydrogen fuel can play a relevant role in this sense, allowing the process towards zero CO_2 emissions and potentially zero-impact pollutant emissions from IC engine (Tank-To-Wake).

The main issues are related to the availability and production of H_2 and its safe storage.

The H_2 IC engines provide a reliable solution based on a well-known existing technology, contributing to the transition towards carbon-free mobility and power generation.

In this paper it has been demonstrated that a standard SI engine can operate with hydrogen blending above 25%-vol at part and low loads by making the necessary adjustments to the settings, plant and safety system, resulting in a significant reduction of greenhouse gas emissions.

The combustion process itself remains largely unchanged with the new settings. Peak firing pressures, combustion duration, and heat release position are comparable to those obtained with natural gas-optimized settings. The main improvements include reduced NOx emissions to natural gas levels and the elimination of unwanted combustion phenomena such as preignition, backfire, and knocking, achieved through the fine-tuning of the settings.

In conclusion, hydrogen IC engines present a viable and effective solution for the transition to sustainable and carbon-free energy systems.

10 DEFINITIONS, ACRONYMS, ABBREVIATIONS

CC. Combustion chamber**.**

CO_2. Carbon dioxide.

CO_{2eq}. Equivalent Carbon dioxide.

CH_4. Methane.

CR. Compression ratio.

CS. Classification Societies.

DF. Dual Fuel.

EGR. Exhaust Gas Recirculation.

EU. European Union.

EWG Exhaust Wastegate.

GHG. Greenhouse Gases.

H_2. Hydrogen.

HMI. Human Machine Interface.

ICE. Internal Combustion Engine.

IMEP. Indicated Mean Effective Pressure.

IMO. International Maritime Organization.

LEL. Lower Explosive Limit.

LFS. Laminar Flame Speed.

LHV. Lower Heating Value.

MFI. Main Fuel Injection.

NG. Natural Gas.

N_2O. Nitrous oxide.

NO_x. Nitrogen oxides.

O_2. Oxygen.

PLC. Programmable Logic Controller**.**

PM. Particulate Matter.

SCR. Selective Catalytic Reduction

SI. Spark Ignition.

SO_x. Sulphur oxide.

TDC. Top Dead Centre.

THC. Total Hydrocarbons.

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12 CONTACT

Stefania Ischia
Senior Performance Expert, Engine Performance Team. Wärtsilä Italy S.p.A.
stefania.ischia@wartsila.com

Kaj Portin
General Manager, Sustainable Fuels, Sustainable Fuels & Decarbonization. Wärtsilä Finland Oy.
kaj.portin@wartsila.com

Diego Delneri
General Manager, System and Engine Performance. Wärtsilä Italy S.p.A.
diego.delneri@wartsila.com

Miguel Prat
Instrumentation & Measurement and Automation Manager, Plant Operation. Wärtsilä Spain S.A.
miguel.prat@wartsila.com