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Successful demonstration of decarbonization through hydrogen blending in power plant engines

Operators Perspective

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ABSTRACT

In contrast to the marine industry, the internal combustion engine is not commonly perceived as part of a decarbonized future energy market. The interest in technologies as solar panels, windmills and battery energy storage systems is increasing as they lower the overall production cost. On the other hand, a higher penetration of renewable power implies higher reliable balancing power capacity to maintain a stable grid.

To showcase the future potential, versatility, and fuel flexibility of new and existing internal-combustion engines, Wärtsilä has performed successfully a hydrogen blending test on a 19-MW Wärtsilä 18V50SG engine at a customer power plant. The test aimed to assess the feasibility of incorporating blends of natural gas and hydrogen into existing internal combustion engines without requiring significant modifications. Remarkably, the test achieved a 25% hydrogen blend ratio without any mechanical changes to the engine, demonstrating both the adaptability and robustness of the Wärtsilä 18V50SG engine.

This paper examines the specifics of the test setup and the safety measures that were implemented to ensure a secure and controlled testing environment. The results of the test are analyzed, showcasing the engine's performance and efficiency with the hydrogen blend. Additionally, the paper discusses the broader implications of these findings, positioning the test as a critical first step in the journey towards decarbonization.

By exploring the practical aspects and outcomes of this hydrogen blending test, the paper highlights the potential of internal combustion engines to play an essential role in a sustainable energy future. This paper thus provides valuable insights into how traditional engines can be adapted to meet the evolving demands of a greener, more resilient power grid.

1 INTRODUCTION

The transition towards cleaner and more sustainable energy systems has accelerated globally as national-power grids incorporate increasing shares of renewable energy sources. Driven by their lower electricity production costs and ability to significantly reduce carbon emissions, renewables are gradually displacing e.g. traditional coal-fired power plants. This shift introduces challenges for grid stability due to the reduction in system inertia, requiring availability of reliable non-intermittent power sources and energy storage solutions that can swiftly stabilize the grid when needed during abnormal conditions, thereby preventing instability and blackouts [1].

Internal combustion engine (ICE) power plants are a proven, reliable and versatile solution to address these challenges. Their inherent flexibility enables them to reliably provide power when needed, whether as a baseload or peaking solution. While these engines are traditionally fuelled by fossil fuels, they can be modified to operate on sustainable alternatives. Wärtsilä have been at the forefront of this transition, advancing the development and deployment of sustainable fuels like hydrogen, methanol, ethanol and ammonia-powered engines, including retrofit solutions for existing infrastructure [1].

The development of the abovementioned sustainable fuels, and emerging biofuel alternatives like ethanol, is heavily influenced by regional legislation, political priorities, and existing infrastructure. For current and future engine power plant owners, the future regulatory compliance of their power plants can be currently perceived as a significant risk. The fuel flexibility and operational flexibility of the ICE technology provides on the other hand a significant added value to utilities and independent-power producers navigating this uncertain landscape.

ICE power plants offer several key advantages that make them an essential component of future energy systems. Firstly, their electrical output can be ramped up and down an unlimited number of times per day, reaching full power within just two minutes. This provides the plant operated with an opportunity to quickly adjust the operation according to current power need and participation in various ancillary-service markets that offers additional revenue streams.

Secondly, the fuel flexibility of the ICE, which includes both multi-fuel capability and the ability to introduce new fuels through retrofitting, provides customers with the opportunity to adapt their operations to changing business environments and requirements. For instance, a Dual-Fuel engine currently running on Heavy-Fuel Oil (HFO) and natural gas can be modified to operate on biodiesel and hydrogen-natural gas blends with minor adjustments. Similarly, a Wärtsilä 32 HFO engine can be converted to run on biodiesel, and methanol or ethanol.

The purpose of this paper is to elaborate on the future role of existing power plants using the ICE as the prime mover. To highlight the fuel flexibility and capability of internal combustion engines of using low-carbon fuels, this paper examines two separate tests involving co-firing of hydrogen and natural gas blends in Wärtsilä power plant engines and the corresponding results. The first test was conducted in collaboration with WEC Energy Group at the A.J. Mihm power plant in Michigan, USA, where hydrogen blends up to 25% hydrogen, by volume, were used. The second test was performed at Wärtsilä's own engine laboratory facilities, where hydrogen-natural gas blends up to 100% hydrogen were tested. These findings showcase the readiness of ICE technology to adapt to future fuel demands and as well as challenges, which furthermore defines the boundaries for the opportunities for hydrogen used as a fuel.

This paper will demonstrate that despite changing energy policies, environmental legislation and technological advancements, the ICE can still adapt to the changing business environment and through its capability to use sustainable fuels, along with its operational flexibility, the ICE power plant is a fundamental component of a resilient and sustainable, future electricity production. While hydrogen is the primary focus of this paper, the potential to convert to other fuels extends to other sustainable fuels such as methanol, ethanol, and ammonia, which depending on the local infrastructure and political incentives, might be as interesting as hydrogen.

2 HYDROGEN

Hydrogen is one of the key sustainable fuels to support a decarbonized electricity production with reliable power. Utilizing existing natural gas pipelines to blend natural gas and hydrogen facilitates both distribution and storage of substantial hydrogen quantities, offering an effective initial step to reduce the carbon footprint. Blending ratios of up to 25-30% by volume are typically considered feasible to avoid significant upgrades to the existing infrastructure. For hydrogen production facilities, this provides a flexible way to manage the production cost and hydrogen price, that is, the natural-gas pipeline can accommodate the fluctuations in production volumes without significantly impacting the consumption side, although it may result in varying hydrogen content in the pipeline. While this approach would provide a flexible platform for increasing the investments in hydrogen production, it remains dependent on using fossil fuels and further steps would be needed to completely decarbonize the electricity production.

In other regions, hydrogen pipelines and on-site hydrogen production have been explored, cf. Figure 1 and 2. The significantly higher investment cost compared to using the existing gas pipelines would likely imply that the hydrogen would be used for higher-value products. The high transportation cost of hydrogen outside the hydrogen pipeline would moreover indicate that the consumption of the hydrogen will probably happen close to the pipeline, or the hydrogen would be turned into e.g. ammonia or other more easily transportable substance.

Figure. 1. Preliminary routing of the Finnish hydrogen pipeline (Courtesy of GasGrid Finland Oy).

As hydrogen can be refined to products with a higher value than electricity, the long-term usage of hydrogen other than peaking and backup plants will not be likely. However, in the short-term during the build of production and consumption capacity, ICE power plants can provide valuable initial off-take capacity for hydrogen producers.

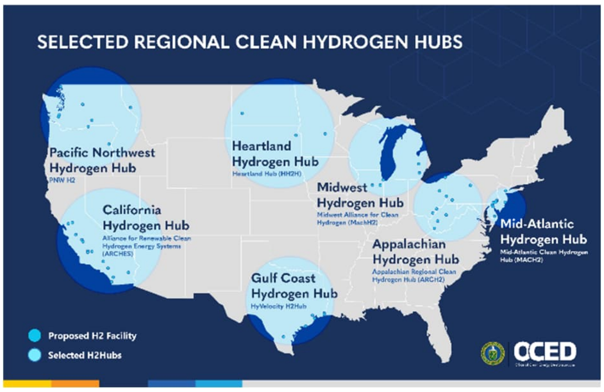

Figure. 2. Planned hydrogen hubs in the USA. Courtesy of US Department of Energy.

2.1 Hydrogen in internal combustion engines

As hydrogen is an easier ignitable gas and the combustion process becomes hence faster, co-firing hydrogen with natural gas in an ICE will naturally affect the overall combustion process and the performance of the engine.

To accommodate co-firing hydrogen on a modern natural gas engine, delaying the Start-of-Combustions and increasing the air-fuel ratio are the typically needed adjustments. The blending ratio is often limited by the peak cylinder pressures, which makes it necessary to de-rate the engines for higher blending ratios.

Considering the engineering requirements related to cofiring of hydrogen, most standards acknowledge a specific blending ratio for which the requirements on the installation changes. For example, IEC 60079 states that installations where a natural gas blends with below 25vol% hydrogen is used still can be considered as natural-gas power plant, as the ignitability of the gas mix is essentially the same. For blending ratios above 25vol%, additional precaution is hence needed to be made, for example, use double-wall pipes to avoid gas leakages of high hydrogen-content gas inside the engine hall.

Wärtsilä gas engines can operate on hydrogen blends up to 25% by volume, which accommodates the first step of introducing hydrogen into existing natural gas pipelines. Older existing gas engines can also be made to co-fire hydrogen with some modifications. To further future proofing existing products and solutions, there is an on-going push to develop and validate the potential for co-firing of higher blends as well as development of a hydrogen engine. The first hydrogen power plant and the W31 engine designed for pure hydrogen operation were released to the market in 2024.

3 HYDROGEN CO-FIRING TEST BELOW 25VOL%

In this section, the first hydrogen blending test together with a customer will be presented. In 2022, Wärtsilä, in collaboration with WEC Energy, Electric Power Research Institute (EPRI), a renown research facility for power production in the US, and Certarus, a leading gas and equipment supplier in the North America, conducted a significant demonstration project at the A.J. Mihm power plant in the United States [2]. This project focused on validating the co-firing of hydrogen on a Wärtsilä 50SG natural gas engine without modifications to the engine or site (other than safety related changes).

The primary objective of the project was to demonstrate that hydrogen-natural gas blends, up to 25vol% hydrogen could be effectively utilized commercially by a grid-connected engine generator set, without modifications to the engine. The A.J. Mihm demonstration (cf. Figure 3) was designed to replicate real-world operational conditions, ensuring that the results would be relevant to various scenarios.

Fig 3. The A. J. Mihm power plant.

3.1 Test setup

To ensure a safe test setup, a joint HAZOP (Hazard and Operability) study was conducted to identify potential risks associated with hydrogen blending and engine operation.

The best way to supply and store the hydrogen to and on the site was by using hydrogen trailers supplied by Certarus Ltd, a leading gas and equipment supplier based in North America. A restricted area was established around the parking area of the hydrogen trailers, as well as the pure hydrogen area.

To ensure proper conditioning of the hydrogen, the hydrogen pressure was reduced to match that of the natural gas, which would allow for a proper mixing of the two gases. To avoid the introducing pure hydrogen inside the power plant itself, a dedicated gas-mixing unit was used. That is, by replacing a part of the natural gas pipe just before the engine with a T-section spool piece, the natural gas was re-routed outside the engine hall to a hydrogen mixing unit, where the flows of the natural gas and hydrogen was controlled to achieve the given blending-ratio setpoint. The physical mixing of the gases happened in a mixing tank to provide a good mixing quality. The blended gas was then reintroduced into the main gas pipeline just before the gas regulating unit of the engine [2].

Detecting gas leakages and managing a potential leakage are important aspects of operating a plant on any gas fuel. Following IEC60079, a leakage of the blended gas with up to 25vol% H2 can be handled as a natural gas leakage and it was concluded that the existing plant design and safety concept was sufficient. Verification risk for gas leakages due to the mixed hydrogen was an important aspect of the project. To this end, a hydrogen-gas sniffer was located above the gas regulating unit to cover the relatively high concentration of flanges. In addition to this, all flanges exposed to the blended gas were wrapped in with hydrogen-detection tape to allow for a comprehensive leakage detection. To further sufficiently dilute a potential leakage, the ventilation in the engine hall was increased. As for the W18V50SG engine, there were no mechanical modifications done.

Although the typical setup would include automatic adjustments of key control parameters as function of the engine load and blending ratio, it was decided to manually calibrate the control parameters to minimize the modifications of the engine.

In Figure 4, a step in blending ratio is shown. The change rate in blending ratio was limited to 1vol% / minute to provide the engine with ample time to adjust to the change in gas composition.

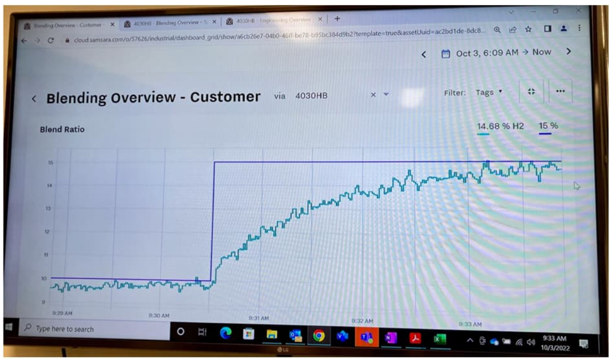

Figure 4. Example of a step in blending ratio from 10 to 15vol% hydrogen.

3.2 Test Program

The test program included predefined test points with incrementally increasing hydrogen concentrations blended with natural gas, cf. table 1. For test point 12 and 13, the idea was to search for the maximum engine load at 25vol% H2 and max blending ratio at full engine load, respectively. Throughout the testing process, essential engine parameters such as cylinder pressures and temperatures were continuously monitored. If necessary, manual adjustments to fuel-injections and charge-air pressure setpoint maps were made to maintain combustion within safe limits. It's important to note that throughout the tests, the standard set of safety features was activated.

Table 1. Steady-state test points for blends up to 25vol% H2.

Test point	Engine load (%)	Hydrogen blending ratio (vol%)
1	50	0
2	50	10
3	50	15
4	50	20
5	50	25
6	75	0
7	75	10
8	75	15
9	75	20
10	75	25
11	100	0
12	max	25
13	100	max

3.3 Test results

For engine loads at 50% and 75%, no adjustment of the control parameters was necessary, as these engine-load levels could effectively accommodate up to 25vol% hydrogen blending ratio, cf. Figure 5. However, at test points 12 and 13, adjustments to the control parameters became essential to maintain cylinder pressures within the design limits. For 25vol%, it became necessary to derate the engine as the control-parameter margins for the engine was exhausted.

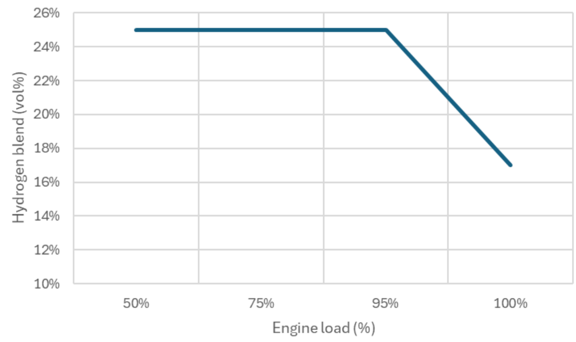

Figure 5. Engine load derating curve for 25vol% H2 blending ratio.

In Figure 6, a comparison of the NOx emissions for the natural gas and for max hydrogen blend hydrogen blend setups are shown. For 50% and 75% engine loads where no adjustments to the control parameters were done, the NOx emission increased compared to natural gas operation, but still below the stipulated regulatory limit of this plant (black solid line). For higher engine loads, where control parameter adjustments become necessary, NOx emissions are reduced compared to natural gas operation.

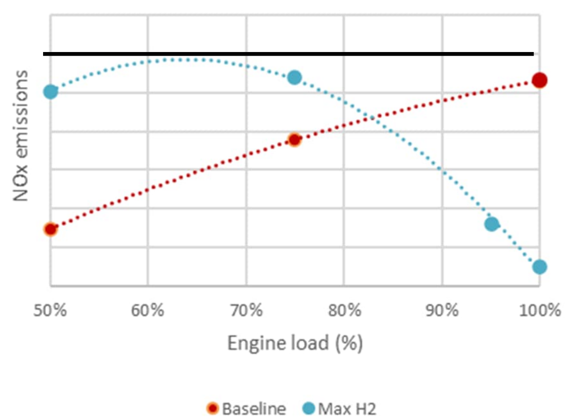

Figure 6. NOx emission comparison with natural gas and with a blended gas.

In Figure 7, the CO and CO2e exhaust-gas emissions are shown for hydrogen blends at 25vol%. To better illustrate the overall climate impact, CO2e (CO2 equivalent) is used instead of just CO2. This metric accounts for the global warming effect of other hydrocarbons as well, following IPCC AR4 guidelines. However, due to limitations in the instrumentation, the influence of N2O was not included. As can be seen, the CO emissions are significantly reduced with the introduction of hydrogen, which is mainly due to a more complete combustion with hydrogen blends. The CO2e emissions are similarly positively impacted by the hydrogen usage, but from two perspectives. First, due to the removal of carbon content in the injected fuel and secondly due to a lower methane slip, especially on lower loads.

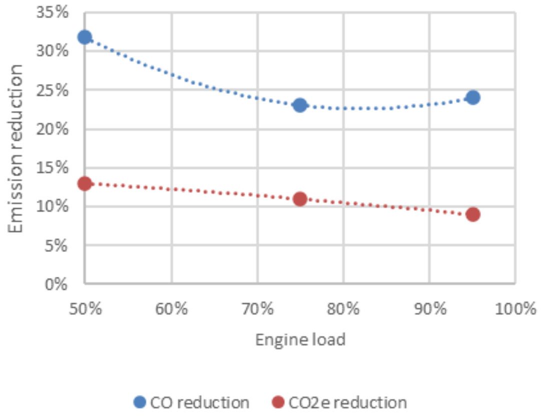

Figure 7. CO and CO2e reduction as function of load and max H2 blending content.

Overall, it was concluded that the unmodified engine responded as expected the introduction of hydrogen. No leakages were detected throughout the testing campaign, which provided evidence of the reliability of the design. It was also seen that hydrogen co-firing reduces many of the emissions constituencies, for example methane slip, CO and CO2e, while NOx emissions can be maintained below the regulator limit. It offers therefore a very interesting way to lower emission components that are otherwise challenging to abate.

4 HYDROGEN CO-FIRING TEST BEYOND 25VOL%

To further explore the engine behavior for hydrogen blends exceeding 25% by volume, a series of internal engine tests were conducted on an unmodified Wärtsilä W6L50SG laboratory test engine. The objective of these tests was to progress from a 25vol% up to a 100vol% hydrogen blend.

Again, the hydrogen was supplied and stored at site in trailers and conditioned to the same pressure as the natural gas before mixing. In opposite to the previous outlined test, the hydrogen was here directly introduced into the natural gas pipeline without additional mixing volumes or nozzles. The quality of the mixing was instead ensured by the distance between the mixing point and the test engine.

The test program included a series of steady-state test points to identify the maximum engine load for each hydrogen blending ratio. In Figure 8, the estimated complete derating curve with an increased hydrogen content. It shows a logical and smooth relationship between the maximum possible engine output and the blending ratio.

Table 2. Steady-state test points for blends up to 100vol% H2.

Load (%)	H2/ (H2+NG) (%-volume)	H2/(H2+NG) (%-mass)	H2/(H2+NG) (%-energy)
93	25	3.7	9
75	58	13.9	28
50	70	21.4	40
25	90	51.5	72
10	100	100	100

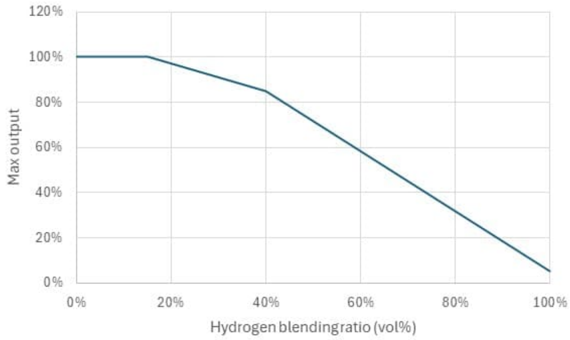

Figure 8. Maximum engine output as function of the hydrogen blending ratio.

The relationship between the hydrogen content and the CO2e reduction is more complex, Figure 9. This can be explained by the switch of the main fuel, which impacts on the overall efficiency of the combustion. The usage of a volumetric blending ratio, as opposed to an energy-based blending ratio, also shifts the x-axis to a more nonlinear relationship. Similarly, the CO emission reduction is shown in Figure 10. For a more elaborate deep-dive into this test, please refer to [2].

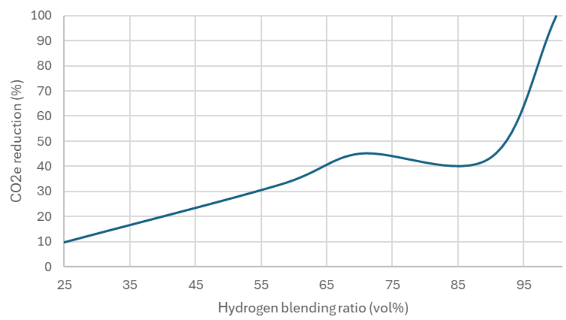

Figure 9. CO_2e reduction as function of the hydrogen blending ratio (at maximum engine load).

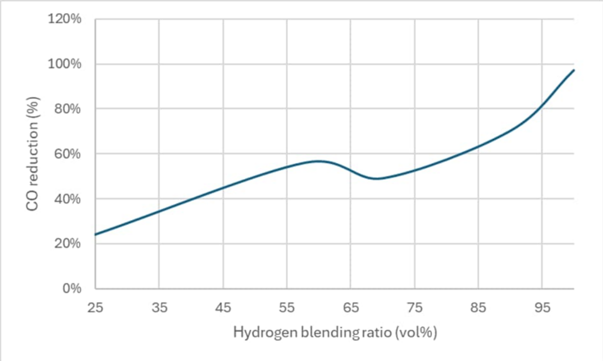

Figure 10. CO reduction as function of the hydrogen blending ratio (at maximum engine load).

5 CONCLUSIONS

The ongoing decarbonization efforts have created uncertainties for power plant owners, increasing the perceived business risks. Questions such as "Will I be able to operate in five years?" plague the minds of many in the industry. However, recent sustainable fuel tests have demonstrated the feasibility of future-proofing existing engines and power plants.

As been stated in this paper, these tests have been done without mechanical modifications with the intent to increase the engine output on higher blending ratios. For example, lower compression ratios and other means for introducing the fuel into the cylinder will significantly improve the maximum output of the engine for higher hydrogen concentrations.

As shown by these tests, hydrogen blends provide a great opportunity for existing gas power plants to comply with future carbon-footprint requirements. Depending on the current decarbonization need and the current availability of hydrogen, the most economically blending ratio can be used.

In conclusion, the integration of hydrogen blending offers a promising opportunity for current power plant owners to position themselves as key players in the future local energy mix.

6 FUTURE ROLE OF HYDROGEN IN ELECTRICITY PRODUCTION

Existing power plants often face uncertainty regarding their role in the future local energy mix, and due to the current consumption of fossil fuel, they are frequently seen as part of the problem rather than the solution.

Along with the impressive operational flexibility, such as fast start-stop capability and rapid loading-unloading, the ICE power plant provides the many of the features that are required to maximise the amount of renewable power in a power system.

Consequently, existing and new ICE power plants will play a crucial role as balancing power sources with a low carbon footprint. For existing power plants, where previous investments have already been recouped, the reduced output from using hydrogen blends may not pose a significant issue when e.g. participating in future PPA (Power Purchase Agreement) auctions. Hydrogen blending offers hence a valuable opportunity for power-plant owners to position themselves and their power plant within the future electricity-production landscape.

7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

HFO: Heavy-Fuel Oil

LFO: Light-Fuel Oil

ICE: Internal-Combustion Engine

SG: Spark-Gas

CO2e: CO2 equivalent

HAZOP: Hazard and Operability

PPA: Power Purchase Agreement

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