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Advancing sustainable shipping: strategies for methane slip reduction in Wärtsilä four-stroke engines

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

The global effort to reduce CO_2 emissions in the marine industry is driving legislators to design carbon tax systems that promote the transition towards more sustainable fuels, with the ultimate goal of largely decarbonizing the marine sector by 2050. One example is the current situation in the EU, where the ETS and FuelEU Maritime legislations are in force and are expected to significantly impact ship operators' balance sheets.

In particular, the FuelEU Maritime regulation will progressively and exponentially penalize the use of high carbon intensity fuels. Highly efficient natural gas-based power solutions are a viable option to control these costs up to and beyond 2035, along with an overall reduced emissions footprint (particulate matter, NO_x, SO_x, CO_2). In this context, the reduction of methane emissions will play a crucial role, quantifiable in a relevant monetary value for shipowners.

Throughout the last decades, Wärtsilä has been constantly developing its gas technologies to reduce methane slip. The Wärtsilä 31 “ultra-low” emission gas concept, also known as NextDF, piloted on the “Aurora Botnia” ferry in 2022 and released for sale in 2023, is one of the latest successful endeavours.

This paper will give an overview of recent efforts in this field, focusing on the follow-up of the first Wärtsilä 31 NextDF production engines, including the long-term experience from the “Aurora Botnia” pilot installation; the scalability and deployment of the “ultra-low” emission concept to other engine platforms; the development of competitive solutions applicable both to newbuilds and as retrofit packages to the Wärtsilä installed base; and the development of an affordable post-turbo aftertreatment concept in partnership with Shell under the umbrella of the EU-funded Green Ray project.

Among the retrofit solutions, one of particular interest is the novel system approach for the LNG tanker fleet powered by Wärtsilä 50, leveraging a mixed configuration of DF and marine SG engines.

Ultimately, there is no unique way to mitigate actual ship methane emissions. A holistic approach is often required to properly consider not only the engine types but also the machinery concept and the typical application profiles, including the dynamics of operation.

1 EMISSION LEGISLATION DEVELOPMENT

The emission legislation on marine transportation and stationary power production is continuously tightening. In addition to mainly concerned nitrogen oxide (NOx), Sulphur oxide (SOx) and Particulate (PM) emissions, also hydrocarbon emissions are getting more interest. During the recent years reduction strategies and new regulations on CO2 and GHG emissions has been published both by international (IMO) and local maritime authorities (EU).

Regarding the air quality pollutants, IMO SOx regulation on fuel maximum sulphur cap of 0,5% was introduced in 2020, and Mediterranean SOx emissions control area (ECA) with 0,1% sulphur limit will complement the existing SOx ECAs in 2025. From the beginning of 2021, addition of Baltic and North Sea NOx emission control area extended the coverage of IMO NOx Tier III areas on many important shipping routes. These existing ECAs will be accompanied by new NOx and SOx control areas in Canadian Arctic and Norwegian sea within next few years. These changes will improve the air quality on coastal areas by considerable reductions on NOx, SOx and PM emissions. Low-pressure dual fuel engines operating on LNG will meet all existing requirements and provide SOx and PM emissions far below liquid fuel operation. The developments of local regulations like the EU Stage V limits for Inland waterways and on-road sector new Euro 7 regulation shows that reducing air quality pollutants will remain important.

During the recent years, the reduction of GHG emissions of maritime transportation have raised increasing interest. Already in 2018, IMO initial GHG strategy defined targets for reducing GHG emissions [1]. In addition to CO2, addressing the emissions of methane (CH4) and nitrous oxide (N2O) was noted in the short-term measures. According to latest IPCC (AR6) report, methane is about 30 times stronger greenhouse gas compared to CO2 in the 100 years' timeframe [2]. To strengthen the earlier decisions, IMO GHG reduction targets were revised in the 2023 GHG strategy [3], introducing target for net zero GHG by 2050 and several milestones and measures for reaching the target. IMO is expected to approve the mid-term measures during this year, including GHG intensity reduction and economic measure aligned with the strategy targets. GHG intensity calculation according to 2024 Lifecycle assessment guidelines [4] includes the GHG effect of CH4 and N2O using the 100-year GWP factors.

In EU, 2021 published "Fit for 55" package contains several initiatives to support the reduction of GHG emissions. From these initiatives, the most relevant for marine transportation are inclusion of marine transportation to EU emission trading system (ETS) [5] and FuelEU Maritime [6]. Both regulations include CO2, CH4 and N2O emissions, and there will also be significant penalties in case of non-compliance. Reporting of CH4 and N2O emissions in addition to CO2 via MRV (monitoring reporting and verification) system started in 2024 and all these emissions will be included in ETS in 2026. FuelEU Maritime sets the guidance on calculating the fuel well-to-wake GHG intensity (unit gCO2eq/MJ fuel energy), yearly reporting, and tightening reduction targets for carbon intensity from 2025 to 2050.

All these regulatory changes require the development of new technologies to reduce emissions. In case of superior emission performance, both IMO and EU regulations acknowledge the use of certified CH4 and N2O emission values instead of pre-defined default values. In addition, there will be a cost of emission/non-compliance, which provides also financial incentive for improvement.

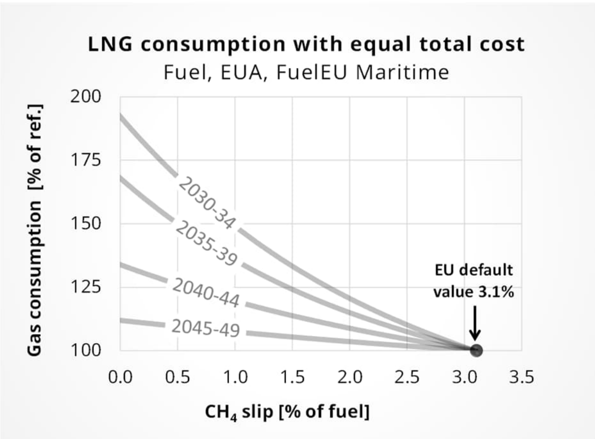

Figure 1. Calculated constant operative cost line by changing gas consumption as function of the methane emissions for a ship operating in European water. The operative expenses include the fuel, the carbon allowances (EUA) and the FuelEU Maritime costs. Overcompliance benefit is considered in the calculation assuming a "pooling" principle.

For LNG-powered vessels, methane emissions will become a driving factor not only from an environmental standpoint but also from an operational cost perspective. Reducing this emission by 1 g/kWh can have a similar operational cost implication as reducing gas consumption by 10% to 15% in the time horizon up to 2040 for a vessel operating in European waters (Figure 1).

The actual trade-off is sensitive to the development of LNG and Carbon allowance (EUA) costs. Beyond 2040, the FuelEU maritime cost will become so dominant that will force the industry to move to zero-carbon or carbon-neutral fuels (such as biodiesel and bio-LNG) to control the ship operating costs.

This paper will provide an overview of recent developments in the field of methane emissions reduction for marine LNG applications, focusing on:

- The advancement of the Wärtsilä 31 NextDF technology, including long-term experience from the Aurora Botnia pilot installation.
- The scalability and deployment of the “ultra-low” emission concept to other engine platforms.
- The development of competitive solutions applicable both to new builds and as retrofit packages to the large Wärtsilä installed base.
- The development of an affordable post-turbo aftertreatment concept in partnership with Shell.

2 THE NEXTDF COMBUSTION CONCEPT, FURTHER DEVELOPMENT AND PRODUCT IMPLEMENTATION

As reported in the previous work [7], the development of the next-generation Dual Fuel low-pressure concept started in 2017 and was first implemented on a Wärtsilä 31 engine in a pilot installation in 2022. In this chapter, a high-level description of the combustion principle will be provided, a summary of the latest developments on the Wärtsilä 31 will be presented, and the concept deployment activities to other platforms will be highlighted.

2.1 NextDF combustion concept principle

When the development of the novel combustion approach started, the main objectives were to significantly reduce methane emissions and improve operational efficiency by addressing the weak points of lean-burn Otto combustion: high sensitivity to the air-fuel ratio and varying cylinder-specific conditions, cycle-to-cycle instability, flame quenching towards the combustion chamber walls, and crevice dead volumes.

From a technology standpoint, the goal was to develop a combustion system with a more spatially distributed and stable ignition source, moving away from the relatively slow and stochastic flame propagation triggered in conventional DF engines by diesel pilot sprays in the middle of the combustion space. To achieve this result, the target was set to operate the engine at the edge of autoignition, a condition determined by the pressure-temperature history of the fuel mix during the firing compression stroke. When a certain thermodynamic state is met, the charge self-ignites in a violent and complete combustion. This is typically an unwanted situation, but if domesticated and made controllable, it would result in optimal engine performance. This approach was enabled by the extensive fuel injection and valve timing flexibility of the newest platform engines, in combination with cylinder-wise triggers actively monitoring and continuously adapting the control parameters (e.g., fuel injection settings). The main closed-loop software functionalities are based on real-time crank-resolved heat release data calculated independently for each cylinder using pressure sensor signals.

To control the combustion speed within the set limits in terms of maximum firing pressure rise rate and combustion noise, the engine runs very lean with a significantly higher air-fuel ratio than traditional DF engines. This condition results in very low NOx emissions, approaching single-digit ppm values in volume concentration across a large part of the operating window.

Eventually, compared to the reference DF engine, methane emissions were cut by more than 50%, NOx emissions by 90%, with an increase in engine efficiency at part load and a remarkable reduction in IMEP cycle-to-cycle variation [7] (Figure 2).

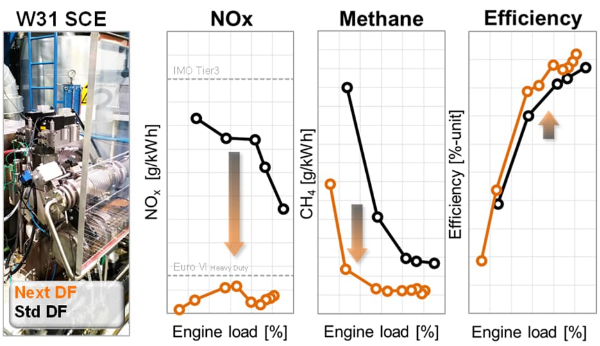

Figure 2. NextDF combustion benefits proved in 2019 on Wartsila 31 SCE.

2.2 Aurora Botnia Wärtsilä 31 pilot installation experience.

Since August 2022, one of the 8V31 engines powering the Aurora Botnia vessel has been upgraded to the NextDF setup. The field pilot upgrade, co-financed by the Seatech EU-funded project, has been a fundamental step towards the concept's industrialization and release for production.

The field engine emissions were measured with laboratory equipment twice: once when the engine was retrofitted in October 2022, and more recently in December 2024. This latest campaign aimed to verify the performance stability over time. Since the upgrade, the engine has run for more than 5,500 hours, with about 4,000 of those hours in gas mode.

In December 2022, a third-party measurement was carried out to assess the emissions of the Aurora Botnia, as this vessel is one of the latest examples of a modern LNG-powered ferry. During this investigation, both the standard Wärtsilä 31 DF (ME4) and the NextDF prototype (ME3) were measured. The published results [8][9] were largely in line with own experiences, once again demonstrating the capability of this novel combustion concept in terms of methane slip reduction (Figure 3). A value close to 1% of the engine's gas consumption was achieved across the entire operating area, with a reduction of more than 50% compared to the reference engine onboard.

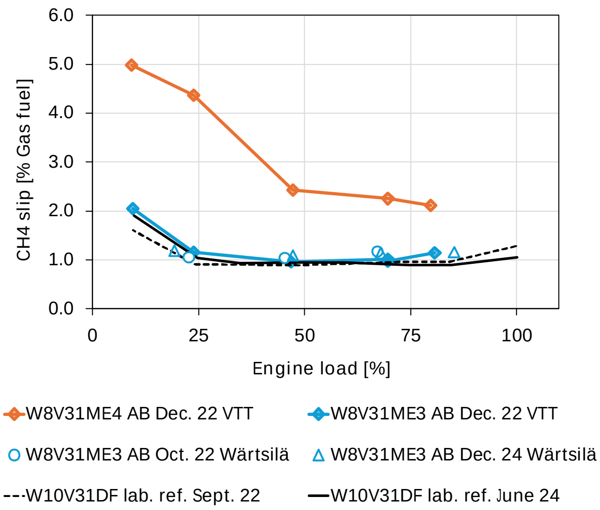

Figure 3. Internal and third-party CH4 measurements done on Aurora Botnia. In light blue NextDF, in orange the reference standard DF.

Furthermore, the Aurora Botnia vessel is connected remotely to Wärtsilä's own database called Expert Insight. It is possible to follow the time history of most of the engine's signals, control parameters, and sensors with 1-second resolution. Of particular interest are the two Continental smart NOx sensors installed on the exhaust line before and after the SCR of the engine retrofitted with the NextDF technology. By tracing back more than one year of NOx emissions, it was possible to further confirm the performance stability over time despite changing operating conditions. In Figure 4, the continuously measured NOx emissions from November 2023 until December 2024 are compared with Wärtsilä's own and third-party spot measurements.

After the first positive feedback from the pilot installation, the NextDF technology was released to the market in October 2023 [10]. The first eight production engines will be delivered from the Sustainable Technology Hub (STH), the name of the Vaasa factory and research center, within the first quarters of 2025.

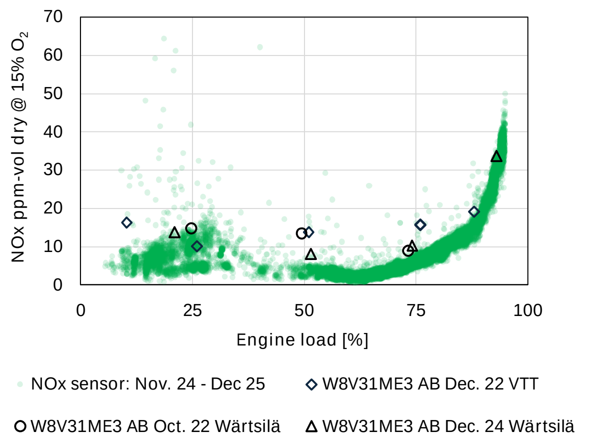

Figure 4. Continuously measured emissions from SCR NOx sensors in green compared to results from measurement campaigns.

2.3 Wärtsilä 31 NextDF development for mechanical drive applications.

Once the NextDF was released for constant speed operation, serving the diesel-electric propulsion system, the next logical step was to further develop this technology to cover mechanical drive applications operated at variable speed along the propeller line.

The new project was initiated in 2022, focusing on the control parameters mapping throughout the engine's operational field and on the turbocharging system. The main identified challenge was to extend the 'extra lean' operation along the propeller speed line, an area typically limited by the available boost pressure delivered by the turbocharger.

The first concept evaluation was conducted on a small-bore SCE to gain a better understanding of the performance trade-offs and to define the main software settings and hardware requirements.

Based on these results, it was eventually possible to evaluate the concept feasibility and to define the turbocharging system specification for the W10V31 laboratory engine. The actual engine optimization test was carried out in the first half of 2024. The results were successful, showing the concept's capability to extend the emission benefits to the variable speed operating range. In Figure 5, the ISO plots of the methane and NOx emissions are reported as a function of engine speed and load. The methane emission is kept below 1% of the gas fuel input in a large part of the operational field, while the NOx is kept well below the Tier 3 level.

One important aspect of the mechanical drive propulsion system is the capability to operate smoothly under wave loading conditions. When the ship is navigating in rough seas, the waves interact with the propellers, leading to load oscillations whose amplitude and period are directly influenced by the wave characteristics and the angle relative to the vessel's direction.

A specific dynamic test was conducted on the laboratory engine, continuously varying the applied load with a given period around the average value to mimic actual operation at sea. In these harsh conditions, the engine continuously faces transient operation. A conventional dual-fuel (DF) engine, therefore, either runs with an air-fuel mixture that is too lean, resulting in higher CH_4 emissions than average, or too rich, with the risk of high NOx emissions. Sometimes the wave conditions are so severe that the engine trips to diesel mode due to excessive number of knocking cycles. The engine transient controls [11] on the newest engine platform can partly mitigate this phenomenon but are not able to fully recover the steady-state performance.

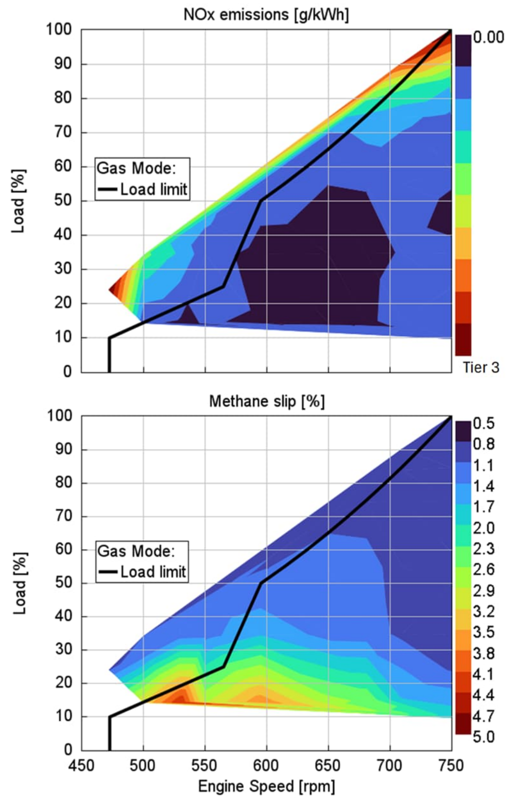

Figure 5. Methane slip and NOx emission isoplots based on 10V31 NextDF prototype testing. The measured values are low and relatively flat across a large part of the operating field.

Thanks to the superior combustion stability, extra-lean operation, and insensitivity to varying air-fuel ratios, the measured emissions of the NextDF concept were significantly better than those of the reference DF engine. The variation of CH_4 emissions was reduced, and the risk of the gas trip to diesel mode was sharply decreased.

In the chart in Figure 6, it is possible to observe the relative improvement in methane slip emissions for a wave period of 10 seconds with varying amplitude at 50% and 80% average engine load. It should be noted that the reference DF engine is not the Wärtsilä 31DF, but an older engine platform. The latest DF engines would perform better due to their enhanced hardware flexibility and advanced controls.

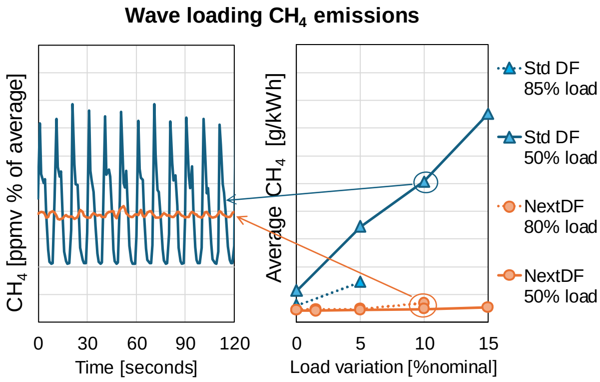

Figure 6. Methane emissions during wave loading: The reference DF engine is shown in light blue, while the NextDF technology is shown in orange. The latter is very stable in varying operating conditions.

Based on the collected data from the laboratory wave loading tests, it was possible to simulate the benefits of the NextDF technology at the vessel level in a real field case. For this exercise, a RoPax cargo ship running in rough seas on the route connecting Spain with the Canary Islands was considered. Figure 7 shows the mechanical drive configuration for such a vessel and the measured wave loads at sea on each of the two main engines.

For the calculation, a 15-minute time window was considered, during which the engines faced large fluctuations of up to +/- 15% load around 85% of the nominal power. In the simulation, the standard mechanical drive architecture was compared with the hybrid mechanical one, highlighted in orange in Figure 7. The hybrid configuration is built on a single-in twin-out gearbox with Power Take In/Out capability (PTI/PTO). A motor generator linked to the ship grid is connected to the PTI/PTO.

In the hybrid mechanical setup, the main engines can simultaneously supply propulsion power to the propeller and auxiliary power to the ship, or receive power support from the auxiliary engines and batteries connected to the ship grid. One feature of the hybrid mechanical configuration is the peak shaving functionality. When the propulsion load is suddenly reduced, the engines charge the batteries for a few seconds, easing the actual ramp rate. This feature stabilizes the engine load during heavy waves, reducing the risk of the engine tripping to diesel mode.

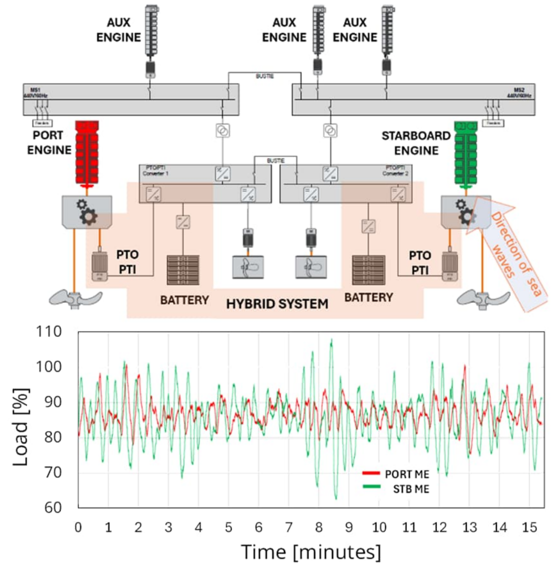

Figure 7. Mechanical drive propulsion system of the RoPax vessel considered in the study. The highlighted hybrid part in orange was added for simulation purposes. At the bottom, the load fluctuations for the port and starboard main engines measured in heavy sea conditions are reported.

Applying the NextDF technology to the vessel can further improve the actual ship performance beyond the peak shaving capability of the hybrid propulsion system. In the chart in Figure 8, the reference setup, the impact of the peak shaving feature, and the benefit of the NextDF technology on top of it are compared. For the considered sailing mode, the calculation showed a 9% improvement in energy consumption and a reduction of 44% and 65% in methane and NOx emissions, respectively. Overall, this represents a quite remarkable improvement from the starting point.

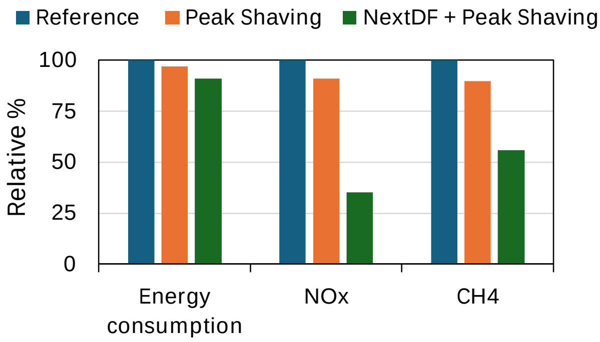

Figure 8. Simulated energy consumption, NOx, and CH4 emissions when applying the hybrid mechanical peak shaving feature and NextDF technology on a RoPax cargo ship in heavy sea conditions.

2.4 NextDF technology deployment on Wärtsilä engine portfolio.

The successful experience with the Wärtsilä 31 triggered the need to apply the NextDF technology to the newest engine platforms capable of hosting the novel combustion concept, thanks to the base engine structure characteristics and the extended flexibility of the fuel injection and valve train systems. In recent years, two projects were initiated to adapt the concept to both the Wärtsilä 25 (W25) and to the Wärtsilä 46TS (W46TS).

The optimization work for the W25 proved to be quite straightforward, as the engine features are very similar to its larger counterpart, the W31. Additionally, the preliminary work done on the W20 research platform [7] provided a set of data across a range of speeds and sizes that fit the W25 product perfectly. The first concept evaluation was conducted in autumn 2021 on the W25 Single Cylinder Engine (Figure 9), starting with a hardware and software set of parameters based on earlier experiences. The expected positive results led to the development of the multi-cylinder engine configuration. Consequently, the W8L25 laboratory engine was first run in NextDF mode in summer 2022. The product was released for production in October 2024 [12], and the first delivery project, which included two NextDF engines, was sold at the end of 2024.

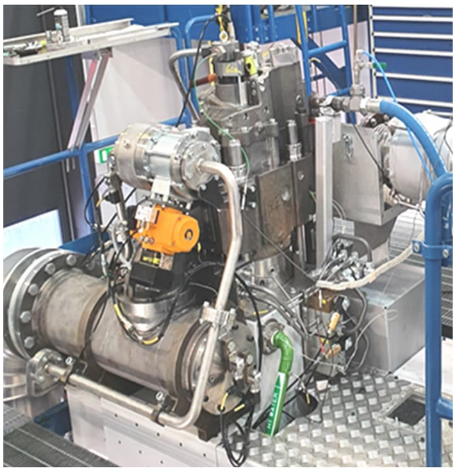

Figure 9. W25 Single Cylinder Engine located in the Vaskiluoto Research Laboratory , Vaasa, Finland.

Scaling up the combustion concept to a 46 cm bore, an engine size significantly larger than those in previous experiences, required more extensive research to develop a solid production concept compared to the Wärtsilä 25. These activities have been co-financed under the umbrella of the EU-funded GREEN RAY project [13], which started in 2022.

Since the large bore single-cylinder engine was not available, unlike in earlier developments, it was decided to put extra effort into simulation, developing a 1-D predictive combustion model utilizing the data acquired during the Wärtsilä 31 NextDF project [7]. This simulation tool was therefore utilized to define the hardware requirements and to provide a preliminary indication of the expected performance. The W6L46TS DF laboratory engine was upgraded to the Next DF configuration at the beginning of 2024. The test results were aligned with the simulation predictions and within the GREEN RAY CH4 reduction project target. As the next step, it was given the green light to proceed with the demo engine assembly, which is expected to be delivered by STH in Q1 2025. The first set of performance data collected on the production test bench is largely in line with laboratory expectations. The current plan is to have the pilot engine running in the field by 2026.

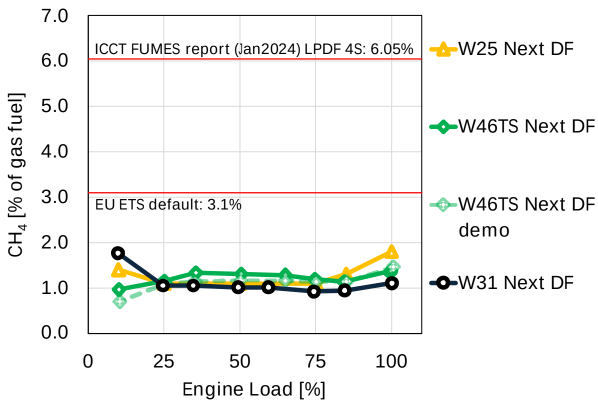

Figure 10. Methane slip factor measured on the NextDF portfolio against the EU ETS default value and the ICCT FUMES report [14] findings.

Figure 10 summarizes the CH4 emissions as a percentage of the gas fuel input for the NextDF engine portfolio, which now includes not only the Wärtsilä 31 but also the Wärtsilä 25 and Wärtsilä 46TS. The achieved performance is from 50% to 70% better than the EU ETS and FuelEU Maritime default value of 3.1%.

Featuring a methane slip factor of 1% from the exhaust across a significant portion of the operational range, this new concept will deliver substantial improvements once implemented. According to the recent ICCT FUMES report released in 2024 [14], the average methane slip emission level for low-pressure dual-fuel 4-stroke technology is 6.05% of the gas fuel input..

This new concept will also bring monetary value to end customers. Thanks to the high efficiency and low emissions, the EU ETS and FuelEU Maritime related costs will be reduced for ships sailing within EU coastal waters. In particular, FuelEU Maritime compliance will be extended to 2035 and beyond.

3 WÄRTSILÄ 34DF RECENT DEVELOPMENTS FOR NEWBUILDS AND RETROFIT

Along with the development of the latest combustion technology on the newest engine platforms, Wärtsilä has also focused in the recent past on improving the greenhouse gas emissions of its well-established dual-fuel products. This effort aims to secure both competitive performance for new build projects and to provide affordable retrofit solutions for the large installed base.

In 2019, the project to develop a customized software tuning, the Greenhouse Gas Optimized (GHO) package, for the Wärtsilä 34DF was approved with the goal of reducing methane emissions and improving engine efficiency at part and low load. This tuning was enabled by upgrading the W34 platform with the latest closed-loop combustion control features.

The basic principle was to operate the engine closer to the optimal area in terms of hydrocarbon emissions, relying on the control system's capability to reduce the risk of abnormal combustion situations, such as knocking. Furthermore, at loads lower than 20%, the cylinder deactivation functionality [15] was enabled. This feature, called 'skip-firing,' aims to increase the mean indicated pressure on the firing cylinders, reducing low-load instability due to excessive air amounts at near-idling conditions, with a positive effect on the engine's hydrocarbon emissions. To improve the transient response with low methane number gases, a 'boost mode' was also introduced, which can be activated on demand to avoid the risk of tripping to diesel.

By May 2020, the new concept was tested and the EIAPP certification was completed, paving the way for its practical application. It was first introduced to the market as a field retrofit in December 2020 on the Scheldt River vessel, a trailing suction hopper dredger (TSHD) belonging to the DEME group. One W9L34DF and one W12V34DF engine were upgraded with the new software package, and the parameters were tuned onboard by Wärtsilä R&D and technical services personnel. Emissions were measured before and after the modification to confirm the effectiveness of the greenhouse gas emissions package. It was found to perform as expected, leading to a reduction of methane slip on both engines by 60% on average, with a 4% associated improvement in gas consumption within the applied load range (Figure 11).

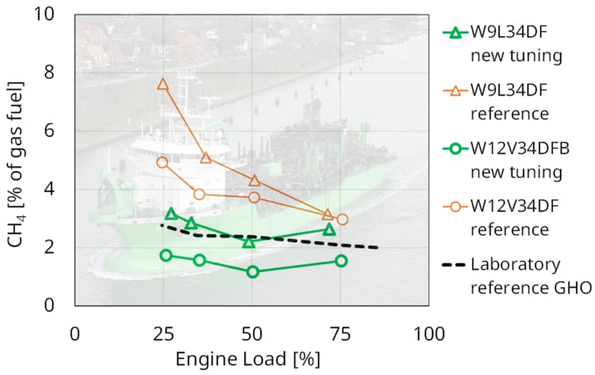

Figure 11. Field measurements done onboard Scheldt River vessel with and without GHO software tuning. Data are compared with laboratory reference.

A similar upgrade on the Seaspan Reliant ferry (Figure 12), executed in 2022, was validated by third-party measurements, confirming the effectiveness of the developed solution with an overall CH4 emission reduction of 24% on the typical ferry roundtrip, and a peak reduction of 57% in the middle load range [16]. Based on these positive experiences, it was decided to guarantee the W34DF methane slip values in customer contracts, boosting the sales of the greenhouse gas optimized version.

Since then, several new build and retrofit projects have been sold, mainly for auxiliary applications on merchant vessels. Thanks to the CH4 guaranteed approach, it was also possible to collect data from the factory acceptance tests, gathering further experiences on the W34DF methane slip performance (Figure 13).

Figure 12. Seaspan Reliant Ferry, where third-party measurements on the W34DF GHO were performed in 2022 and published in 2023.

A further development step was recently taken with the development of the W34DF EnviroPac version for genset applications [17]. This feature exploits high-temperature-resistant SCR elements to keep NOx emissions at Tier 3 levels in gas mode, where engine-out emissions are compliant with the Tier 2 limit.

By relaxing the NOx and exhaust gas temperature constraints, it was possible to further optimize hydrocarbon emissions, which were reduced approximately by half at lower engine loads compared to the reference, with an associated further boost in engine efficiency. The achieved level of methane emissions, compared to the laboratory reference and a set of historical data collected during factory acceptance tests in production, is reported in the chart in Figure 13.

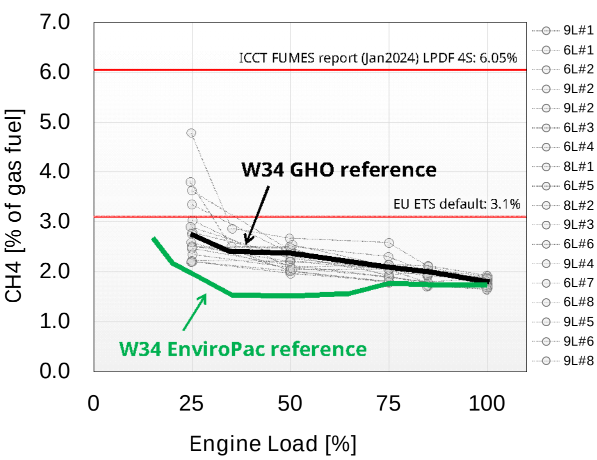

Figure 13. The EnviroPac tuning methane factor is compared to the W34DF GHO reference and a comprehensive dataset from 18 production W34DF GHO engines.

The new concept underwent pretesting in 2022. By summer 2023, the first EnviroPac project was sold, followed by optimization in production in fall 2023. The EIAPP certification with SCR was completed in early 2024. A notable achievement was the sale of 32 W34DF EnviroPac units to CMA CGM in 2024 [18]. These advancements highlight the ongoing commitment to environmental sustainability and the continuous enhancement of emission reduction technologies, benefiting both new vessels and existing fleets through retrofit opportunities.

4 SPARK GAS (SG) FOR MARINE APPLICATIONS

Spark Gas (SG) is a new and evolving technology development within the marine industry. The SG concept (Figure 13) is designed to operate with one fuel only, this opens more possibilities to optimize the engine for lowest possible methane slip emissions.

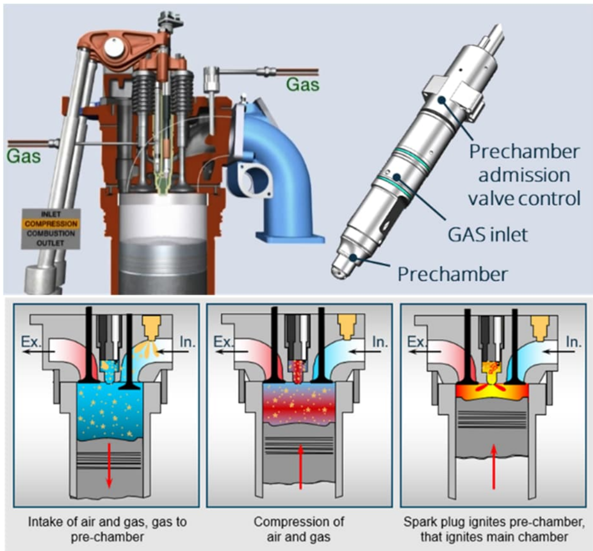

Figure 13. SG layout and concept working principles.

As reported in previous works [7], the lean burn gas engine hydrocarbon emissions are mainly generated by the following three sources (Figure 14): the cylinder dead volumes (crevices), the short circuit between intake and exhaust port (scavenging losses) and the incomplete combustion at the periphery of the combustion chamber (bulk quenching). By moving from DF to SG technology it is possible to improve on all these three aspects.

The piston crevices volumes, one of the largest in the combustion chamber, can be effectively addressed since the diesel mode operation is removed from the components design boundary conditions. Compared to the lean burn gas mode, the diesel process generates both higher components peak temperature and uneven thermal load throughout the combustion space. Therefore, in the SG concept, thanks to the lower and more equally distributed temperatures, the piston clearances and the piston top land height, the distance between the first piston ring and the piston edge, can be reduced resulting in a crevices volume reduction that impacts positively on the methane slip emissions.

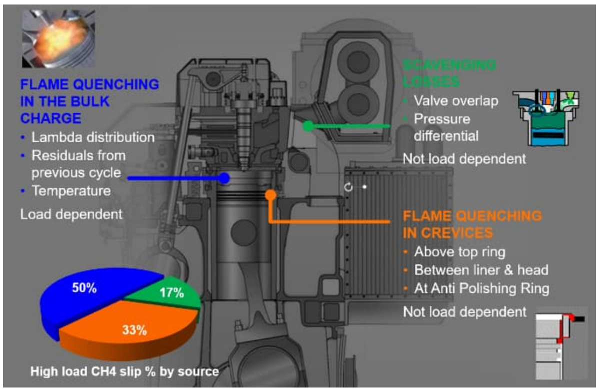

Figure 14. The three main sources of hydrocarbon emission in dual fuel lean burn otto gas engine

The valve timing can be as well effectively optimized to minimize the fuel slip during the scavenging period. The resulting improvement versus the DF technology is bigger on the older engine platforms with limited hardware flexibility. In these cases, the DF valve timing is a compromise between gas and diesel operation, the later one limited by the more stringent exhaust gas operating temperatures for both the cylinder components and the turbocharging system, a direct consequence of the marine fuel oil characteristics.

Combustion wise, thanks to the pre combustion chamber technology (PCC) (Figure 13), the SG engines are also generally better than the DF from the cycle-to-cycle stability point of view at part load. The PCC is operated close to lambda one condition by adding gas through a dedicated feed line. The spark ignites timely and reliably the rich charge in the prechamber and the resulting strong flame jets coming out from the prechamber nozzle holes do strongly ignite the lean mixture in the main chamber. The improved stability results in statistically less “weak” cycles that are characterized by higher-than-average unburned fuel mass fraction. As a further effect the better combustion stability is also leading to averagely higher engine efficiency in the middle/low load range. Similarly to the scavenging losses, the improved combustion effect on the methane emissions is mainly noticeable when comparing SG and DF technology on the older engine platforms, lacking the hardware and controls flexibility of the newest ones. To be noted that the NextDF concept, recently lunched on the latest Wartsila DF engines, is combustion wise equally good or better than the best SG engines developed so far by Wärtsilä for the land-based market.

In conclusion the SG technology potentially leads to a general improvement in the engine performance, but the redundancy of the DF set-up is naturally lost lacking the diesel back up mode capability. Furthermore, the loading performance is weakened since the newest DF engines can leverage on the multi-injection features of the diesel common rail system to improve the transient response [11], functionality obviously not available on the SG engines.

Considering the benefits and drawbacks of the SG technology for marine it was concluded that a pure machinery concept based on SG engines only is not an ideal solution especially for ocean going vessels. A Diesel Electric (DE) propulsion system built on a mixed configuration of DF and SG engines was instead evaluated as a viable option to improve the GHG emission footprint and its related costs preserving at the same time the fuel redundancy and safety features typical of the Dual Fuel technology. According to DNV rules the redundancy is still granted if more of the 40% installed power is made of DF engines.

The LNG carriers and the large passenger vessels are listed among the target marine applications for such type of mixed machinery concept. Since the relative benefit of moving from DF to SG technology is the largest starting from the older engine platform it was logical to evaluate first the feasibility of a field retrofit. The large fleet of LNG carriers delivered since 2000, powered by diesel electric configuration based on Wärtsilä 50DF engines seamed to be an excellent opportunity and a perfect match.

During 2024 the W50SG engine retrofit concept was optimized on the Wärtsilä 6L50 laboratory engine located in Bermeo (Spain). The starting point for this development was the well-established combustion system of the latest W18V50SG powerplant engine genset version. The engine performance tuning was customized for the marine use and the SG specific hardware was checked and modified to fulfill the marine class requirements. The automation and mechanical type approval tests as well as the IMO EIAPP test were successfully run in June 2024 on the laboratory engine.

The achieved results in terms of engine efficiency, methane and NO_x emissions compared to the reference data are reported in Figure 15. Over 50% methane slip reduction was measured on average, peaking up to 75% in the lower engine loads. The engine energy consumption was also reduced between 1.5% to 5% with the largest improvement in the medium load range.

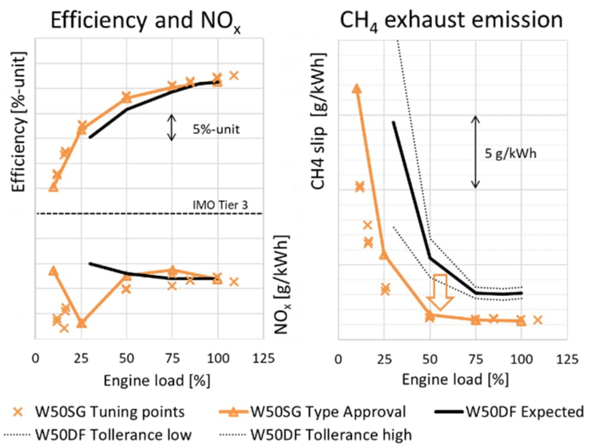

Figure 15. In orange the measured efficiency and emissions on the 6L50SG laboratory engine in Bermeo during the tuning sessions and the official type approval and EIAPP tests. In black the W50DF marine engine reference data.

During the type test the crankcase breather methane emission was also measured. This contribution was found to be rather small, in the range of 10% of the total CH4 emissions at higher loads where its impact is the largest. In the Figure 16 is shown the calculated CH4 factor as % of the gas fuel consumption at the IMO loads including both the direct emission from exhaust and the one from the crankcase breather. The E2 cycle average value is approaching 1% of fuel input a value significantly lower than the 3.1% IMO default factor.

To be noted that the multiple engines diesel electric configuration, thanks to the flexibility of the propulsion system, enable the possibility to minimize the engine running hours below 50% of the nominal power, load range where the methane emission is typically the highest.

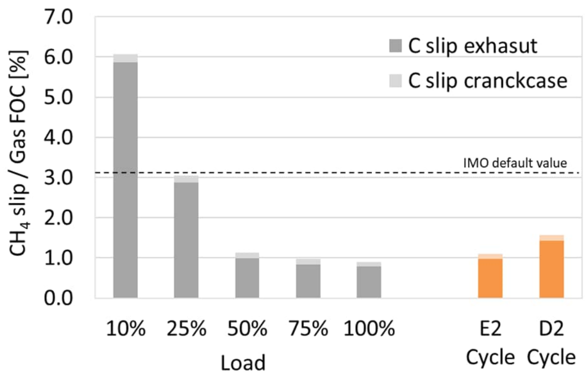

Figure 16. Methane slip factor as % of the gas fuel consumption at the IMO loads and the calculated value according to the E2 and D2 cycles.

Based on the engine laboratory measurements it was possible to quantify the overall benefit of the proposed technical solution by running an example case vessel simulation. The selected target application was a 175000 m^3 capacity LNGC ship powered by four Wärtsilä 50 engines. The modified machinery configuration compared to the standard one is shown in the picture 17, where two out of four gensets are converted from DF to SG technology.

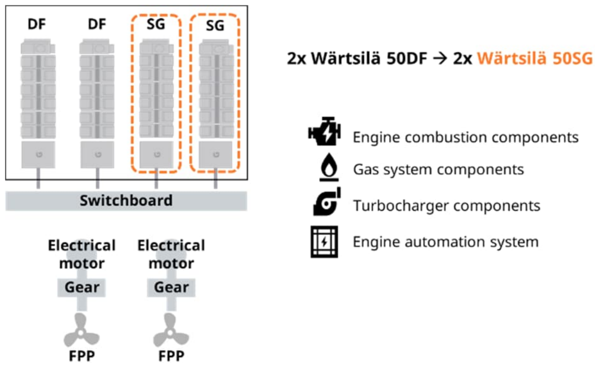

Figure 17. High level machinery configuration layout for the case study.

To perform this calculation one-year actual operational data have been collected and analysed with a scenario of 40% navigation time in EU waters. The total operating cost includes the fuel, the ordinary maintenance and the European regional related expenses: the EUA CO_2 allowances and the FuelEU Maritime carbon intensity penalties/credits. The study horizon was set up to 2040 with gradually increasing EU allowances price up to 2035 [19].

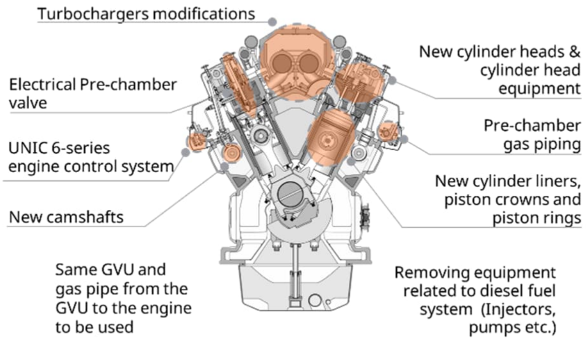

Figure 18. Conversion scope from Wärtsilä 50DF to Wärtsilä 50SG configuration

The investment calculation was based on the engine conversion scope including the following items: cylinder head, piston assembly and liner, camshaft, SG prechamber and related gas feed, turbocharger matching parts and SG specific automation modules and controls (Figure 18).

The business case evaluation proved the potential of the proposed concept. In the considered scenario the yearly average operating costs are cut by more than 10% compared to the reference case and the solution payback time is in the range of 5 years, a reasonable time frame considering that the economical benefits are stretching up to 2040 and beyond. As relative reference, the cumulative net savings in the analyzed time horizon are twice as much as the yearly calculated vessel operating expenses in 2025 (Figure 19).

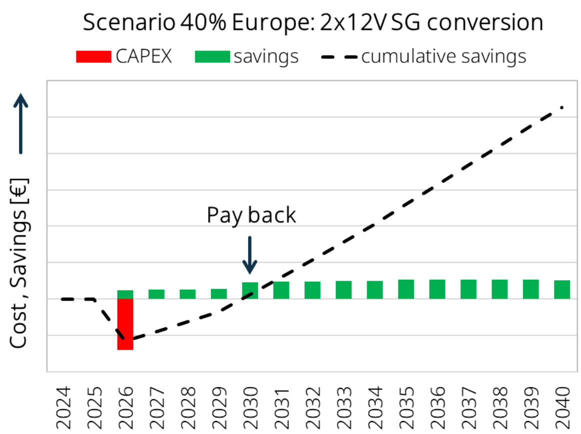

Figure 19. Business case summary chart showing the initial investment cost and the yearly saving up to 2040. The payback time is less than 5 years from conversion start, here assumed to be completed in beginning 2026.

In September 2024 Wartsila announced that, in partnership with Chevron Shipping Company LLC, will convert one engine on six of Chevron Transport Corporation Ltd.'s LNG Carriers from dual-fuel to SG operation [20]. The first conversion project is expected to be delivered in Q4 2025.

5 POST TURBO CATALYST SOLUTION DEVELOPMENT

Within the frame of the GREEN RAY EU co-funded project, besides the Next DF combustion concept scaling-up to large bore engine, Wärtsilä and Shell have teamed up to develop a catalytic technology aiming to significantly reduce the engine out methane emissions. The target is to design a solution that will be installed after the engine turbocharger and compatible with the typical exhaust gas temperature range of the medium speed single stage turbocharged engines. The goal is to meet the future needs for both new builds and existing installations, enabling easy retrofits for vessels currently in operation.

The Methane Abatement Catalyst system, MAC is built on two functional units: the Methane Oxidation Catalyst, MOC and the Sulphur Guard Bed, SGB (Figure 20). The methane is oxidised in the MOC, which is based on a chemical composition including noble metals. As MOC is sensitive to sulfur content in the exhaust, the MAC includes an exhaust pre-conditioning step in a Sulfur Guard Bed (SGB), which functions to remove unwanted sulfur from the exhaust before it enters the MOC. Shell has developed a proprietary formulation for both the SGB and the MOC that have been previously tested in the lab and in land-based field demonstration and have proven successful respectively in removing SOx and other contaminants such Phosphorus & Zinc from exhaust gas and in converting methane slip from gas engines.

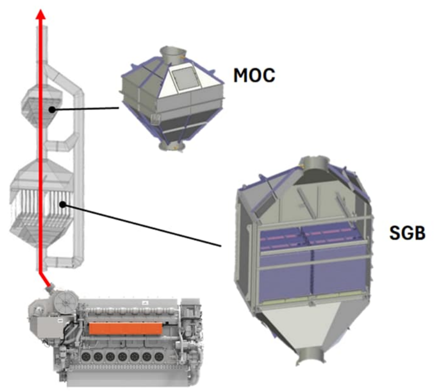

Figure 20. MAC system layout with SGB, MOC and by-pass system.

The optimized SGB and MOC catalyst validation under real marine engine exhaust conditions is one of the key GREEN RAY project targets. The MAC scaled prototype (Figure 21) has been developed and installed on a dedicated laboratory rig at Wärtsilä, build in the STH, Sustainable Technology Hub, in Vaasa, Finland.

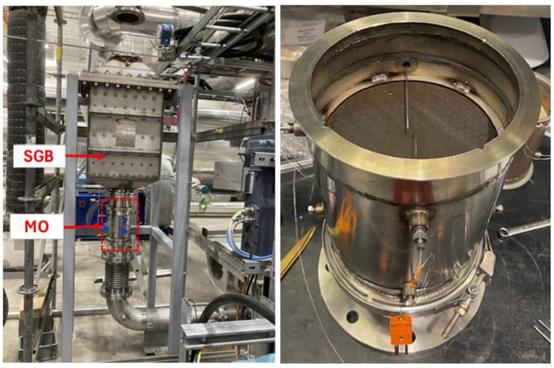

Figure 21. MAC scaled prototype for rig testing. Detail of the Canned Methane Oxidation Catalyst on the right picture.

This special facility, whose schematic view is represented in Figure 22, is conditioning the exhaust gas coming from the production and R&D engine test cells to the target temperature and flow to create the desired boundary conditions for the catalyst system. The flow is adjusted by partializing the gas stream while the temperature is controlled with electrical heaters. The gas methane composition is varying depending on the type of engine under testing in STH and its relative load. This variability is a plus since it enables the possibility to test the system efficiency in a meaningful range of methane concentrations. Finally, the rig is equipped with state of art instrumentation to characterize accurately the emission reduction performance.

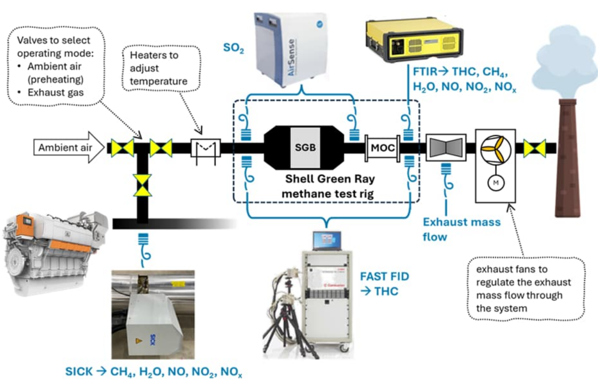

Figure 22. MAC laboratory rig at STH in Vaasa

This laboratory test facility started its operation in October 2023, and it was demonstrated to the GREEN RAY consortium in April 2024. So far around 100 running hours have been accumulated and have generated already precious information on the MAC efficiency and performance trade-off varying the key critical boundary conditions such as exhaust gas temperature, space velocity and methane concentration.

Thanks to these tests it was possible to identify the optimal temperature operating range for effective methane conversion, its match with the target engine application and the MAC volume dimensioning criteria to achieve the target conversion rate at a given methane concentration in the exhaust stream. Some examples of the measured catalyst performance are shown in the Figure 23. It was possible to achieve over 90% conversion efficiency within a reasonable temperature window for the engine operation. During the testing higher space velocity than the project target was used to stress the performance of the catalyst system.

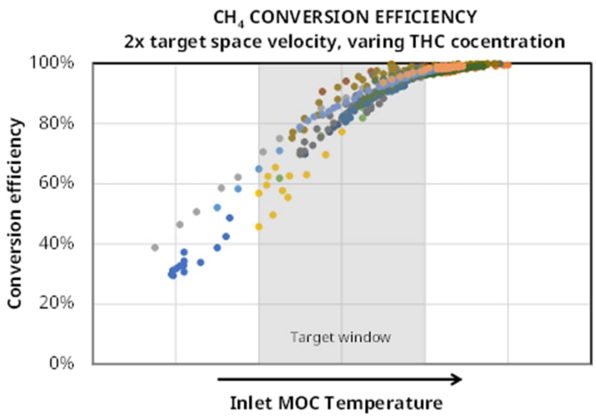

Figure 23. Measured MAC performance with varying THC concentration at exhaust temperature

One aspect that still need to be further investigated is the MOC methane conversion stability over time strictly connected with the SGB performance in effectively removing the sulphur from the incoming exhaust stream. This type of verification requires more running hours that will be collected in 2025.

To assess the mechanical strength of the MAC a dedicated mechanical rig was built to simulate the pulsating forces and induced vibration caused by the engine actual exhaust flow dynamics. In particular the SGB catalyst durability was tested extensively to access the resilience of its structure.

Tests were carried out at Technobothnia/VAMK in their shaker table test bench (Figure 24) able to generate up to 3g vibration level continuously for 24 hours; the outcome was positive and the SGB catalytic elements showed good stability during the accelerated vibration test.

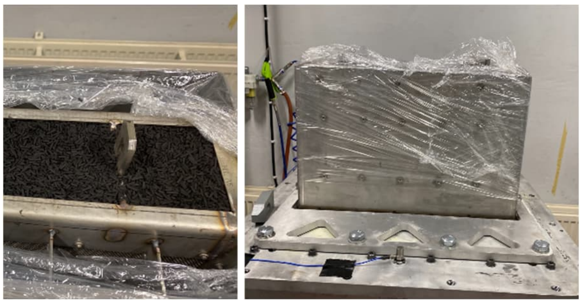

Figure 24. Wrapped SGB for vibration bench testing.

From safety perspective a system FMEA was carried out in collaboration with DNV GL to define the safety concept and the related design and automation features.

Eventually all the data collected during the laboratory testing are supporting the system design in the view of the full-scale testing planned on a field installation still within the scope of the GREEN RAY project: this technology demonstrator will prove the effectiveness of the solution and its reliability versus time.

6 SUMMMARY AND CONCLUSIONS

Recent regulations by international and local authorities, such as the IMO and EU, aim to reduce CO_2 and GHG emissions, with significant milestones set for 2025 and beyond. CH_4 emissions are included in the legislative framework and will significantly impact the operational costs of LNG-fueled vessels. On the other hand, LNG remains the most promising transition fuel for marine industry decarbonization, and its market penetration is expected to grow in the next decade. Therefore, addressing methane emissions and improving vessel operational efficiency will be of strategic importance for ship operators.

Wärtsilä, being a major player in the marine industry, recognizes the importance of improving the environmental footprint of its products and solutions. A large R&D effort has been put in developing new technologies to go beyond the upcoming stringent regulatory requirements. Examples provided in this paper include the advancement and market deployment of the NextDF technology on the newest engine portfolio, the introduction of cost-effective solutions for new builds and retrofits for the Wärtsilä 34 and Wärtsilä 50 product families, and the research project in partnership with Shell to develop an affordable post-turbo aftertreatment concept for methane emissions.

The NextDF combustion concept aims to reduce methane emissions by more than 50% and improve the operational efficiency. The concept was first implemented on the Wärtsilä 31. The Aurora Botnia pilot installation demonstrated the concept's effectiveness, with continuous monitoring confirming stable performance over time. The technology has been released to the market in 2024 and is being adapted for mechanical drive applications and other engine platforms, such as the Wärtsilä 25 and Wärtsilä 46TS.

Wärtsilä has also focused on improving the greenhouse gas emissions of its established dual-fuel products, such as the Wärtsilä 34DF, through software tuning and hardware upgrades. The Greenhouse Gas Optimized (GHO) package has shown significant reductions in methane emissions. The development of the W34DF EnviroPac version for genset applications further optimizes hydrocarbon emissions and engine efficiency.

The potential of Spark Gas (SG) technology for marine applications has also been explored. This technology offers improvements in methane slip emissions but lacks the redundancy of dual-fuel setups. A mixed configuration of DF and SG engines is proposed as a viable solution for certain marine applications, such as LNG carriers and large passenger vessels, thereby enhancing the flexibility of the Diesel Electric propulsion system.

Finally, the paper discusses the development of a post-turbo catalyst solution, the Methane Abatement Catalyst (MAC), in partnership with Shell. The MAC system aims to significantly reduce engine-out methane emissions and is currently undergoing laboratory testing, with plans for full-scale field testing.

In conclusion, the ongoing development and deployment of advanced emission reduction technologies are critical for meeting regulatory requirements and improving the environmental sustainability of marine transportation. The financial incentives associated with compliance will further drive the adoption of these technologies, ensuring a cleaner and more sustainable future for the industry. Regarding methane slip, the Wärtsilä portfolio is approaching 1% of the gas fuel input, a remarkable result considering that the IMO and EU default factor is set at 3.1%. Additionally, there are plans to further reduce this percentage in the future.

7 ACKNOWLEDGMENTS

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