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Methanol upgrade solution for the existing M 32 & M 43 platforms

Retrofit Solutions

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ABSTRACT

The urgency of greenhouse gas (GHG) reduction requires the use of lower-carbon intensity fuels in the maritime sector. Lower-carbon intensity methanol is considered one of the most promising fuel candidates to quickly achieve the IMO and European Union reduction targets for international shipping. While many studies for carbon-free fuels are currently underway, there is still a long time until their common market introduction. Methanol is a well-known fuel for internal combustion engines and has several advantages in marine applications in terms of storage, handling, combustion process and emissions. In addition, methanol can be produced sustainably from biologic and renewable electricity origin. The interest of ship owners in using methanol to reduce GHG-emissions in their existing fleets is steadily increasing. The properties of methanol enable different combustion recipes, such as a premixed Otto cycle or a diesel cycle using high-pressure direct injection (HPDI). Caterpillar Motoren has chosen the high-pressure direct injection concept and a diesel combustion recipe for its MaK Methanol Upgrade Kit. The advantage of DI diesel combustion is its robustness and thus its very high tolerance to the different variants that are usual when converting existing engines on ships. This fact also limits the components that must be replaced for the conversion, which has a positive effect on conversion costs. Another market demand is offering a maximum flexibility in terms of fuel use. The derived dual-fuel concept gives the operator the greatest possible independence in terms of operating routes, fuel availability and fuel price. This paper describes the development of Caterpillar's methanol upgrade solution, which enables the use of methanol as the main fuel for the well-known MaK M 32 and M 43 platforms. It can be shown that the performance of the dual-fuel engine is as efficient when running on methanol as on conventional diesel, with the advantage of the significant reduction in lifecycle in GHG emissions.

1 INTRODUCTION

The urgency of greenhouse gas (GHG) reduction requires the use of lower-carbon intensity fuels in the maritime sector. Lower-carbon intensity methanol (referred to hereinafter as methanol) is considered one of the most promising fuel candidates to quickly achieve the reduction targets of the IMO and the European Union for international shipping. Although many studies on zero-carbon fuels are currently being started, it still takes a quite long time to be introduced to the industry. Methanol is a well-known fuel for internal combustion engines and offers several advantages in maritime applications in terms of storage, handling, combustion and emissions. In addition, methanol can be easily produced from biological and renewable sources. Ship owners' interest in using methanol to reduce GHG emissions in their existing fleets is steadily increasing. The properties of methanol allow for different combustion recipes, such as a premixed Otto cycle or a high-pressure direct injection (HPDI) diesel cycle. Caterpillar Motoren has chosen the concept of high pressure direct-injected methanol with diesel pilot ignition for the MaK^{TM} brand. Another industry requirement is a high fuel flexibility. The derived dual-fuel concept offers the operator the greatest possible flexibility in terms of operating routes, fuel availability and fuel price. This paper describes the motivation and the development of Caterpillar's methanol upgrade solution, which enables the use of methanol as the main fuel for the well-known MaK M 32 C and M 43 C platforms. It can be shown that the performance of the dual-fuel engine when running on methanol is just as efficient as with conventional diesel, with the advantage of a significant reduction in lifecycle in GHG emissions, although stack GHG emissions are essentially the same as traditional fuels.

2 BUSINESS AS USUAL IS NOT AN OPTION – IMPACT OF EU ETS AND FUELEU MARITIME

The EU Emissions Trading System (ETS) and the FuelEU Maritime Regulation are initiatives to reduce GHG emissions in the maritime sector by the European Union. FuelEU Maritime sets specific targets and measures to defossilise shipping and promote lower-carbon intensity fuels. It applies to all ships over 5000 GT and considers all energy consumption on board.

Key elements include:

- Introduction of EU ETS start in 2024
- FuelEU introduce targets to gradually reduce GHG intensity with a well-to-wake perspective of 2% from 2025, 6% from 2030, 14.5% from 2035, 31% from 2040, 62% from 2045 and 80% by 2050.

The EU ETS is an emissions trading system that caps the total CO_2 emissions of certain sectors, including the maritime sector from 2024. Shipping companies must buy emission allowances, each covering one ton of CO_2 and in the future the equivalent of other GHGs with higher global warming potentials such as methane (CH_4) or nitrous oxide (N_2O). The allowances are auctioned, and companies can trade them on secondary markets. The price of the allowances fluctuates, with forecasts suggesting an increase. This paper assumes a constant price of 100 €/ton of CO_2 to study the impacts of the FuelEU Maritime Regulation under a business-as-usual scenario in which shipping companies continue to use fossil fuels such as VLSFO (Very Low Sulphur Fuel Oil).

The FuelEU Maritime Regulation includes, among other things, penalties for not achieving the targets for reducing GHG intensity. The non-compliant levels for not meeting the FuelEU Maritime targets increases every five years and this leads to a significant penalty cost.

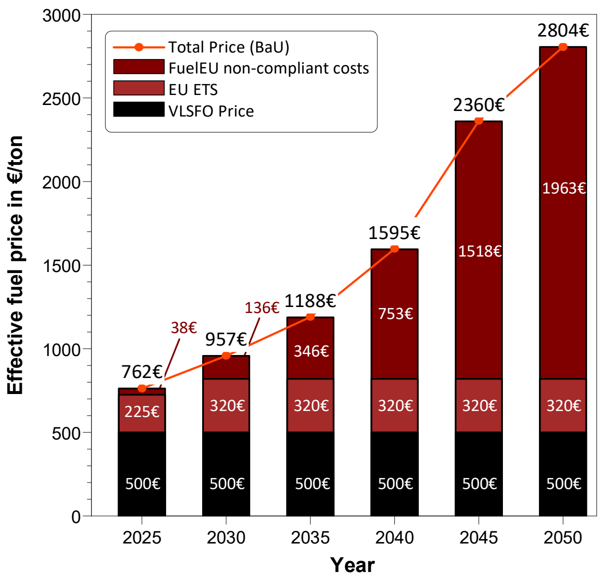

Figure 1: Example of total price for Business-as-Usual using VLSFO

The costs of the EU ETS are tied to the price of an EU emission certificate. Assuming a constant price level of 100 €/ton CO_2 equivalent and considering that 1 ton of diesel emits around 3.2 tons of CO_2, the ETS certificates will result in additional costs of 320 €/ton diesel from 2026 (it will be 225 €/ton, because only 70% of CO_2 emissions must be covered by certificates in 2025).

Figure 1 shows that in the first two steps from 2025 onwards, the costs from the ETS still dominate, while from 2035 onwards the costs for non-compliance with the GHG intensity limits exceed the additional costs of the EU ETS.

Given the significant costs of non-compliance in the business-as-usual scenario, ship operators are considering strategies to comply with the regulations. There are several options, including the use of biofuels, e-fuels, or pooling. Pooling considering and averaging the CO_2 emissions of several vessels. This allows a ship to share the overachievement of the GHG reduction targets with other vessels. This is permitted if the entire pool achieves the targets. This paper focuses on mitigating the costs of non-compliance by using methanol.

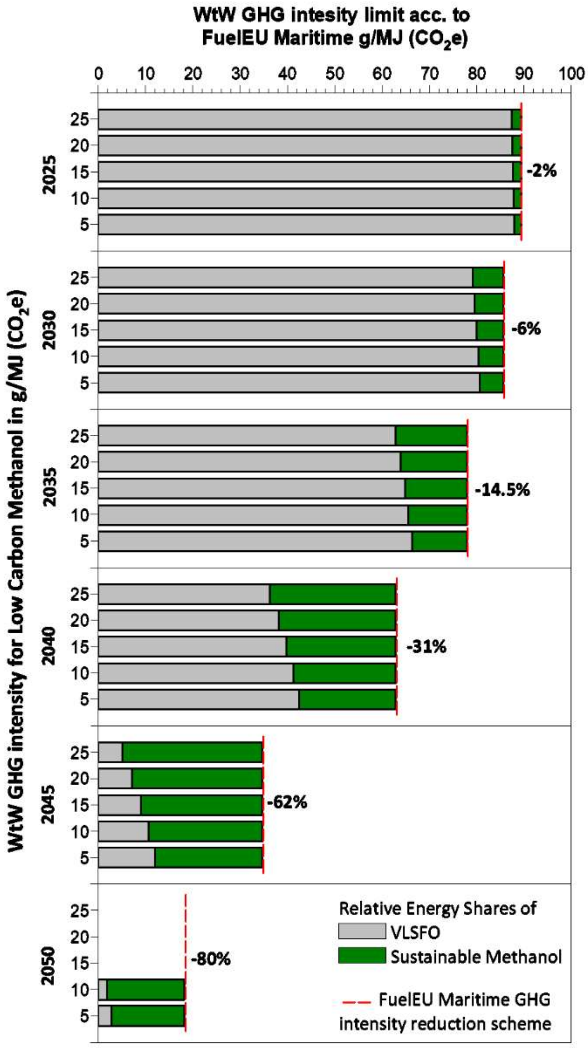

Figure 2: Energy shares of VLSFO and methanol in dual-fuel operation

Due to the high fuel flexibility requirement, ship operators currently prefer the dual-fuel technology for methanol. With this technology it is possible to adapt the share of methanol to the GHG intensity requirements. In the following analysis the annually average (or minimum) quantities of methanol are determined to achieve the FuelEU targets. The results are valid for a single ship but can also be transferred to a pool of ships by adjusting accordingly.

Figure 2 shows the energy shares of VLSFO and methanol to achieve the FuelEU Maritime GHG reduction targets. The possible spectrum of the WtW GHG intensity of methanol is plotted on the y-axis. The spectrum is approximately in a range of 5 g/MJ (CO_2e) to 25 g/MJ (CO_2e). The higher values suggest a biogenic origin. The values for so-called RFNBO (**R**enewable **F**uel **N**on-**B**iological **O**rigin) are primarily less than 15 g/MJ (CO_2e). The shares increase with the GHG intensity of the methanol. The higher the GHG intensity, the higher the energy share. The methanol share shown in Figure 2 refers to the actual value GHG intensity of the utilized methanol. If a RFNBO is used, a reward factor of 2 can be granted until 2034, which halves the necessary energy share. In the first two stages, the influence of GHG intensity on the fuel share is still very small. In 2025, all shares are below 3%. In 2030, these increase to 6% to 8% and in the last stage in 2050, only fuels with 12 g/MJ (CO_2e) lower can meet the FuelEU Maritime target due to the required diesel pilot.

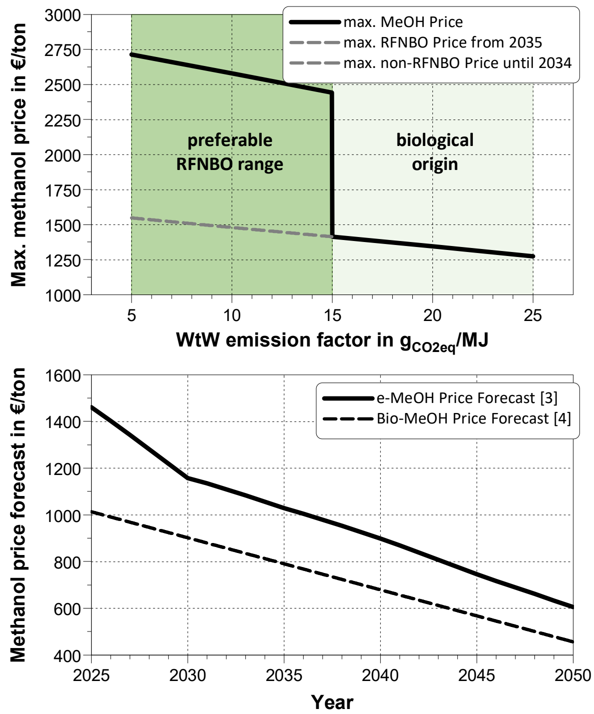

Figure 3: Max. fuel price limit for methanol (bio & RFNBO) and price forecasts according to [3] & [4]

From the total costs for a business-as-usual scenario determined in Figure 1, a maximal price limit for methanol can be determined (Figure 3). This calculation does not consider the additional penalties for non-compliance in consecutive years. The results represent the “best worst case” scenario. These price limits are independent of the necessary substitution rate caused by the increase in GHG intensity reduction scheme. This means that the price limits are valid for any point in timeframe from 2025 to 2050. However, the prices are a function of the GHG intensity of the methanol used (upper diagram). The lower the GHG intensity of the fuel, the higher the allowable price. In [3] and [4], price forecasts are made for various alternative fuels. Figure 3 shows price forecasts for methanol from biological hydrogen source and as a RFNBO. For the RFNBO the projected price will fall from around 1500 €/ton in 2025 to around 600 €/ton in 2050. And the price for bio-methanol is also falling from 1000 €/ton in 2025 to less than 500 €/ton in 2050. These values are below the determined price limits throughout the entire period and thus represent an attractive alternative scenario to business-as-usual. An internal ROI analysis shows that the break-even will be reached around 2035 if the conversion is completed by 2030. The product upgrade presented in this paper therefore represents not only a technically attractive but also a financially beneficial solution for reducing the operating costs of ships.

3 AVAILABLE OPTIONS

Currently, FuelEU Maritime only affects ships over 5000 GT. Due to the associated size of the ships, they are equipped with the larger 4-stroke platforms. The developed upgrade concept is therefore available for the MaK series M 32 C and M 43 C. Both have a large population and therefore have a large potential for possible conversions. The methanol upgrade concept is identical for both engine platforms regarding configuration and components to achieve a maximum of synergies. The technical data is summarized in Table 1.

As shown in chapter 2, ship operators have the requirement for maximum fuel flexibility. Therefore, both platforms are dual-fuel applications, in which the engines can be operated with several main fuels. Due to the diesel combustion process, the performance in diesel operation is maintained and is not negatively affected, for example, by an adjusted compression ratio. Furthermore, HFO operation is still possible after the conversion. This ensures the operator a maximum of flexibility regarding fuel type, fuel availability and fuel price. This gives the operator the opportunity to positively influence operating costs. The methanol upgrade will be available for the M 43 C from 2026 and for the M 32 C from 2027. This ensures that operators have an effective solution available for the first significant stage of FuelEU Maritime to achieve compliance with the FuelEU GHG targets.

Table 1: Technical data of the available methanol upgrade options

	M 32 C – MeOH	M 43 C - MeOH
Bore	320 mm	430 mm
Stroke	480 mm	610 mm
Speed	600 rpm	500 / 514 rpm
Cylinder Output	up to 500 kW	up to 1050 kW
Configuration	Inline (6,8,9)	Inline & V-Type (6 to 16)
Main Fuels	Methanol or HFO/Distillate Bio-Fuels	Methanol or HFO/Distillate Bio-Fuels
Pilot Fuel	MDO (ISO8217) / Bio-Fuel	
Load Range	0% to 110% in Diesel Operation 20% to 100% with Methanol as Main Fuel	
NOx Level	Same as baseline - minimum IMO Tier I	

4 EXPERIENCE WITH METHANOL

Since 2016, Caterpillar Motoren has been conducting tests with methanol on research engines. In a first step, various combustion recipes were examined for their suitability. Both Otto- and Diesel combustion processes were considered. Even at this early stage, the positive properties of a Diesel combustion process regarding robustness, efficiency and emissions were evident [5].

In further campaigns, a combustion process with methanol high-pressure direct injection and diesel pilot ignition was investigated on the M 34 single cylinder test engine. The key findings are the basis for the development of the MaK methanol upgrade kit.

5 MULTI-NEEDLE INJECTOR AS AN ENABLER FOR A METHANOL DUAL-FUEL APPLICATION

To convert an existing diesel engine into a methanol-capable dual-fuel engine with a diesel combustion recipe, a modified injector is the key component. Due to the different properties of methanol and diesel, it is necessary to separate the two fuels from each other. This can be done by using several injectors or by integrating both fuels into a common injector body.

The newly developed Multi-Needle HPDI Injector combines a conventional diesel injector and an electrically controlled methanol injector with an integrated accumulator in one housing. The maximum pressure level for methanol in this application is 600 bars. In this design, the two separated nozzles are arranged next to each other.

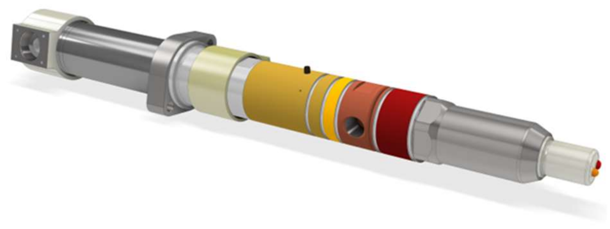

Figure 4: New Multi-Needle HPDI Injector for dual fuel application

Both nozzles are designed to be full-load capable. On the diesel side, the arrangement corresponds to the proven MaK pump line nozzle (PLN) design. In addition to the main injection in diesel operation, this nozzle is also used as a pilot injection to ignite the methanol. A constant amount, corresponding to idling quantity, is used for ignition in methanol operation. To optimize the reproducibility and timing of the pilot injection, a modified characteristic is used in the mechanical injection pump. This ensures a high substitution rate as well as an optimal timing of the methanol injection.

The integration of two injectors into one housing is a design challenge. This applies to the internal arrangement of the flow channels as well as to the arrangement of the injection holes. When two nozzles are arranged next to each other, it is unavoidable that the nozzle tip of the neighboring nozzle will be an obstacle. The solution is a gap in the arrangement of the injection holes. This should be as small as possible reach the combustion chamber as complete as possible and it must be large enough so that the injection jets do not interact with the other tip. To solve this design conflict and to optimize the system, extensive CFD studies were conducted.

6 COMPONENT AND PROCESS OPTIMIZATION USING CFD

During this project, extensive CFD studies and optimizations were done to define the design of the injector and to optimize the combustion process. This includes, among other things, the optimization of the spray hole distribution and the enclosed injection angle. This was done for diesel and methanol operation. For diesel operation, the system was optimized that it matches the current performance of the M 43 C.

CFD simulation results of a 50% engine load operating point is shown in Figure 5. Here, the upper right image of each frame represents the mass fraction of fuel vapor (diesel upper half; methanol lower half) and iso-surfaces of the

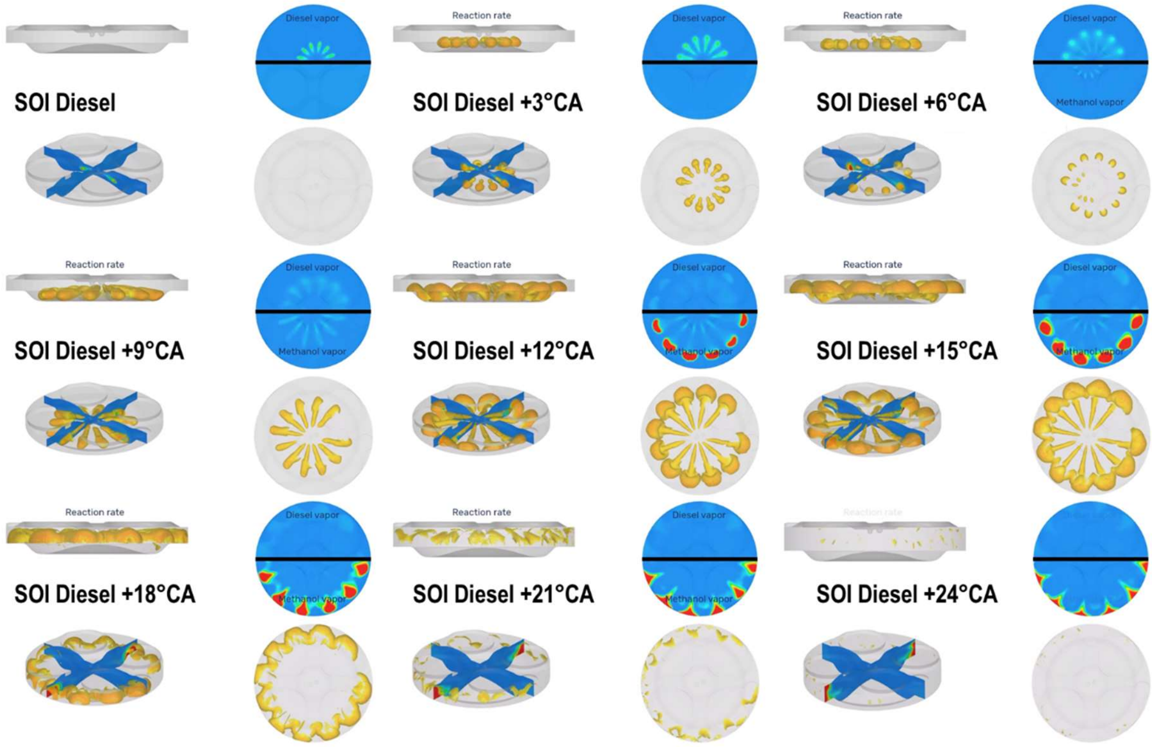

Figure 5: CFD Injection and Combustion simulation for the M 43 C at 50% engine load at rated speed

reaction rate (240 J/s) are shown in the other pictures.

Accordingly, the diesel pilot is injected first into the combustion chamber. Due to the PLN principle, the small amount is injected with a low injection intensity. However, the ignition of the pilot jet is not affected by this, so that a clear energy conversion can be seen shortly after the start of injection (SOI). Furthermore, the diesel gap (chapter 5) in the injection spray can be seen in the second frame of the upper row. With the ignition of the pilot jet, the methanol injection can be applied. The timing of the methanol injection can be optimized regarding center of combustion, peak pressure and pressure rise rate. Immediately after methanol has been injected, it ignites (3rd frame bottom right). Due to the off-center position of the methanol nozzle, the methanol initially ignites on the left side. It is also obvious that the methanol jet within the diesel gap ignites with a slight delay (Figure SOI Diesel +9°CA). But in all following time steps, all methanol jets show an identical reaction rate. From frame +12°CA, a small mass fraction of diesel vapor can still be seen around the edge of the piston bowl. This diesel mass fraction was not fully converted during the pilot phase. However, the diesel fuel is fully converted during methanol combustion. From frame +18°CA, the methanol injection is complete, and the conversion takes place in the outer area of the cylinder and the piston bowl. The conversion rate continues to decrease as the combustion progresses until the injected methanol is fully converted.

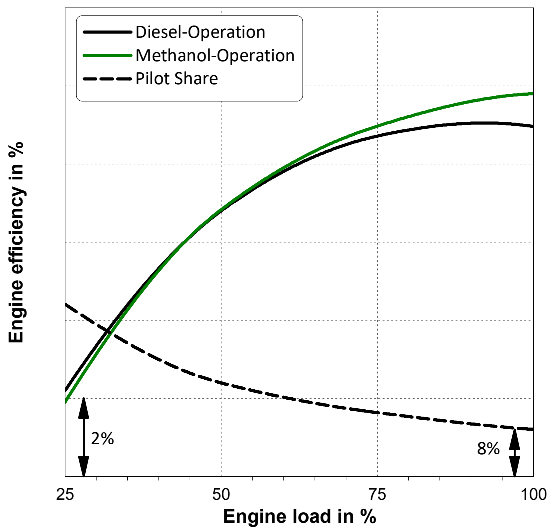

Figure 6: Performance of M 43 C methanol after conversion

Based on the physical tests on the single-cylinder and the detailed results of the CFD simulation, the engine performance for the M 43 C methanol can be calculated (Figure 6). It can be shown that the performance in diesel operation is like prior conversion. For methanol operation, the performance is the same or even better than in diesel operation. All parasitic load of the modules were considered when determining the performance. On average, methanol operation has a NOx reduction of 30%, has an almost soot-free combustion and has a lower exhaust gas temperature of around 30 K compared to diesel operation.

6.1 Substitutions rate and GHG reduction for the HPDI Concept

Part of the concept is that the PLN system is also used for the pilot injection and thus for the ignition of the methanol. Using the PLN system as the pilot has the advantage that no additional pilot ignition fuel system is required. This is particularly advantageous for packaging and costs. The full-load design of both nozzles means that the minimum quantities that can be injected are limited. If the minimum quantities of both systems are added, the sum of the injected energy is larger than the required idle quantity. For this reason, the engine is operated with diesel fuel only in the lower load range and methanol injection is only activated when the engine load is above 20% (Figure 7). Above this lower load limit, the substitution rate of methanol increases steadily and reaches an energetic substitution rate of 92% at rated power. The change of operating mode is done automatically by the newly developed automation system mMACS and the engine control unit in methanol mode. During diesel operation in methanol mode, all methanol-relevant systems remain active to enable a smooth change between both operating modes. According to this operating strategy, the following states are possible (Table 2):

Table 2: Possible mode and operating states for the M 32 C and M 43 C Methanol engine

	Diesel Operation	Methanol Operation
Diesel Mode	YES (disired)	NOT Possible
Methanol Mode	Possible (if conditions for methanol operation not met)	YES (disired)

Due to the very high substitution rate, the lifecycle GHG emissions of the engine is significantly reduced when using methanol. Taking a WtW-perspective into account, GHG emissions are reduced by an average of 80%. The reduction rate can be further increased by using biodiesel, so that reduction rates of 90% are possible in the customer-relevant power range (Figure 7) even though stack GHG emissions are essentially the same as traditional fuels.

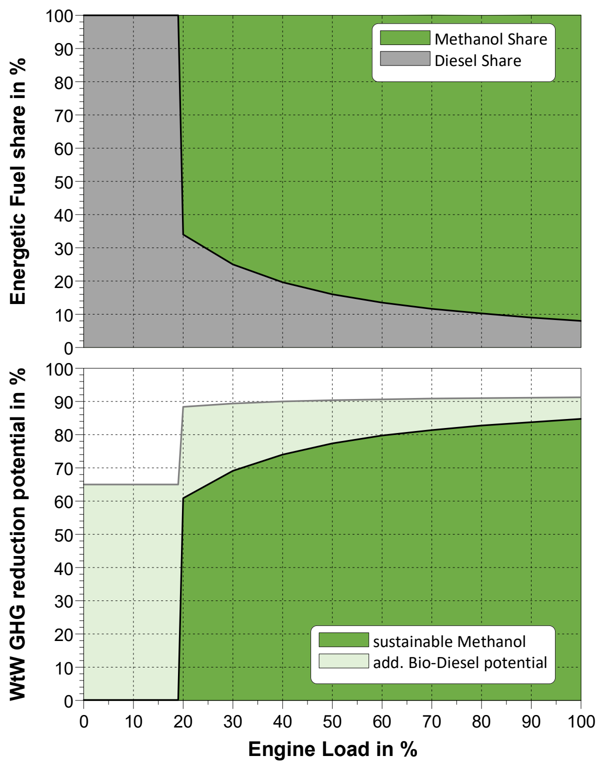

Figure 7: Energetic share of methanol & Improvement of GHG Emissions for the HPDI Concept

7 IMPLEMENTATION ON THE ENGINE

Figure 8 shows the implementation on the engine. The ship-side connection is made via the "Ship Connecting Block" (SCB). This is the interface for high-pressure methanol, high-pressure control and sealing oil and the methanol return line. The methanol return is only used during filling process and during emptying and inerting of the Methanol system during mode change from Methanol- to Diesel-Mode. During operation, the high-pressure supply line is closed by the hydraulically controlled "Start & Purge Valve" (SPV) so that the methanol system pressure of up to 600 bar can be build up. The engine piping is designed as a single double-walled system in accordance with the specifications of the Interim Guideline - MSC.1/Circ.1621 [6].

The methanol is fed from the SCB to the "Engine Connecting Block" (ECB) via a flexible hose element. From there it is fed to the Cylinder T-Block using a standardized piping system. The cylinder T-block connects all other cylinders and the individual injector via a double-walled Injector Supply Line. These two elements are part of the newly designed cylinder head, which must be modified due to the dimensions of the new multi-needle injector. The head design is based on the proven MaK design and can be applied to all M 43 C variants without any further modifications. Furthermore, care was taken to ensure that all new functions and functional parts are integrated into new parts or are placed in a position that has previously not been used on MaK engines. This means that the Methanol Upgrade Kit can be used without specific adaptations to the specific engine configuration.

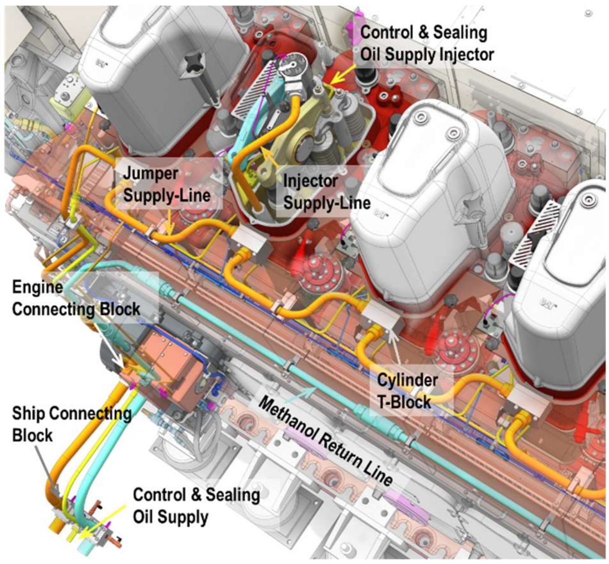

Figure 8: Implementation of the Methanol Upgrade Kit on the engine (here 6 M 43 C)

8 METHANOL SYSTEM INTEGRATION

The scope of supply of the MaK Methanol Upgrade Kit does not only consist of the modification of the engine. It represents a complete solution from the outlet of the methanol tank to the exhaust system (Figure 9). The Methanol Upgrade Kit includes a total of three support modules that must be integrated into different areas of the ship in accordance with the Project-Planning-Guide [7] installation regulations [6]. Due to the implementation on the engine, the engine is still liquid and gas-tight and can still be operated in a non-hazardous machinery room. The pressurized and inerted double-wall solution also means that no complex ventilation system is necessary, which is particularly advantageous for retrofit solutions. In addition to the engine, the Control & Sealing Oil Module is also located in the machinery room. This module supplies the injector with hydraulic oil (SAE40) at a pressure level of up to 700 bars. The module is equipped with its own tank and uses fresh oil and has no connection to the engine's lubricating system. Since the amount of sealing oil loss is very small compared to the amount of control oil, which is circulating, the engine can be operated for several days without refilling the lube oil tank. The engine alarm and control system (MACS) will also be replaced as part of the methanol upgrade. All engines will receive the

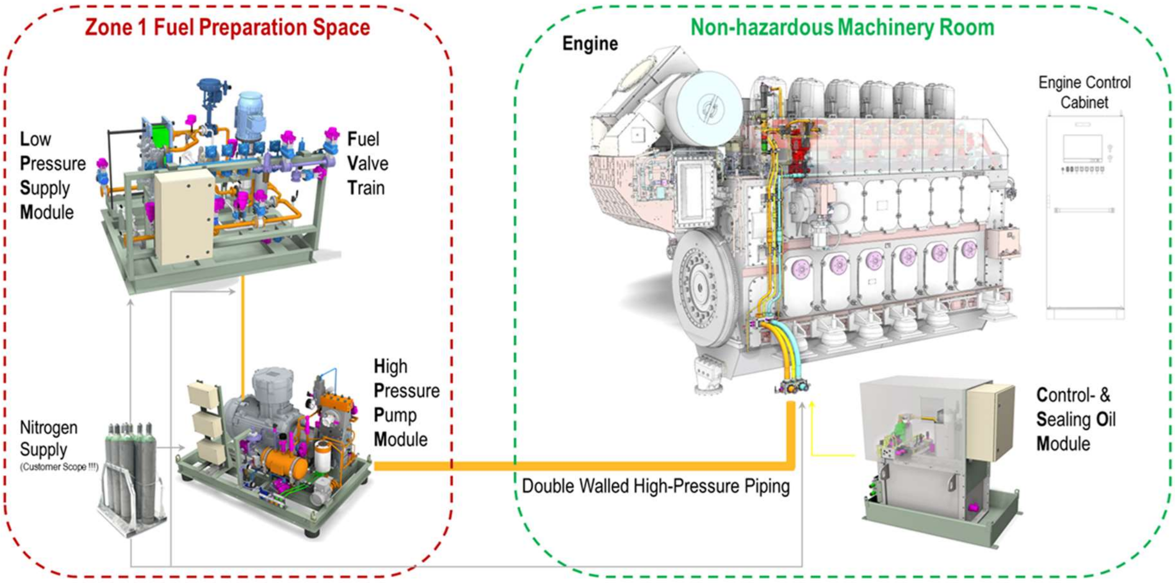

Figure 9: Methanol System Integration Concept

newly developed Caterpillar® mMACS. This is based on the proven aMACS of the MaK diesel engines with an expanded range of functions for methanol-specific requirements.

The other support modules are arranged in a special Zone 1 area. The so-called fuel preparation space contains the Low-Pressure-Supply-Module (LPSM), which supplies the methanol from the tank to the High-Pressure-Pump-Module (HPPM). The LPSM can supply up to three HPPMs or engines. On the LPSM there is a heat exchanger that cools or heats the methanol to guarantee a proper inlet temperature at the HPPM and a double filter ensures the purity of the fuel. Downstream of the filter, the supply line is divided into the individual engine paths. Each is followed by a Fuel Valve Train (FVT). This double block & bleed unit protects the individual engines from each another. From the FVT, the entire supply line can be emptied and inerted with nitrogen.

The FVT is followed by the HPPM. This pump controls the desired methanol pressure via a variable frequency drive (VFD). The HPPM also has an internal leakage detection and collection system. This ensures that losses occurring in the piston pump are collected and discharged via the drain connection. The HPPM outlet has a special connection block for the ship's double-walled piping system. Both the LPSM and the HPPM have their own control system with an interface to the engine automation system for remote-controlled operation via mMACS. The nitrogen supply system in Figure 9 is not part of the scope of Caterpillar Motoren, as it is dimensioned by the methanol tank size and therefore is very individual for each project.

9 PROJECT ROLES, RESPONSIBILITIES AND TIMELINE

Figure 11 shows a generic project plan. This is split into 4 phases and begins with the first contact and exchange of information to the actual conversion of the vessel. The Caterpillar Motoren Methanol Upgrade Kit was presented in the previous sections. It enables dual-fuel operation with methanol and is an attractive future opportunity to reduce lifecycle GHG emissions and operating costs, considering EU ETS and FuelEU Maritime, while keeping stack GHG emissions essentially the same as traditional fuels. The conversion of the engine is fully covered by Caterpillar Motoren and the Caterpillar Motoren dealers. However, further steps are necessary for a ship to operate on methanol. The Project Planning Guide Methanol [7] provides all necessary information for the integration of the Methanol Upgrade Kit. It describes the interfaces and the adjustments to the existing engine. Based on this, a feasibility study is assigned by the owner. Figure 10 summarizes typical topics of a feasibility study.

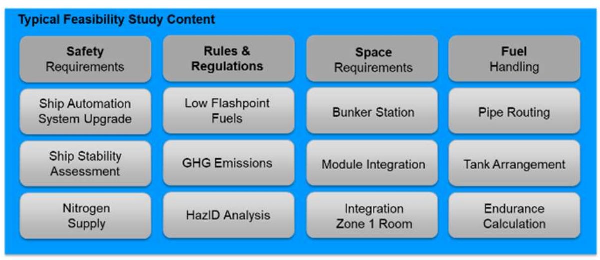

Figure 10: Typical content of Feasibility Study

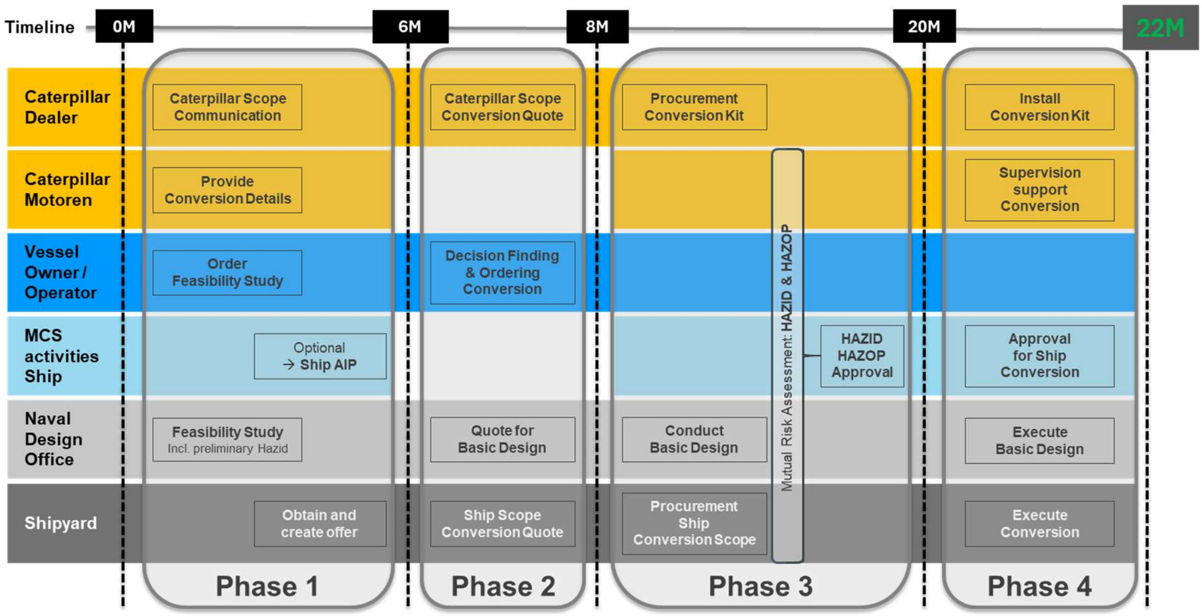

Figure 11: Schematic view on Project Roles, Responsibilities and Timeline

The result of this study is the baseline for a quote from potential shipyards and, in cooperation with Marine Class Societies, an Approval in Principle (AIP) can be granted. The subsequent phases generically describe the process of a conversion project. The entire process, from the first exchange of information to the completion of the conversion in the shipyard, is expected to take approximately 22 months.

10 SUMMARY

This paper describes the motivation and development of the Caterpillar Motoren Methanol Upgrade Kit, which enables the use of methanol for the well-known MaK platforms M 32 C and M 43 C. It was shown that the performance of the dual-fuel engine when running on methanol is just as efficient as with conventional diesel, with a significant reduction in lifecycle GHG emissions while keeping stack emissions essentially the same. The concept presented represents a complete solution for the engine, as all support modules and the entire control system are part of the Caterpillar Motoren scope. A generic project plan was presented for the entire ship conversion. The available Project Planning Guide [7] is the basis for the ship-side integration. This makes it possible to start already the project and to do a feasibility study. The published Project Planning Guide has already proven that a feasibility study and an AIP are possible on its basis.

11 ACRONYMS

ECB	Engine Connecting Block
ETS	Emissions Trading System
FVT	Fuel Valve Train
GHG	Greenhouse Gas
HPDI	High-Pressure Direct Injection
HPPM	High-Pressure-Pump-Module
IMO	International Maritime Organization
LPSM	Low-Pressure-Supply-Module
MACS	Modular Alarm and Control System
MCS	Marine Class Society
PLN	Pump Line Nozzle
RFNBO	Renewable Fuel Non-Biological Origin
SCB	Ship Connecting Block
SOI	Start of Injection
SPV	Start & Purge Valve
VFD	Variable Frequency Drive
VLSFO	Very Low Sulphur Fuel Oil
WtW	Well-to-Wake

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