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New retrofit solutions for MAN B&W marine two-stroke engines

Retrofit Solutions

Dorthe Marie Sveistrup Jacobsen, MAN Energy Solutions

Amol Sharadpant Dashpute, MAN Energy Solutions
Amar Atul Parikh, MAN Energy Solutions

ABSTRACT

Transoceanic shipping needs to decarbonize in order to meet global greenhouse gas (GHG) reduction targets, as shipping accounts for around 3% of global GHG emissions. In order to meet the targets, decarbonization must be introduced both on new-built vessels and vessels already in service.

MAN Energy Solutions has developed multiple solutions for energy efficiency optimisation and for operation on different fuel types for the MAN B&W two-stroke marine engines to facilitate the decarbonization of transoceanic shipping. There are many opportunities to transfer the latest developments to the existing fleet, and also customized solutions targeted directly for retrofitting the existing fleet are developed.

This paper will report on some of the newest retrofit products, that has been developed and also present an overall comparison of a number of different energy efficiency optimization solutions. Example cases for selection of the different solutions will be shown, and CAPEX and OPEX evaluations will be included.

The paper will focus on the development of the conversion from a traditional single-fuel engine, capable of operating on diesel, biofuel and heavy fuel, to a dual-fuel engine, capable of operating both on methanol and the traditional fuels: diesel, biofuel and heavy fuel. The paper will look into the conversion process on an already developed engine type (G95ME-C9.5-LGIM), and also the development of a totally new engine type for dual-fuel operation: S90ME-C9/10.5-LGIM, which is planned only for retrofitting the LGIM (methanol) platform to ships in service.

There are many possible solutions for energy efficiency optimization, and the best solution for the specific ship will depend on factors for this specific ship and operation pattern. This paper will present three different solutions for a vessel already in service, and show the pros and cons for the different solutions. The three different solutions, that will be compared, are: 1. derating the engine power to support a general reduction of fuel consumption and possibly a lighter propeller, 2. cutting out a turbocharger to support reduced fuel consumption at low load, 3. install EcoTuning product, which is a new engine control supporting energy-optimized operation at the present load profile.

1 INTRODUCTION

The marine and shipping industry, a vital cornerstone of global trade, needs to undergo a transformative shift driven by environmental regulations, fuel efficiency goals, and the need to reduce greenhouse gas (GHG) emissions. Retrofitting, especially for two-stroke engines, has emerged as a practical solution to modernise vessels and achieve compliance with international standards such as the International Maritime Organization’s (IMO) 2023 energy efficiency and emissions requirements. The IMO has set ambitious targets including a revised GHG strategy aiming for net-zero emissions from international shipping by around 2050, with significant reductions targeted for 2030 and 2040.

1.1 Why retrofit?

The "why" behind retrofitting lies in the pressing need to address the environmental impact of shipping, which accounts for approximately 3% of global GHG emissions. Stricter regulations are prompting shipowners to seek effective solutions that comply with these mandates and also enhance operational efficiency and reduce fuel costs.

Retrofitting offers a pathway for shipowners to upgrade their fleets without resorting to full vessel replacement. It extends the operational life of ships while improving their environmental and economic performance. Retrofitting also enables lower GHG emissions compared to building a completely new ship. Retrofits can range from simple energy efficiency improvements to adopting a dual-fuel system on board vessels.

Energy efficiency products like turbocharger cut-out (TCCO), EcoTuning, and derating are easier to implement compared to dual-fuel retrofit solutions. However, dual-fuel retrofit systems provide a viable pathway for vessels to significantly lower GHG emissions by enabling use of cleaner fuels such as methane, methanol, or ammonia, especially when these fuels are produced sustainable. For more details see Section 6.2.

1.2 How is it addressed?

The "how" encompasses not only the technical aspects, but also a commitment to responsibility in achieving sustainability goals. Shipowners play a crucial role in driving this transition by investing in retrofitting projects that align with international climate objectives. Additionally, regulatory bodies like the IMO must continue to support these initiatives by providing clear guidelines and incentives for adopting cleaner technologies. Cargo owners and financial institutions also play a crucial role, as they are chartering the assets to move the cargo. Ultimately, the entire ecosystem needs to join the decarbonisation journey.

1.3 What is involved in retrofitting?

The "what" of retrofitting encompasses adapting to GHG emission reduction technologies, digitalisation and implementing fuel optimisation technologies, or converting existing two-stroke engines to dual-fuel capabilities along with a combination of the above. This process typically involves several key activities. These key activities are described further in the following sections.

1.3.1 Process

To ensure a smooth retrofit process, several steps and multiple partners should be involved. See Figure 1. A systematic approach begins with a comprehensive feasibility study. This involves evaluating the actual goals for the vessel, the current engine specifications, assessing the compatibility of energy efficiency products and dual-fuel systems, etc., and deciding on the actual solution. This is followed by an engineering design customised for the specific series of vessels, and the development of a detailed retrofit plan.

The practical execution phase includes sourcing the components and shipping them to the installation location. The actual installation should be thoroughly planned and executed, as many partners will be involved. After installation, the retrofit product should be commissioned and tested for compliance and functionality, allowing the ship to resume normal service.

The number of partners required depends on the scope of the retrofit. Generally, the more complex the retrofit, the more partners are needed. This is described in more detail in Section 1.3.3.

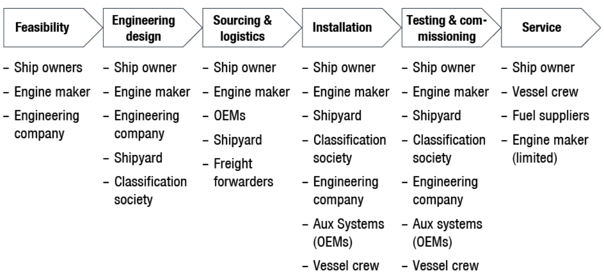

Figure 1*. A smooth retrofit process involves a number of steps and multiple partners.*

1.3.2 Products

Several technical solutions are available to reduce GHG emissions from the actual vessel. When selecting the actual solution, it is important to consider the goals for the company and the actual vessel as well as factors such as vessel age, the cost of a newbuilding, retrofit complexity, etc., see also Section 6.3.

Generally, fuel-efficiency improving technologies are simpler and faster to implement than dual-fuel retrofits. However, a dual-fuel retrofit can achieve a significantly higher GHG reduction, as is described in Section 6.2.

The dual-fuel retrofit involves modifications to engine components such as cylinder covers, cylinder liners, fuel injection valves, turbochargers, auxiliary systems, and fuel supply systems, to name a few. In some cases, changes to the vessel structure are also necessary. Such modifications are critical to ensure efficient operation with the retrofitted upgrades and to ensure the targeted emissions reduction and compliance with safety standards. This is further detailed in Section 2.2.2.

1.3.3 Partnerships

Successful retrofitting often requires collaboration among various stakeholders, including shipowners, engine manufacturers, shipyards, OEMs (original equipment manufacturers), charterers, financers, and fuel suppliers. These partnerships facilitate knowledge sharing and resource allocation, ensuring that the retrofit process is efficient and effective.

In this paper, we elaborate on some of the engine optimisation technologies and the retrofitting of two-stroke marine engines to dual-fuel systems. By addressing regulatory pressures and environmental concerns through innovative engineering solutions, shipowners can comply with international standards while enhancing operational efficiency. The collaborative efforts of all stakeholders – engine manufacturers, shipyards, OEMs, fuel suppliers, and regulatory bodies – are essential in fostering a responsible approach to this transition, ultimately contributing positively to global climate goals.

2 PATHWAY TOWARDS DUAL-FUEL RETROFIT

As the maritime industry increasingly focuses on sustainability and compliance with international regulations, retrofitting existing two-stroke marine engines to dual-fuel systems emerges as a viable solution. This pathway encompasses various fuel possibilities – methane, LPG, ethane, biofuels, methanol, and ammonia. Each of these options presents unique benefits and challenges.

As the environmental regulations are tightening and the market conditions are fluctuating, it becomes ever-more important to have engines that support fuel-flexibility, so that the engines can switch between different fuel types.

The modular design of MAN B&W two-stroke engines supports retrofitting to various engine configurations – GI (high pressure gas (methane) injection), LGIM (liquid gas injection methanol), LGIP (liquefied gas injection LPG) and possibly LGIA (liquefied gas injection ammonia) in the near future.

The fuel mix for newbuild engines ordered in 2024 is shown in Figure 2. The numbers are based on engine power for more than 1,900 two-stroke engine orders across all engine types.

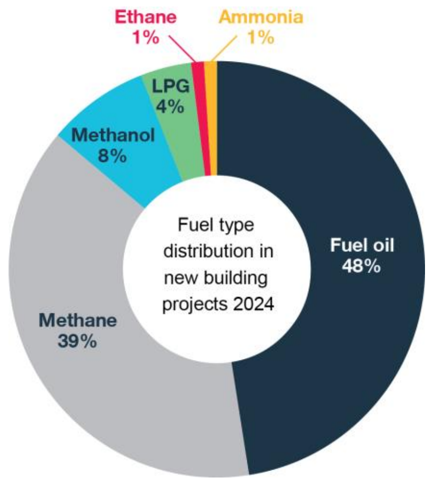

Figure 2. *Fuel type distribution on new engine projects in 2024 based on power.*

It is expected that the share of new dual-fuel engines will continue to grow, and that such a trend will be supported by retrofitted dual-fuel engines in service. The growth rate will depend on future regulations.

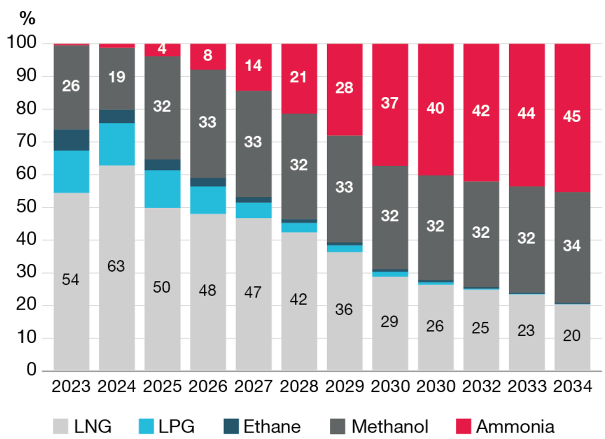

Figure 3. *Two-stroke dual-fuel mix forecast for newbuilding orders based on number of ships [MAN Energy Solutions].*

Figure 3 illustrates a forecast from the author's company for a dual-fuel mix in new orders for two-stroke engines based on number of ships. Methane (LNG) and methanol are expected to dominate the fuel mix in a short to medium term, while a rapid uptake in ammonia is expected when launched. Future legislation is expected to further guide the selection of fuel types.

2.1 Understanding fuel possibilities for the existing fleet

The previous section gave insight into the fuel mix for the ongoing and the expected newbuilding assets. Therefore, it is clear that similar fuel options are necessary to integrate into the existing fleet of vessels. Dual-fuel conversions are not a new phenomenon, a few conversions have been completed in the past, and many are now following. This is detailed in the following sections.

MAN Energy Solutions (MAN ES) provides a comprehensive dual-fuel retrofit package to convert the assets to dual-fuel capabilities. Table 1 shows an overview of engine types that can be retrofitted for dual-fuel capability.

Table 1. *Overview of engine types that can be retrofitted for dual-fuel capability.*

Original engine type	**ME-C**				
Dual-fuel engine types	GI (Methane)	LGIP (LPG)	GIE (LEG)	LGIM (Methanol)	LGIA (NH_3)
Retrofit	Design on request				In the pipeline
Size: Bore and stroke	G95 S/G90 S/G80 S/G70 S/G60 S/ 50	S/G60 G50	G60 S/G50	G95 S90 G80 S60 S/G50	TBD

2.1.1 Engine type: GI (methane)

The GI system allows for the use of liquefied natural gas (LNG) as a primary fuel source, with pilot injection of conventional fuels or biofuels. The ME-GI technology is designed for high efficiency and lower emissions, making it a popular choice among shipowners looking to comply with stringent environmental regulations. The successful retrofitting of an engine from 7S90ME-C9.5 to 7S90ME-C-9.5-GI demonstrates the practicality of this approach.

2.1.2 Engine type: LGIM (methanol)

Methanol is gaining traction as an alternative fuel due to its lower emissions profile when using the green version. Retrofitting engines to utilise the LGIM system enables vessels to operate on methanol, which can be derived from renewable sources, thus further enhancing sustainability. The recent conversion on the *Maersk Halifax* from 8G95ME-C-9.5 to 8G95ME-C.9.5-LGIM has paved the way for the dual-fuel methanol retrofits, which are detailed in this paper in the following sections.

2.1.3 Engine type: LGIP (LPG)

LPG offers another viable option for dual-fuel retrofitting. It provides a cleaner combustion process compared to traditional marine fuels, contributing to reduced SO_X emissions. The flexibility of propane as a fuel source makes it an attractive choice for many operators, especially for ships carrying propane. MAN ES has successfully retrofitted a number of engines to 6G60ME-C9.5-LGIP.

2.1.4 Engine type: LGIA (ammonia)

As the maritime industry looks towards zero-emission solutions, ammonia is emerging as a potential fuel candidate. Retrofitting engines for LGIA could facilitate the use of ammonia, which, when produced sustainably, offers significant reductions in GHG emissions. MAN ES has successfully tested ammonia as a fuel on a 4-cylinder test engine. We expect to add the ammonia LGIA engine as a retrofit offering in the future when positive service experience has been obtained.

2.2 The retrofit process

The pathway to dual-fuel retrofitting involves several critical steps, which are detailed below.

2.2.1 Ship feasibility assessment

Shipowners must evaluate their existing vessels to determine the compatibility with dual-fuel technologies. Factors like the vessel's age, trade pattern, and future deployment are the primary considerations followed by engine type, bore size, etc. Any previous modifications play a crucial role in this assessment.

2.2.2 Engineering design

Once the ship feasibility has been confirmed, the detailed engineering designs of engine and vessel structure designs are developed. This includes modifications to the fuel supply systems, installation of new fuel injectors compatible with the fuels chosen, and integration of advanced control systems. Engineering companies work on the auxiliary systems to be installed in the engine room, piping layouts, structural modifications to the vessel including new fuel tanks, and any modifications to cargo space. The above layouts are generally detailed in the engineering phase.

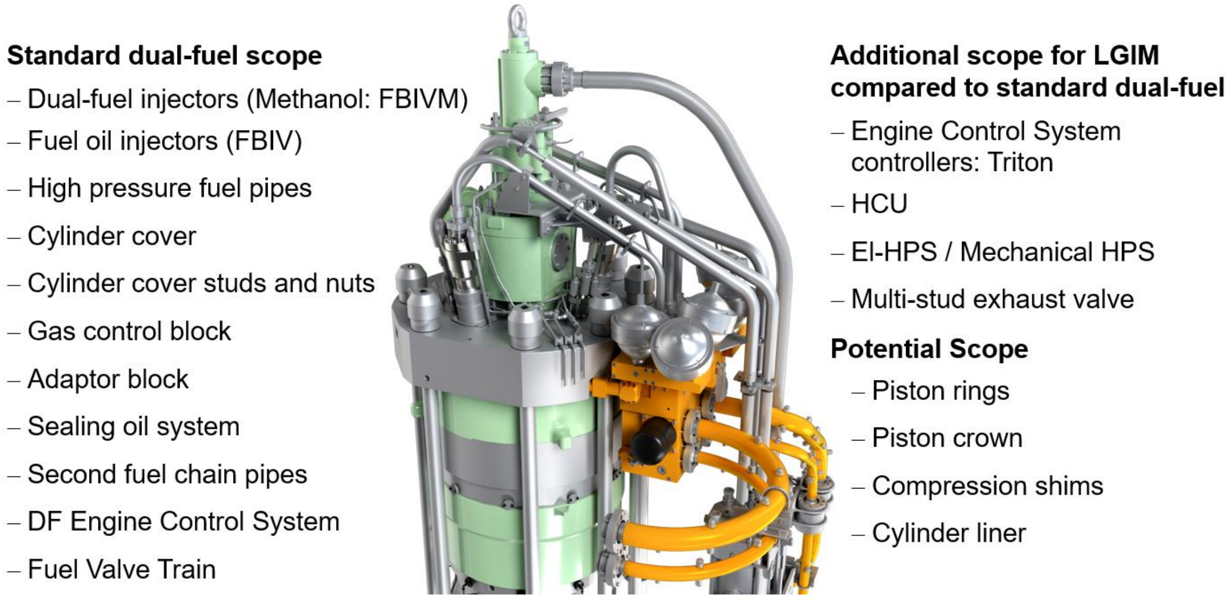

Figure 4. *Summary of main engine dual-fuel conversion scope.*

Figure 4 summarises the engine components that are assessed during the detailed engineering for dual-fuel conversion. These components primarily support the dual-fuel capability, but the assessment also includes actual conditions of the components and NO_X certification elements

2.2.3 Procurement

As soon as the engineering design is complete and verified, the sourcing of the necessary and long-lead components – such as cylinder covers, gas blocks, fuel storage tanks, piping systems, and safety equipment – is essential for a successful retrofit process. Partnerships play an important role, and early discussions and preparations facilitates an optimal planning, cost control, and reduce vessel downtime at the yard.

2.2.4 Installation and cold commissioning

The retrofit process requires skilled labour for installation during drydocking, OEM service engineers to commission, and surveyors to witness and approve the installations. Following installation, comprehensive function tests are performed alongside the quay before proceeding for sea trials. Such simulations, and leak and pressure tests ensure that the engine operates efficiently under dual-fuel conditions while meeting regulatory compliance. All of this must be done with safety in mind during the conversion.

2.2.5 Commissioning and sea trials

After successful cold commissioning, the vessel is commissioned for operational use in dual-fuel mode along with extensive sea trials to obtain class approvals and safe operation of the asset. Ongoing monitoring and maintenance are critical to ensuring optimal performance over time.

Figure 5 summarises the process with estimated timelines.

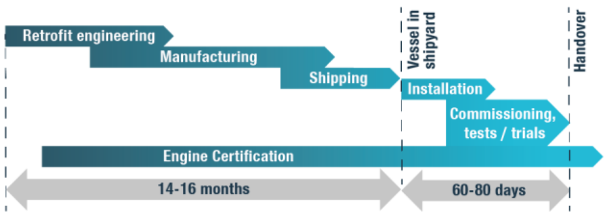

***Figure 5**. Summary of the retrofit process with estimated timelines.*

2.3 Collaborative partnerships

The success of dual-fuel retrofitting heavily relies on partnerships among various stakeholders.

2.3.1 Engine manufacturers

Collaboration with manufacturers like MAN ES ensures access to cutting-edge technology and expertise in retrofitting processes and tailor-made solutions.

2.3.2 Shipyards

Shipyards play a crucial role in executing retrofits efficiently. Their experience in handling complex modifications is essential for minimising downtime during installations.

2.3.3 Fuel suppliers

Partnerships with fuel suppliers are vital for ensuring reliable access to alternative fuels such as methane, methanol, propane, or ammonia.

2.3.4 Regulatory bodies

Engaging with regulatory bodies helps navigate compliance requirements and fosters an environment conducive to innovation in dual-fuel technologies. These include, for instance, classification societies and flag states.

3 CONVERSION FROM G95ME-C9.5 TO G95ME-C9.5-LGIM

This section outlines the detailed process for retrofitting methanol dual-fuel capability to a G95ME-C9.5 engine, converting it into a G95ME-C9.5-LGIM engine type. Figure 6 shows the team after the successful conversion.

Figure 6. *Team at G95ME-C9.5-LGIM conversion.*

The retrofit installation was carried out at the Zhoushan Xinya Shipyard in China, where the *Maersk Halifax* underwent an extensive 88-day conversion. The project involved several key modifications, which are described in more details below. This paper only details the engine modifications and NO_X certification.

3.1 Engine conversion

The two-stroke main engine was retrofitted from an 8G95ME-C9.5 type engine to an 8G95ME-C9.5-LGIM engine, enabling the vessel to run on methanol. This upgrade allows for a potential reduction of CO_2 emissions by up to 95% when operating on e-methanol compared to traditional marine oil fuels. Refer to Section 6.2.

3.1.1 Key components for an LGIM dual-fuel retrofit

This section illustrates some key components that are always changed during a dual-fuel retrofit, see also Figure 4 in Section 2.2.2.

Figure 7 illustrates the new engine components that support dual-fuel injection. These include the gas fuel (methanol) inlet and return pipes over the engine as well as the sealing oil unit, which ensures separation of the gas fuel (methanol) from the hydraulic oil in the gas fuel (methanol) injection valve.

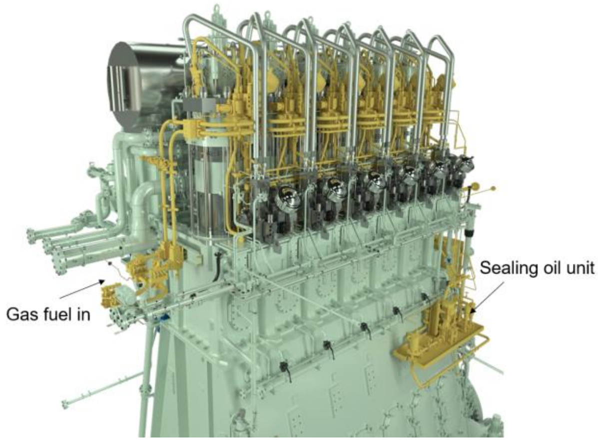

Figure 7. *Retrofit components supporting dual-fuel injection (yellow parts).*

Methanol fuel injection

The second fuel injection system for LGIM (methanol) is more than twice the volume of the standard fuel oil system, owing to methanol's lower heating value compared to traditional fuel, and other technical updates and considerations. Figure 8 gives an overview of the added methanol system mounted on the cylinder cover.

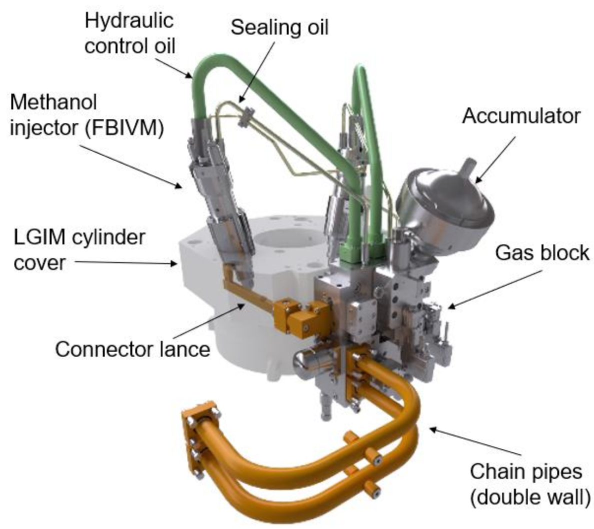

Figure 8. *Overview of LGIM (methanol) fuel injection system on the cylinder cover.*

A chain pipe system is fitted for the distribution of second fuel to a gas block on each cylinder. From the gas block, and through control valves, the methanol is led to the methanol injectors via the connector lances inside the cylinder cover. See Figure 8.

The methanol gas block also controls the hydraulic oil for fuel injection control and the sealing oil. Separate accumulators are connected to each of the lines for methanol, hydraulic oil, and sealing oil, and are used to stabilise the pressure.

The methanol fuel booster injection valve (FBIVM) shown in Figure 9 has been designed as a batch injector, combining a hydraulically actuated plunger pump with a spring-held injection needle valve that opens at a given fuel pressure. The pump functionality of the FBIVM uses hydraulic oil pressure to increase the methanol pressure to the required injection pressure of approximately 600 bar from the methanol supply pressure of 13 bar. A suction valve ensures the filling of the pump chamber after each stroke. The fundamental function of the FBIVM is similar to the FBIV used on many engine types for traditional fuel oil. A small pilot injection from the diesel fuel system ignites the methanol during combustion.

Figure 9 illustrates the design of the FBIVM and the function of the sealing oil to separate the methanol and the hydraulic oil, which is used to control the fuel injection.

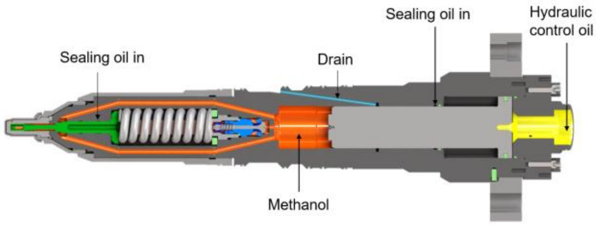

Figure 9. *Methanol injector (FBIVM) for G95ME-C10.5-LGIM.*

Cylinder cover

The LGIM cylinder cover has a central bore for the exhaust valve, three bores for fuel oil injection valves, three methanol injection valves (FBIVM), a starting valve, and an indicator valve. See Figure 10.

Control system upgrade

The retrofit included an upgrade to the vessel's engine control system, utilising MAN Energy Solutions' latest Triton system for enhanced operational efficiency.

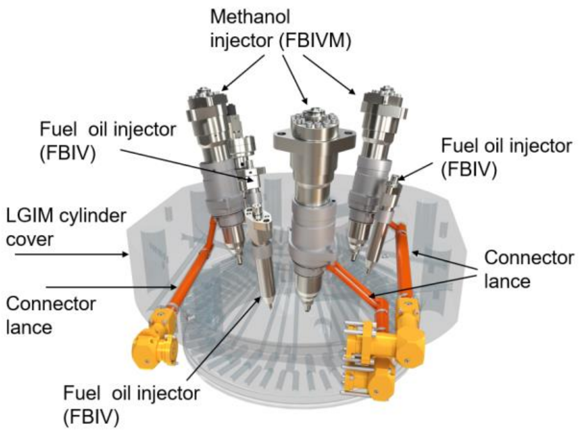

Figure 10. *Cylinder cover for G95ME-C10.5-LGIM.*

3.2 NO_X certification concept

The engine type G95ME-C-LGIM has already been developed in both 9.5 and 10.5 versions, and new 10.5 engines are currently being built and tested at engine manufacturers.

This provided the opportunity to rebuild a production engine of the 10.5-LGIM version to a 9.5-LGIM version in the new updated/actual rating (power and RPM) to replicate the retrofitted engine. The rebuilt production engine could then be tested at the engine builder for NO_X compliance and fuel consumption (SFOC). The rebuilt production engine was reverted to the original 10.5 version and rating, and was delivered for the new-built vessel.

As for newbuilt engines, the retrofitted engine must demonstrate NO_X compliance for relevant combustion parameters when it enters into service. Figure 11 gives an overview of the process.

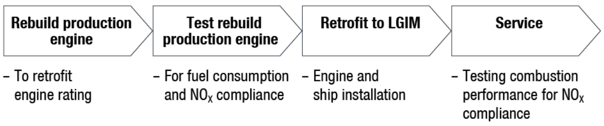

Figure 11. *Overview of 1:1 engine compliance process: Compliance process to retrofit an engine in service, when the engine type is still in production.*

3.3 Fuel system enhancements

New fuel tanks were installed, along with a fuel preparation room and an advanced fuel delivery system. The hull was lengthened by 15 metres, increasing the overall length of the ship to 368 metres and its capacity from approximately 15,000 TEU to 15,690 TEU.

3.4 Final step and outlook

Following successful sea trials conducted in mid-October 2024, MV *Maersk Halifax* returned to service on November 5, 2024. The successful conversion serves as a blueprint for future retrofit projects across the industry.

4 CONVERSION FROM S90ME-C TO S90ME-C-LGIM

This section outlines the process for retrofitting methanol dual-fuel capability to S90ME-C Mk. 9 and 10 engines, converting them into S90ME-C9/10.5-LGIM engines.

Retrofitting dual-fuel systems for engines that are no longer in production presents unique challenges, particularly when it comes to designing new components and ensuring compliance with regulations.

4.1 Test engine and prototype testing

The author’s company has designed and built a 4S90ME-C10.5-LGIM engine for prototype testing and to address the certification for this engine type in both Mk. 10.5 and Mk. 9.5 versions, see Figure 12. This will enable the retrofitting of about 300 existing vessels in service.

More than 10,000+ work hours have been put in and an investment has been made in a test engine at Kanadevia Corporation (formerly known as Hitachi Corporation) in Japan. This engine will act as a prototype and parent engine, and it will run for more than 1,000+ hours to carry out various R&D tests followed by certification tests, all performed by the author’s company. This engine is used to assess the heat load on the components, and measure fuel consumption and NO_X compliance along with many other critical parameters at various engine loads.

Figure 12. *Test engine: 4S90ME-C-10.5-LGIM.*

4.2 NO_X certification concepts

The S90ME-C-LGIM Mk. 9 and 10 engine types have not been developed as new versions of the existing engine programme, i.e., no new S90ME-C engines are currently being produced by engine manufacturers.

This presents an additional task, as the S90ME-C-LGIM engine type must first be developed as a prototype before it can be retrofitted to engines already in service. Therefore, it was decided to build a test engine to be able to develop the prototype for the S90ME-C-LGIM. With the engine now available for testing, it can also be used for NO_X certification.

Two different NO_X compliance processes have been used: A 1:1 engine compliance process, and one aimed at supporting future retrofit cases.

The 1:1 compliance process is similar to the process used for the G95ME-C-LGIM conversion (Section 3.2), and it has been used for dual-fuel conversions already contracted.

Both methods involve testing the test engine at different ratings for fuel consumption and NO_X compliance, and that the retrofitted engines must demonstrate NO_X compliance for relevant combustion parameters when it enters service. See Figure 13.

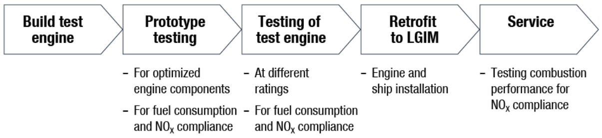

Figure 13. *Overview of the compliance process to retrofit an engine in service, when the engine type is neither developed, nor in production.*

5 EFFICIENCY-IMPROVING PRODUCTS

Energy efficiency is paramount. The fuel contributing the most to the transition of shipping towards net-zero carbon operation is the fuel not burned in the engine. Energy efficiency is a top priority from both a legislative compliance perspective and for the commercial aspects. This chapter highlights some of our popular efficiency-improving products:

- TCCO (turbocharger cut-out)
- EcoTuning
- Derating

5.1 Introduction

Today, most ships operate at low loads most of the time, but they need some extra power to catch up on delays or in emergencies. It is well known that a power reduction will decrease fuel consumption more than it will reduce vessel speed. See Figure 14. The reduction in fuel oil consumption corresponds to an equivalent reduction in greenhouse gasses (CO_2).

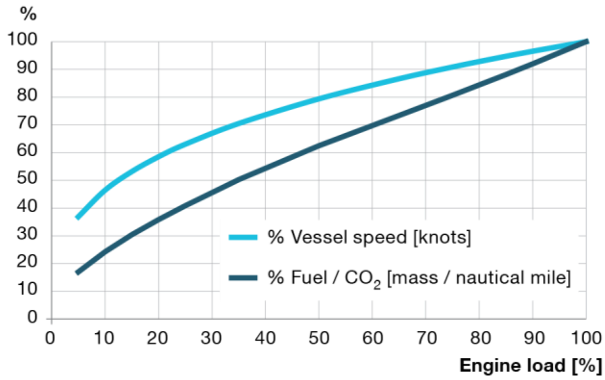

Figure 14. Sketch of reduction in fuel consumption and vessel speed (y-axis) depending on engine load [2]. The actual numbers will depend on vessel type and layout of vessel, but the tendency will be the same.

Tighter legislation and higher fuel prices have led operators to change the originally expected high vessel speed and high engine load operation to reduced speed and low-load operation, as illustrated in Figure 15.

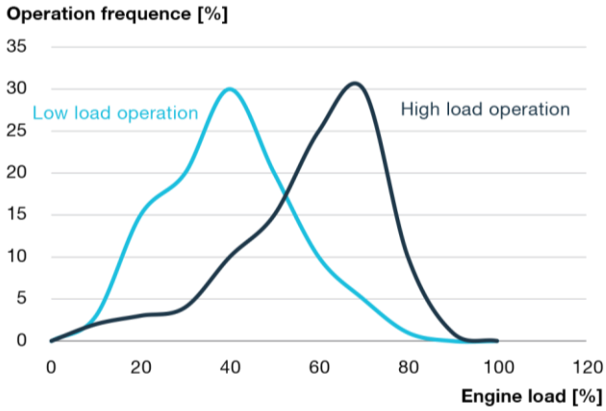

***Figure 15.** Examples of high-load and low-load operation patterns.*

Such a changed operating pattern calls for a focus on improving energy efficiency at low loads instead of the original focus on low fuel oil consumption at higher loads. This has led to the development and success of the low-load energy-improving products, which has been implemented both on newbuilt engines, and also on engines in service as retrofit.

Table 2 shows an overview of the low-load energy-improving products described in this paper. The products are described in more detail in the following sections. It is common for all the solutions that the combustion performance of the engines is changed, and thereby the NO_X formation is also changed. NO_X emissions are regulated based on the original engine testing at the manufacturer. So when changes are introduced, this must be agreed upon with the authorities, and the ship certificates must be updated to support the legislative process. Such certificate updates could be amendments to the Technical File or a new Technical File.

***Table 2.** Overview of low-load energy-improving products.*

Retrofit solution	Physical changes	SFOC savings [g/kWh]	Fuel type	NO_X chan-ges	Cost indication
TCCO	Yes	0 to 5	As original	Yes	++
EcoTuning	No	-1 to 4	As original	Yes	+
Derating	Yes	0 to 10	As original	Yes	++++

5.2 TCCO – turbocharger cut-out

The energy efficiency in the low-load range can be improved significantly by increasing the scavenge air pressure. This can be achieved by cutting out the exhaust gas flow to one of the turbochargers. Figure 16 shows a sketch for an engine with three turbochargers, where one can be cut out.

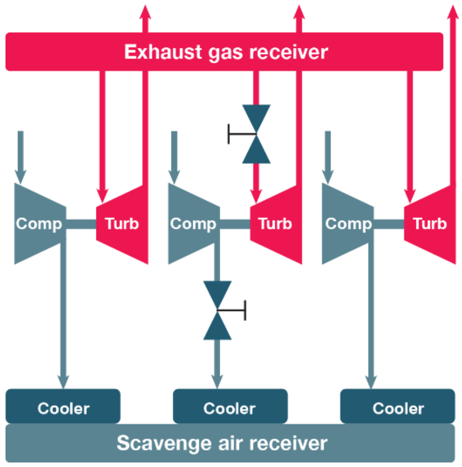

***Figure 16.** Sketch of a 1:3 TCCO, where 1 turbocharger out of 3 can be cut out from the exhaust gas flow [2].*

A retrofit example

Figures 17-19 show data from an actual case. The figures show that when cutting out one turbocharger out of four, the scavenge air pressure increases, and thereby the compression and combustion pressures increase, and the fuel consumption decreases.

At high load, the engine requires that all turbochargers are in operation to scavenge the cylinders. This is easily handled on the ME-type electronically-controlled engines (ME-type). On mechanically-controlled engines (MC-type), TCCO can be combined with a semi-automatic engine control (PMI-VIT), which can control the valves for the TCCO and also optimise the combustion performance to the original level.

Turbocharger cut-out is applicable for engines with three or four turbochargers and, in special cases, for engines with two turbochargers. The turbocharger cut-out will improve the specific fuel oil consumption at low load and can reduce the heat load on engine components, especially the exhaust valves. The installation will also move the auxiliary blower cut in/out to a lower load area, and thereby reduce the electrical power consumed by the blowers and the number of running hours.

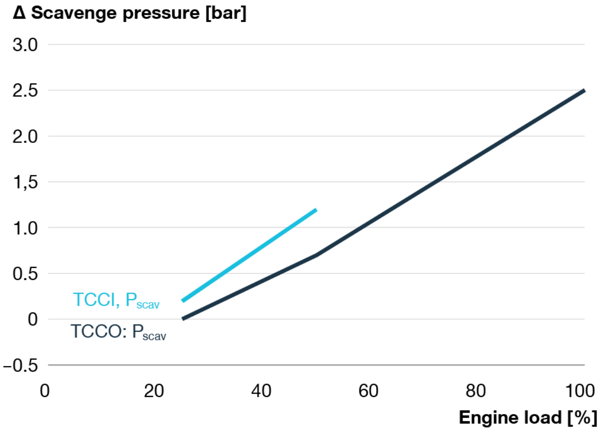

Figure 17. *Data for changes in scavenge pressure (P_{scav}) from an actual case of 1:4 TCCO on a 12K98MC-C (Tier I).*

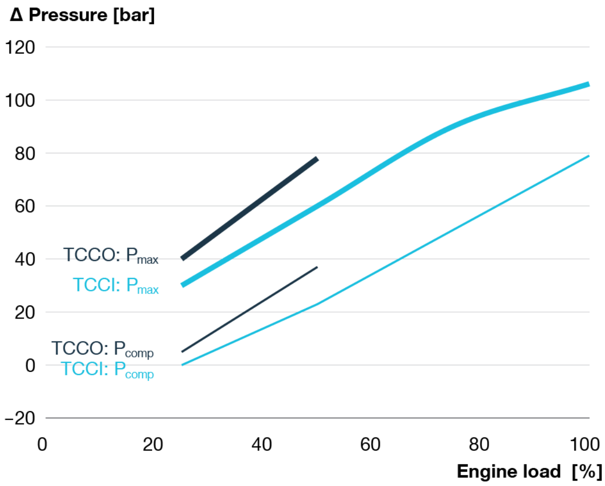

Figure 18. *Data for changes in compression (P_{comp}) and combustion pressure (P_{max}) from an actual case of 1:4 TCCO on a 12K98MC-C (Tier I).*

Turbocharger cut-out involves the installation of cut-out valves, pneumatic control in case of TCCO control, indicator panels, etc., recalculating of the torsional vibrations, updating NO_X certification, installing the new engine control parameter file for electronically-controlled engines (ME-type) and for MC-engines with the newest PMI-VIT control.

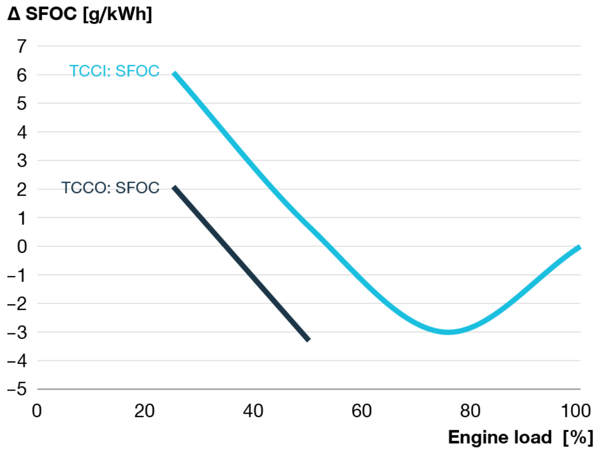

Figure 19. *Data for changes in fuel consumption (SFOC) from an actual case of 1:4 TCCO on a 12K98MC-C (Tier I).*

5.3 EcoTuning

EcoTuning is a low-load tuning method that can increase the engine efficiency in the low-load range, where the vessel typically operates. The increased efficiency in the low-load range is achieved by increasing the combustion pressures. EcoTuning modifies essential combustion parameters through a software update to the engine control system (ECS). This update modifies the control parameters for the exhaust valve timing and fuel injection timing, which, in turn, regulate compression and maximum combustion pressures. EcoTuning is applied as a pure software update, and there are no changes to actual engine components. EcoTuning uses well-known and class-approved correction methods to determine the effect of the new tuning on fuel consumption (SFOC) and NO_X emissions, and does not require engine tests or sea trials for NO_X re-certification.

EcoTuning is available for electronically-controlled ME and ME-C two-stroke engines with a fixed maximum pressure (P_{max}) control strategy. EcoTuning is not applicable for vessels fitted with TCCO, or vessels limited to power below 75% load of original MCR, e.g. by an OPL (overridable power limitation) to fulfil EEXI requirements.

A retrofit example

EcoTuning was applied and tested on an S90ME-C9.2 engine. EcoTuning involves re-optimisation of the combustion parameters, recalculating the torsional vibrations, updating NO_X certification, installing the new engine control parameter file, and checking that the combustion performance is as expected. Figure 20 shows the original and the EcoTuning combustion pressures, and Figure 21 shows the corresponding fuel changes.

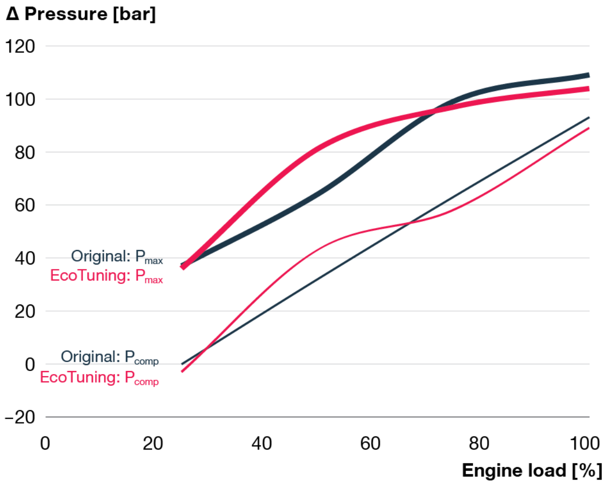

Figure 20. *Data for changes in compression (P_{comp}) and combustion pressure (P_{max}) from an actual case of applying EcoTuning on an S90ME-C9.2 (Tier II) engine.*

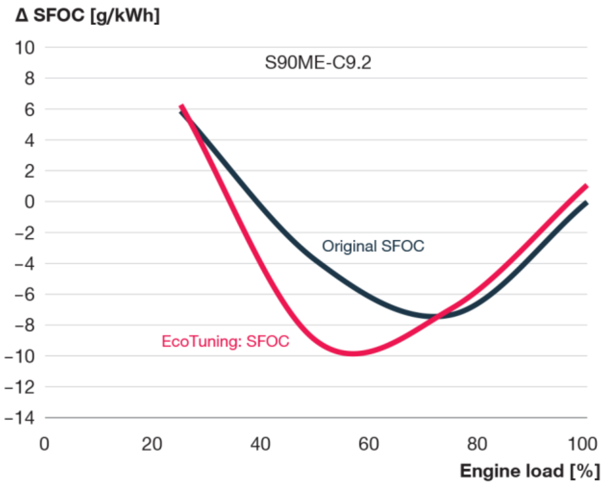

Figure 21. *Data for changes in fuel consumption (SFOC) from an actual case of applying EcoTuning on an S90ME-C9.2 (Tier II) engine.*

5.4 Derating

An engine can be freely chosen within the layout diagram for power and speed for the specific engine. The layout diagram is limited by lines for constant MEP (mean effective pressure) and constant speed, see Figure 22. An engine can be derated for MEP, speed, or both.

MEP derating

The ratio between P_{max} and MEP influences the efficiency of a combustion engine. If the P_{max}/MEP ratio is increased, the specific fuel consumption (SFOC) will be reduced. The engine is designed to withstand a certain P_{max}, and this P_{max} is utilised by the engine control system when other constraints do not apply.

The MEP at the SMCR (specified maximum continues running) can be chosen among a range of values defined by the layout diagram of the engine, and it is therefore possible to specify a reduced MEP to achieve a reduced SFOC. See Figure 22.

Speed derating

When the engine is derated on speed, i.e., if the layout point is moved parallel to the constant MEP lines, SFOC for the engine is not reduced. However, a lower revolution speed can support the installation of a larger propeller, which may lead to higher propulsion efficiency. See Figure 22.

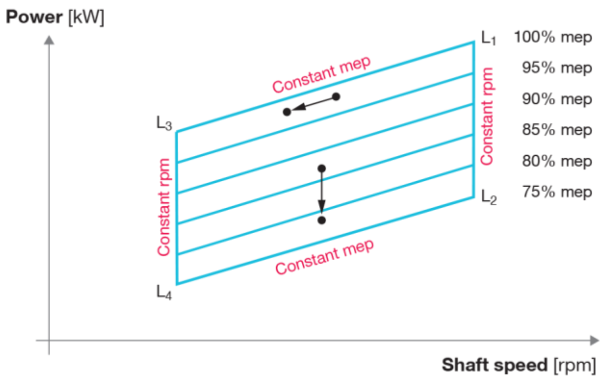

Figure 22. *Layout diagram showing MEP derating along L1-L2 (→ reduced SFOC) and power and speed derating along L1-L3 (→ SFOC is unchanged, but a larger propeller can be used leading to improved ship efficiency) [1].*

Derating history

Figure 23 shows the development of the power rating of the ordered engine series. Before 2010, almost all engines were ordered with full power, but from 2010, the ordering of derated engines started. Today, engines are ordered in the range of 60-90% power with an average of around 70-75% power.

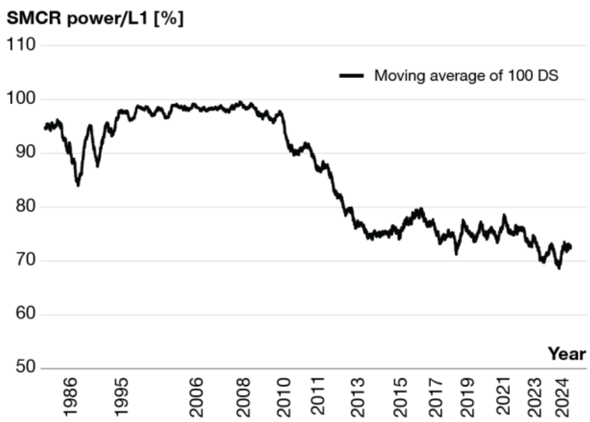

Figure 23. *Development of power rating of ordered engine series (= Design Specifications (DS)).*

Retrofit example

Below is an actual example where full derating on both power and speed was investigated. See Figure 24.

Derating the engine involves re-optimisation of the combustion parameters, changing the volumetric compression ratio, recalculating the torsional vibrations, rematching the turbocharger to the new amount and pressure of the exhaust gas, updating the NO_x certification, optimising cylinder cooling, lube oil amount, pump and cooler capacity, etc. The new propeller must be designed to match the power output and shaft speed of the derated engine.

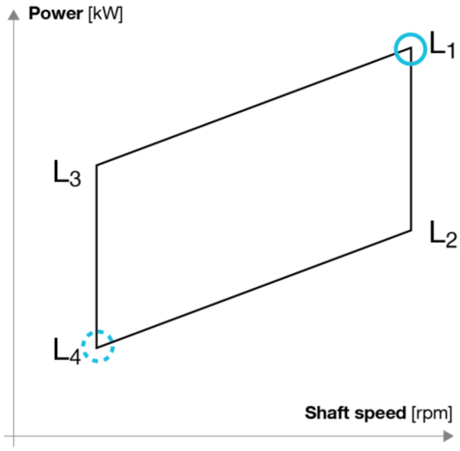

Figure 24. *Example of derating an 6S60MC-C8 from full power and speed to minimum power and speed. L1: 14,280 kW, 105 RPM. L4: 9,660 kW, 89 RPM.*

Fuel consumption data for the two cases have been calculated, and the differences are illustrated in Figure 25. It is clear that fuel consumption decreases at lower power levels.

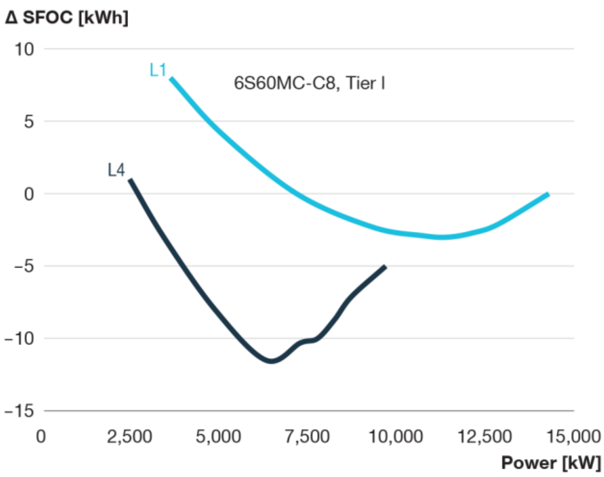

Figure 25. *Calculated data for fuel consumption (SFOC) changes from an actual case of full derating of a 6S60MC-C8 from L1 (high load tuned) to L4 (low load tuned).*

6 HOW TO CHOOSE THE BEST SOLUTION?

When evaluating retrofit solutions, it is essential to balance greenhouse gas (GHG) reduction potential, associated costs, and regulatory compliance.

Different retrofit options vary significantly in their effectiveness and expense, making it essential to consider factors such as the specific needs of the vessel, the available budget, and the long-term benefits to select the most suitable and cost-effective retrofit solution.

6.1 Drivers for change

To drive change, several parameters must be fulfilled. The technology to support the change must be developed and commercially available. The market acceptance and implementation will be driven by regulation, costs, or a combination of these two. Public pressure can support both these drivers promoting tighter regulation and increased costs. See Figure 26.

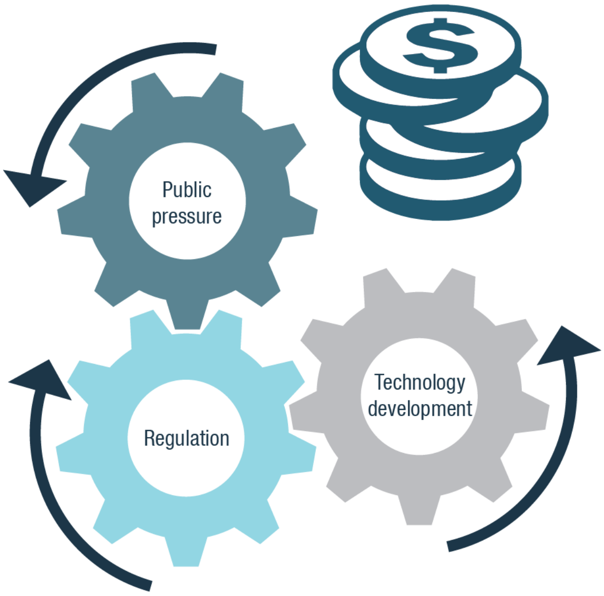

Figure 26. *Parameters for driving change.*

Figure 27 shows an example of the introduction of new technology. The technologies showed proof of concept on a production engine in 2012, Tier III regulations came into in force in 2016 and, after some years, almost 100% of all engines were ordered with Tier III technology.

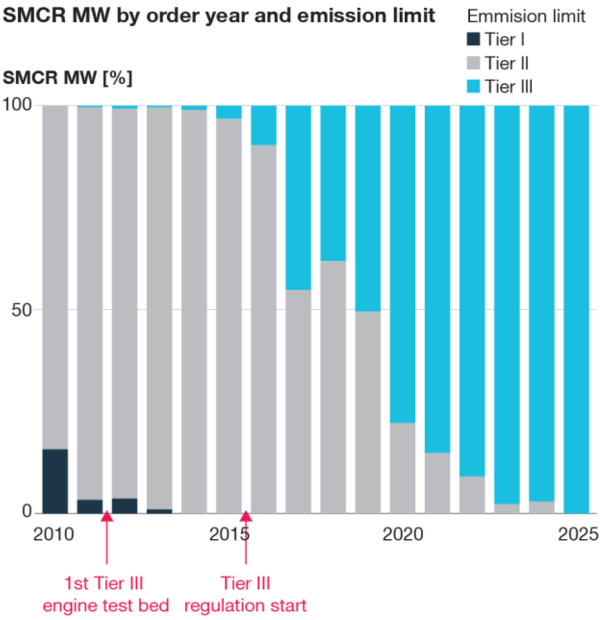

Figure 27. *Market introduction of NO_X reduction technology for Tier III compliance. SMCR: Ordered power.*

6.2 GHG reduction potential versus cost of different retrofit solutions

When evaluating potential solutions for GHG reduction, it is essential to use an LCA (life cycle analysis) approach.

Figure 28 illustrates the generic emission scopes in the LCA approach: well-to-tank (WtT) covers emissions from production, transport, and bunkering, tank-to-wake (TtW) emissions from on-board operations and WtW (well-to-wake) the total emissions.

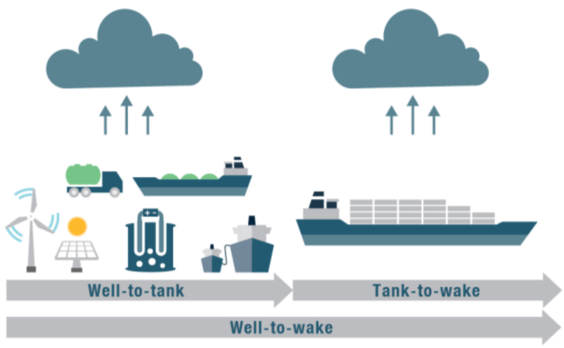

Figure 28. *Emission scopes in life-cycle analysis.*

Different fuel production pathways result in varying emissions, some remove CO_2 from the atmosphere, others generate CO_2. Emissions from on-board operations depend on the fuel type and engine technology.

Figure 29 compares the GHG impact of selected fuels to heavy fuel (VLSFO) operation. It highlights that e-fuels or biofuels have the highest GHG reduction potential.

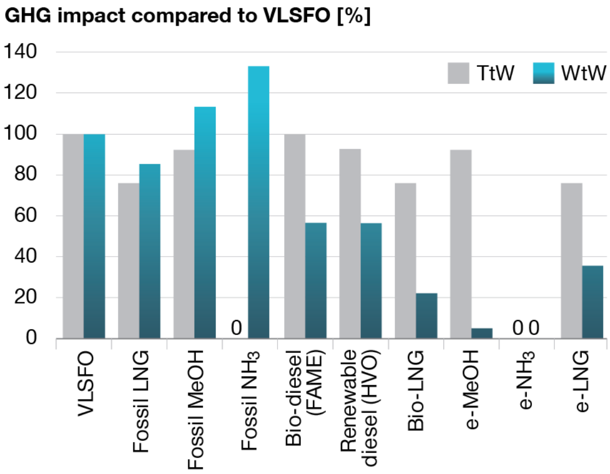

Figure 29. *GHG impact of selected fuels compared to VLSFO (heavy fuel) for both tank-to-wake (TtW) and well-to-wake (WtW) emissions. Data are based on [3], using LNG: High-pressure gas injection principle, low speed engine, $GWP_{100,CH4}$ = 29.8 CO_{2e}.*

The GHG reduction potential and the cost of retrofitting different technologies vary considerably. The energy efficiency-improving technologies are relatively low in cost, but offer limited GHG reduction potential. In contrast, dual-fuel conversions provide the highest GHG reduction potential, though implementation costs are significantly higher. Generally, GHG reduction potential and retrofitting cost are correlated, as illustrated in Figure 30.

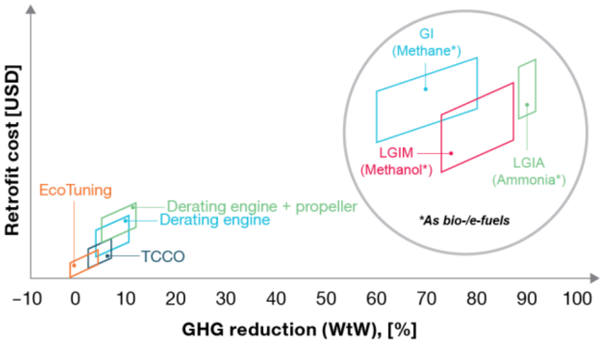

Figure 30. *GHG reduction (WtW) versus cost of retrofit overview. Numbers are ball-park figures. GHG reduction for dual-fuel engines is based on a well-to-wake LCA approach [3].*

6.3 Considerations for choosing a retrofit solution

When retrofitting with dual-fuel technologies or other engine optimisation products, the decision-making process involves evaluating these technologies to determine which suits operational needs and sustainability goals best, while also considering the technical challenges posed by new technologies.

6.3.1 Cost and value for the retrofit

The cost and value of the retrofit should be carefully evaluated. The total cost of ownership (TCO) includes all costs associated with acquiring, operating, and maintaining an asset over its lifecycle. The total value of ownership (TVO) provides a broader perspective by incorporating costs but also the potential benefits and value, such as attracting eco-conscious customers and top talent. Together, TCO and TVO offer a comprehensive view for making strategic investment decisions.

For retrofits optimising fuel efficiency, a conventional return on investment (ROI) model is generally used.

Total cost of ownership (TCO)

A TCO model can facilitate decision-making by encompassing key parameters essential for a thorough analysis:

- Initial capital expenditure (capex)
- Operating costs (opex)
- Regulatory compliance cost

Cost of new vessel compared to conversion to dual-fuel capability

For various vessel types, the cost of building a new dual-fuelled vessel is compared to the same dual-fuel retrofit of an existing vessel.

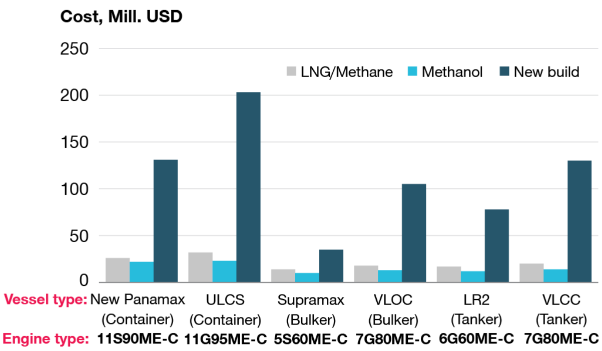

Figure 31. *Graph illustrating the initial cost of retrofits vs newbuilds for different types of vessels/engines.*

Figure 31 shows that retrofitting is significantly less capex-intensive than a newbuilding.

Time frame for dual-fuel capability

Newbuilding yards currently have a strong order book, with programmes generally taking 30-36 months from contract signature to delivery of the first vessel in a series. Alternatively, a dual-fuel retrofit requires 14-18 months from concept to complete conversion.

Furthermore, retrofitting an existing vessel does not add unnecessary capacity to the market, helping to keep supply and demand in check.

Construction emissions

Retrofits significantly reduce total construction emissions compared to newbuild vessels, with some reports suggesting up to 97% reduction [4].

Example of TCO for dual-fuel retrofit

A 14,000 TEU container vessel is used for the TCO and TVO model. A dual-fuel newbuilding is compared to dual-fuel retrofitting a single-fuel vessel. Both will be operated for at least 10 years after delivery or conversion. The retrofit vessel is 4 years old, soon to dock for its first special survey at a repair yard. The newbuild vessel is scheduled for delivery in 30 months.

The cost of a newbuild 14,000 TEU vessel is approximately $200 million, while a retrofit costs around $30 million (all inclusive). It is assumed that fuel consumption is the same for both vessels, summing up to about 40,000 metric tons of methanol for 10 years of operation. The price of VLSFO is assumed at 550 $/metric ton and green methanol at 2,000 $/metric ton. Both engines are expected to operate on methanol. For simplicity, vessel replacement costs and lost freight costs during the retrofit period are out of scope.

Figure 32 shows the TCO for the two cases. Over the 10-year period, the newbuild case is approx.

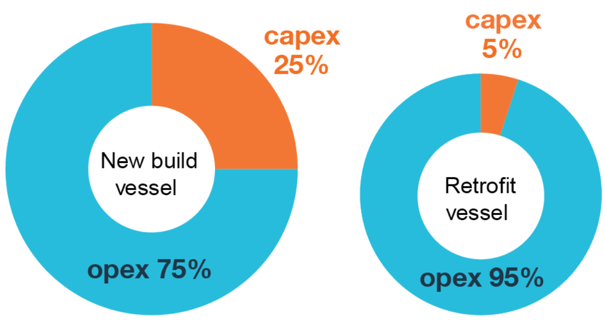

Figure 32. *Dual-fuel TCO wheel (%) – newbuild and retrofit vessel. Calculated over 10-year period.*

20% more expensive than the retrofit case, primarily due to the difference in capex.

Total value of ownership (TVO)

As opposed to TCO, TVO focuses on the non-monetary factors that also play a crucial role in a company's approach to decarbonisation. The points in Figure 33 may be included when assessing various technologies from a TVO perspective.

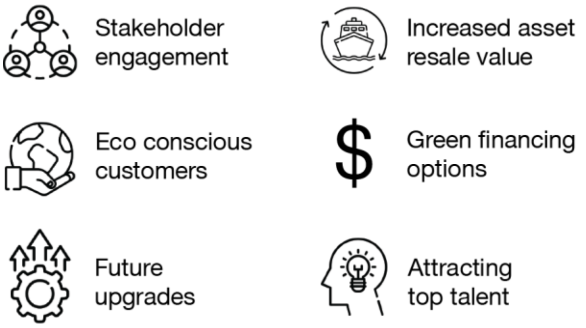

Figure 33. *Overview of TVO considerations.*

Stakeholder engagement

Demonstrating a commitment to sustainability through retrofitting can strengthen relationships with stakeholders, including investors, regulators, and local communities. Positive stakeholder perceptions can translate into enhanced brand loyalty and support for future initiatives.

Attracting eco-conscious customers

As sustainability becomes a key consideration for customers, having dual-fuel capabilities can enhance a shipowner's reputation and attract business from environmentally conscious clients. This potential increase in market share adds value beyond immediate financial metrics.

Future upgrades

Evaluating whether the technology allows for future upgrades or adaptations as new fuels and technologies emerge.

Increased vessel resale value

Vessels with dual-fuel capabilities may retain higher resale values as the demand for environmentally-friendly shipping solutions grows.

Green financing option

Investment in dual-fuel capabilities may attract options for green financing.

Attracting top talent

Decarbonising efforts attract top talent due to the urgent need to combat climate change and the exciting opportunities for innovation in renewable energy and sustainable technologies.

6.3.2 Technical aspect of operating a dual-fuel asset

Operating dual-fuel vessels presents technical challenges that shipowners must navigate to ensure safe and efficient operations. These challenges include, e.g., maintenance complexities, increased crew competency, and the safety tasks related to handling new fuels and systems.

Addressing these challenges should be a collective effort, with active participation from the entire ecosystem, including engine manufacturers, ports, fuel suppliers, fuel producers, classification societies, shipowners, and their engine crew among others.

7 CONCLUSIONS

Retrofitting two-stroke marine engines is a crucial step toward sustainable shipping, offering a compelling business case for reducing emissions, improving fuel efficiency, and meeting future regulatory requirements through innovative products, thorough processes, and strong partnerships.

Retrofits, from energy efficiency improvements to adopting a dual-fuel system, let shipowners upgrade their fleets without full vessel replacement, extending the ship operational life and improving the environmental and economic performance.

This paper describes that dual-fuel capabilities have now been retrofitted in service for operation on methane (ME-GI), LPG (LGIP), and methanol (LGIM).

Retrofitting in service is complex, requiring industry collaboration. Partnerships between shipowners, engine manufacturers, fuel suppliers, and regulatory bodies can streamline efforts and drive innovation.

Retrofitting suitable asset based on age, size, fuel pricing and consumption will undoubtedly drive future retrofit demand. MAN Energy Solutions is well-positioned to support customers in providing these solutions and aiding the shipping industry’s decarbonisation.

8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

ECS: Engine control system

FVT: Fuel valve train

GHG: Green house gas

LEG: Liquified ethane gas

LFSS: Low flashpoint fuel supply system

MEP: Mean effective pressure

PMI-VIT: Pressure measuring instrument - variable injection timing

ROI: Return on investment (ROI)

TCCI: Turbocharger cut-in

TCCO: Turbocharger cut-out

TEU: Twenty-foot equivalent unit

TCO: Total cost of ownership

TVO: Total value of ownership

SFOC: Specific fuel oil consumption

SMCR: Specified maximum continuous rating (power and speed)

9 ACKNOWLEDGEMENTS

We thank our industry partners who have contributed to the retrofit decarbonisation journey.

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11 CONTACT

Dorthe Jacobsen. DortheM.Jacobsen@man-es.com

Amol Sharadpant Dashpute. Amol.Dashpute@man-es.com

Amar Atul Parikh. Amar.Parikh@man-es.com