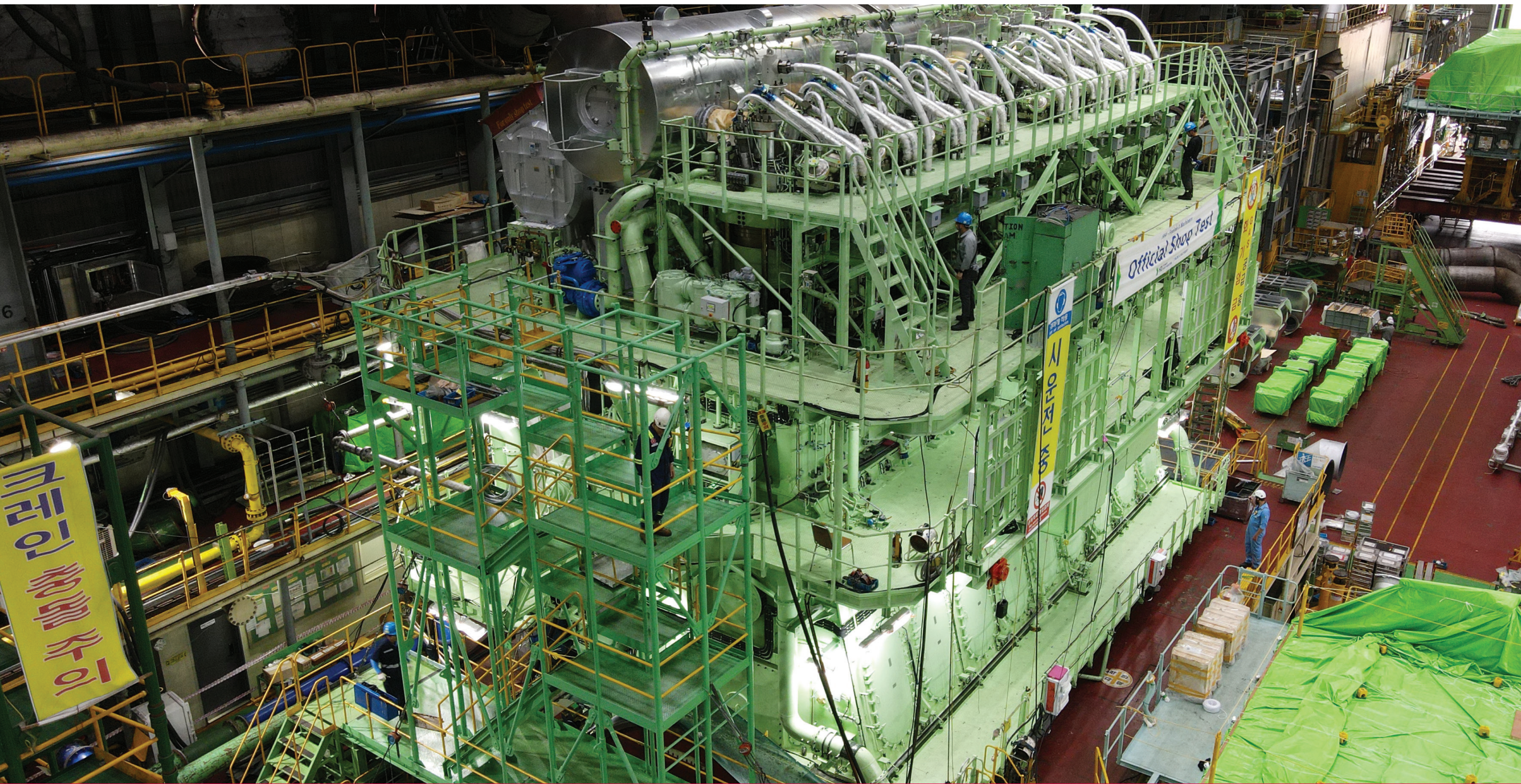
Everllence B&W
two-stroke
marine engines



Application, service experience and latest development of the ME-LGIM engine

The methanol-fuelled Everllence B&W ME-LGIM engine

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Cover photo: First 8G90ME-C10.5-LGIM engine during its official shop trials

The methanol-fuelled Everllence B&W ME-LGIM engine

The Everllence B&W ME-LGIM engine is the methanol-burning version of our dual-fuel solution for liquid injection of fuels, the ME-LGI engine. This paper describes the service experience from the two generations of ME-LGIM engines, which have accumulated more than 500,000 running hours in total.

In the further development of the LGIM engine, an updated engine portfolio is launched with more engine sizes and bores joining the methanol-fuelled family.

For the LGIM-engine, methanol as a drop-in fuel is readily achieved by blending increasing amounts of green or blue methanol. A net carbon-neutral solution that may co-evolve with an increasing production of green or blue methanol. The high uptake of the technology during the most recent years demonstrates that the industry believes in this fuel as a potential alternative for carbon intensity reductions.

This provides fuel flexibility for the ME-LGIM engine, and combined with the ability to burn green methanol, when available, the engine becomes advantageous for other vessel types as well and not only methanol carriers having the methanol on board already.

1. Developing dual-fuel Everllence B&W ME-LGIM engines

In 2012, Everllence decided to expand its dual-fuel engine portfolio by looking at low-flashpoint fuels (LFFs) and, as a result, the ME-LGI engine series were introduced. The Everllence B&W ME-LGI engine is the dual-fuel solution for low-flashpoint liquid fuels injected in liquid form into the engine. Fig. 1 shows the development milestones of the methanol-burning version of the ME-LGI engine, the ME-LGIM engine.

Since the introduction of the LGIM engine type, 158 engine orders have been registered (October 2023) covering practically every shipping segment. Moreover, more than 500,000 operating hours have been logged on these engines with positive results for shipowners and operators.

Like all Everllence B&W GI and LGI engines, the LGIM engine is based on the Diesel combustion principle. Utilising the Diesel principle ensures the methanol burning engine the same power output and efficiency as the ME-C fuel oil burning engine. In addition, the benefits apply in both methanol (dual-fuel mode) and diesel oil (compliant fuel only mode) operating modes. The engine power output is not affected by ambient conditions, and it is only slightly sensitive to the quality of methanol, which is currently benchmarked to International Methanol Producers & Consumers Association (IMPCA) [1].

Even though, initially, the list of orders was related to methanol carriers, the market shows an increasing interest in installing the engine in non-methanol carriers especially for the merchant tanker trade and the container market segment. many operators consider methanol as one of the future carbon-neutral fuels. Methanol is easy to handle, and it is stored and injected into the engine as a liquid, just as easily as conventional bunker fuels. The use of methanol as a fuel calls for a simple and cost-efficient fuel gas supply system (FGSS).

As for other types of Everllence B&W dual-fuel engines, that is as liquid natural gas (LNG) or ethane for the GI-engine and liquefied petroleum gas (LPG) for the LGI-engine, methanol has the potential as a retrofit solution for ME-C engines already in service. All ME-C engines are delivered as so-called ´dual-fuel ready´ engines. Therefore, in new projects, the engines are prepared for later conversion to dual-fuel independent of vessel application (tanker, bulk, container, etc.).

Shipowners operating the ME-LGIM engines are important marine players, such as Mitsui, O.S.K. Lines, Marinvest and Westfal-Larsen. More recently, in addition to the Proman Group and Stena Bulk, container carrier operators like AP Møller-Mærsk, CMA-CGM, Evergreen, and China Merchant Shipping, opted the ME-LGIM technology and added methanol references to their operating fleets.

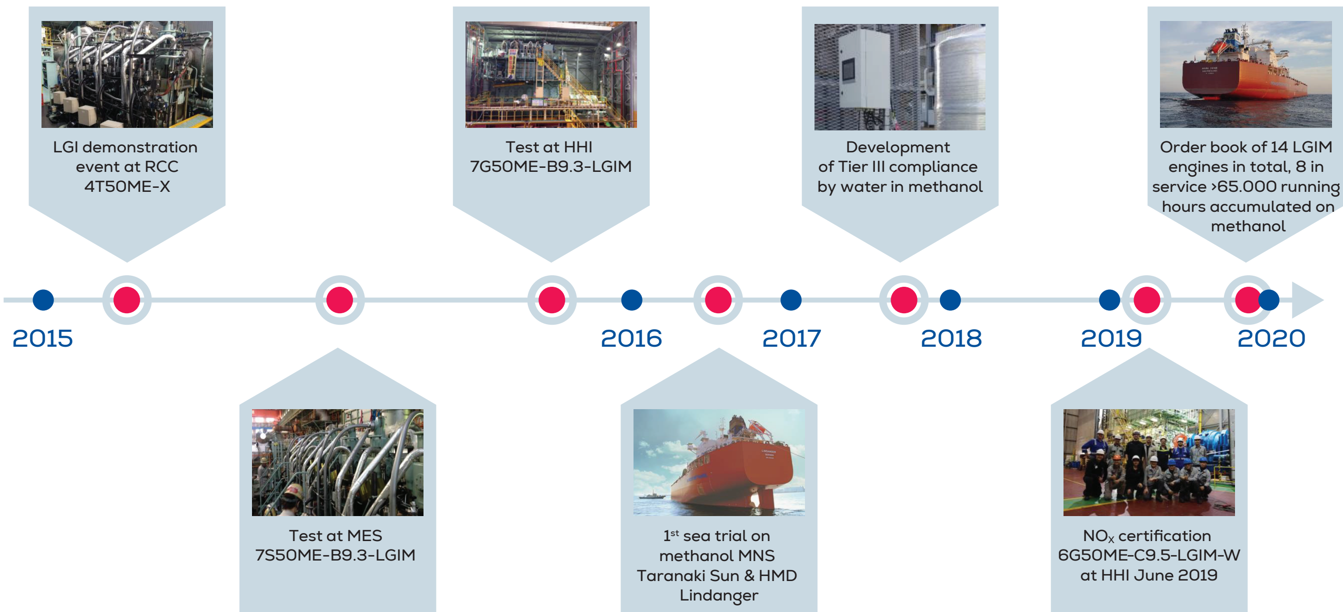


Fig. 1: ME-LGIM development milestones

2. Fuelling the ME-LGI engine

Contrary to the ME-GI engine, operating on fuel in a gaseous state, the Everllence B&W ME-LGI engine is the dual-fuel solution for low-flashpoint-liquid fuels. The ME-LGI engine is available in various versions depending on the choice of LFF type. Due to the differences in fuel properties, the ME-LGI injection system components and auxiliary systems will be different from those of the ME-GI engine. Despite these differences, the operating principle and safety concept of the ME-LGI engine are similar to those of the ME-GI concept.

Fuels for the ME-LGI engine are categorised by their vapour pressure at 60°C. The vapour pressure (and the related boiling point) is a fundamental physical property describing the transition between liquid and gaseous states. The boiling point has been included in Table 1 in the first column (energy storage type), i.e. for LPG, for example, to remain in liquid form it has to be cooled to below -42.4°C. If the temperature increases above the boiling point, additional pressure needs to be applied to maintain the LPG in liquid form. The pressure required to maintain the state of equilibrium between liquid and vapour states is the vapour pressure at a given temperature.

For comparison, Table 1 shows the characteristics of methanol, LPG, ammonia and hydrogen. Methanol is characterised by a low cetane number, lowering the self-ignition quality and requiring a small amount of pilot fuel (95% methanol and just 5% diesel pilot fuel).

As of November 2020, methanol has been approved and will be incorporated in the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF code) [2].

Energy storage type/ chemical structure	Energy content, LHV [MJ/kg]	Energy density [MJ/L]	Fuel tank size relative to MGO	Supply pressure [bar]	Flashpoint [°C]	Emission reduction compared to HFO Tier II [%]			
						SO_x	NO_x	CO_2	PM
Ammonia (NH_3) (liquid, -33°C)	18.6	12.7(-33°C) / 10.6 (45°C)	2.8 (-33°C) / 3.4 (45°C)	80	132	100	Compliant with regulation	~90	~90
Methanol (CH_3OH) (65°C)	19.9	14.9	2.4	13	9	90-97	30-50	11	90
LPG (liquid, -42°C)	46.0	26.7	1.3*1	50	-104	90-100	10-15	13-18	90
LNG (liquid, -162°C)	50.0	21.2	1.7*1	300		90-99	20-30	24	90
LEG (liquid, -89°C)	47.5	25.8	1.4*1	380		90-97	30-50	15	90
MGO	42.7	35.7	1.0	7-8					
Hydrogen (H_2) (liquid, - 253°C)	120.0	8.5	4.2		Not defined				

*1 assuming fully refrigerated media

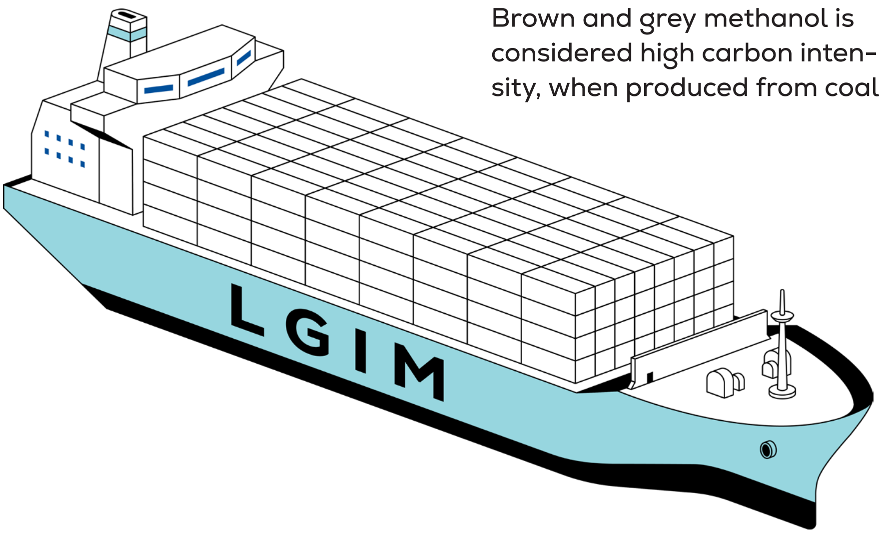
Table 1: Alternative fuel properties. Note that the values in the table show the emission reduction potential for fossil-based methanol, a much higher potential is available with the right feedstock, see chapter 3.

3. Methanol as a fuel has beneficial aspects

Methanol is interesting for ship operators because it contains no sulphur and is liquid in ambient air conditions. This makes it easy to store on board ships, similar to distillate fuels.

For ships operating in International Maritime Organization (IMO) emission control areas (ECA), methanol is a feasible solution to meet the lower-sulphur requirements and, by using the Everllence EGR, the very low Tier III NO_X requirements. When operating the two-stroke ME-LGIM engine on methanol, the SO_X, NO_X and particle emission reductions are similar to the reduction obtained by operating on LNG thanks to the lower working pressure, and the fact that methanol remains in liquid phase. However, installation costs are only a fraction of the costs for LNG.

Furthermore, methanol can be produced from biomass, municipal solid waste (MSW), or other biogenic matter, as well as via electrolysis and carbon capture, utilisation and storage (CCUS) technology, thus allowing for other "harder to decarbonise" industries such as cement, steel or even power generation to utilise their by-product, CO_2 emissions.



Producing and distributing bio-methanol and fossil-based methanol

Today's investment in power-to-X (PtX) is a clear demonstration of the possibilities and technologies available for producing synthetic and e-fuels, including methanol. The final product always has the same molecular basis, though it can have different colours (black, grey, blue and green) depending on the carbon source and the process utilised. Methanol, irrespective of the production pathway, is a clear liquid and an organic water-soluble chemical that is readily biodegradable.

- Black (or brown) methanol production is based on coal and is largely concentrated in China.

- Grey methanol is produced predominantly from natural gas by reforming the gas with steam, converting and distilling the resulting synthesised gas mixture to get pure methanol.

Brown and grey methanol is considered high carbon intensity, when produced from coal or natural gas without carbon capture (CC) or use of renewable power input.

- Blue methanol is produced from waste streams or by-products of other manufacturing processes, with the methanol produced considered renewable.

- Green methanol can be produced in different ways, all of which are CO_2 neutral:
  - Methanol produced from biomass or from the biodegradable part of production waste, for example wood.

  - Methanol produced from renewable energy sources like solar panels or wind power, the electricity is stored in the chemical bonds of methanol and later converted into energy. This method is termed green methanol synthesis.

Blue and green methanol are considered to have a lower carbon intensity when produced from fossil fuels combined with the use of renewable energy, carbon capture, or a combination of these.

Since methanol can be classified as either renewable or non-renewable, it has been defined what qualifies as renewable methanol: all feedstocks used to produce the methanol need to be of renewable origin (biomass, solar, wind, hydro, geothermal, etc.) [3].

Many vessels can function as bunker vessels if the interest in using methanol increases, with conventional methanol already available at over 115 of the world's top ports. Exact locations can be found via DNV GL's AFI Portal [4].

An indexed market price for methanol as a marine fuel is not yet fully established. However, Methanex (the largest global producer and distributor of methanol) suggests that the price has closely collated to that of MGO over the past five years on an energy equivalent basis. This being subject to the amount, the place where the methanol is sold, and the proximity to any of the major methanol storage hubs globally in Fig. 2.

The Methanol Institute has tracked more than 80 renewable methanol projects around the globe [5]. These are projected to produce around eight million metric tonnes of e-methanol and bio-methanol per year by 2027. Fig. 3 shows the projected production capacity expansion in the next few years.

Today, green methanol production only exists on a small scale, but an upscaling is possible for both bio-methanol produced from biomass, and e-methanol produced from green hydrogen from renewable power and biogenic CO_2.

Green methanol is in general regarded as a technologically scalable solution ready to make a clear impact in the near future. Green ammonia is also considered a promising future marine fuel.

The discussion and interest in methanol is increasing with its suitability as a sustainable marine fuel candidate, with many shipowners and class societies now of the belief it will capture a reasonable share of the future fuels market. Initially, conventional methanol will be adopted with increasing amounts of blue or green methanol being blended in, and further reducing its CO_2e footprint. It is expected that, eventually, more blue and green methanol than grey will be produced, likely post-2040.

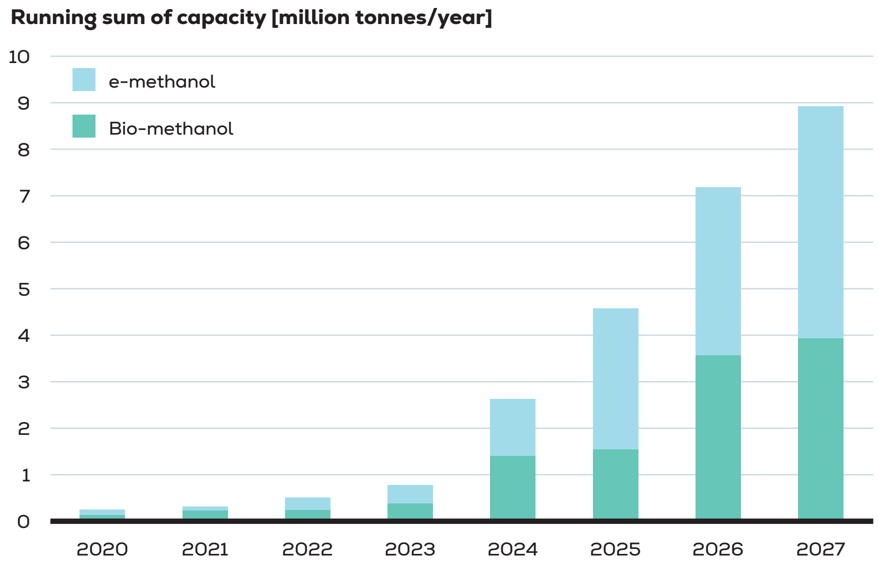


Fig. 3: Global production distribution of methanol projects (The Methanol Institute)

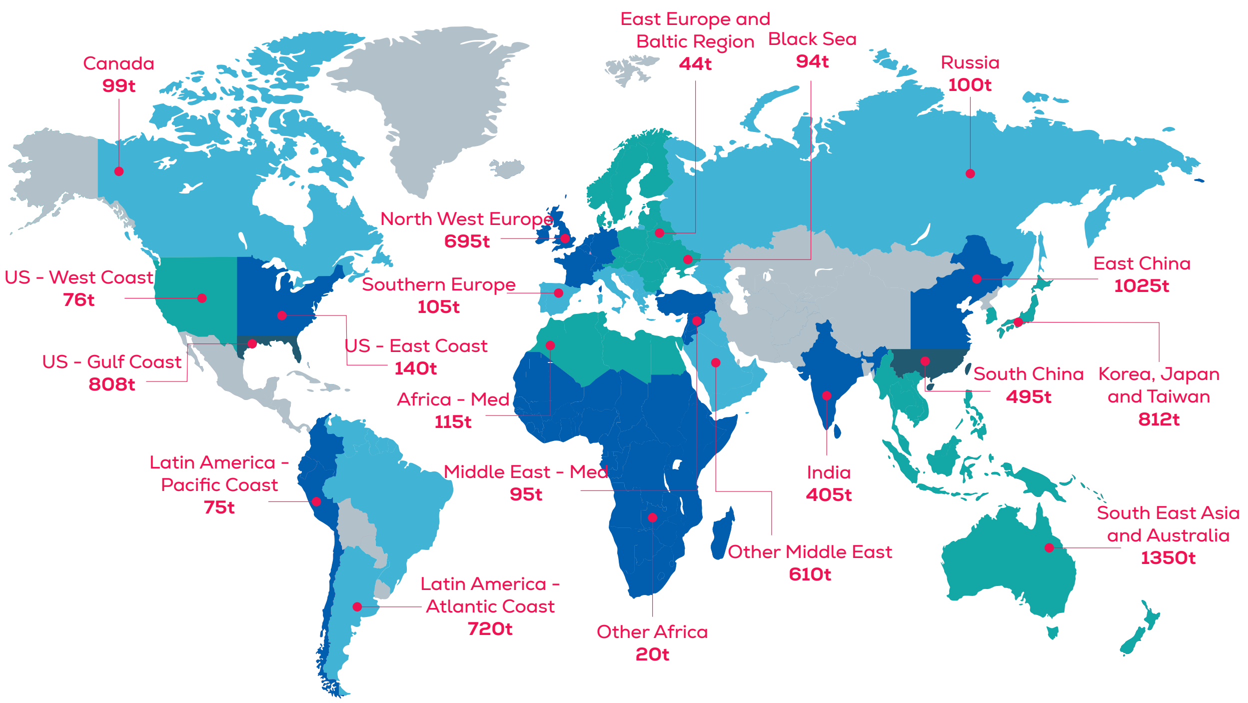


Fig. 2: Methanol storage hubs worldwide (courtesy of the Methanol Institute)

Representing the world's leading methanol producers, distributors, and technology companies, the Methanol Institute serves as the trade association for the global methanol industry to promote the use of methanol for numerous applications.

The explanatory illustration from the Methanol Institute in Fig. 4 shows some of the production pathways of methanol and the advantages of marine application of methanol.

Methanol as a drop-in fuel can co-evolve with green methanol production

Methanol, as a sulphur-free fuel, is fully compliant with the 2020 IMO low-sulphur regulation. Low-sulphur compliance is not the only beneficial reason for adopting methanol though, as the lower CO_2 formation (up to 7% lower than HFO) during the combustion process is also advantageous. Furthermore, since the methanol molecule contains no carbon-to-carbon bonds, it does not produce particulate matter or soot when burned.

With IMO's CO_2 and greenhouse gas (GHG) targets for 2030 and 2050, the number of drop-in fuels is expected to increase during the transient period (initially to 2030 and subsequently to 2050), towards a lower carbon footprint. For the LGIM-engine, methanol as a drop-in fuel is readily achieved by blending increasing amounts of green or blue methanol with grey methanol (conventional methanol using natural gas as a feedstock and steam methane reforming technology) until, eventually, the lower carbon methanol becomes the main fuel. This is a net carbon-neutral solution that may co-evolve with an increasing production of green or blue methanol and gradually assist the industry in meeting the IMO's target for CO_2 and GHG emissions.

This provides fuel flexibility for the ME-LGIM engine, and combined with the ability to burn green methanol, when available, the engine becomes advantageous for other vessel types than methanol carriers having the methanol on board already. As methanol is easily bunkered, this is in a very similar method as diesel.

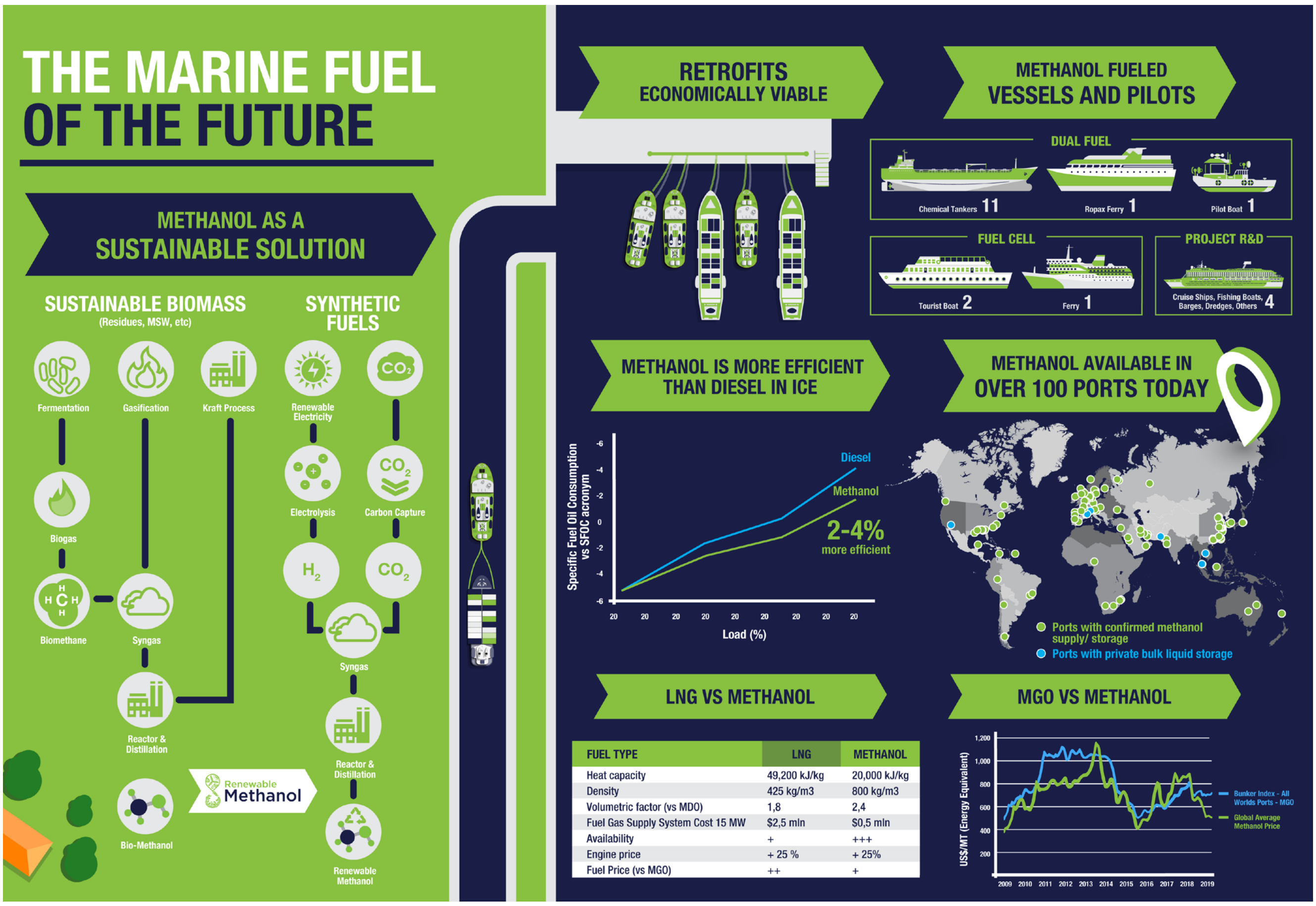


Fig. 4: Methanol as the marine fuel of the future (courtesy of the Methanol Institute)

4. Vessel design considerations

In December 2020, the MSC.1/ Circ.1621: Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel were accepted by IMO, and the design principles for methanol-fuelled container vessels were based on this regulation.

The background of the guideline was the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC) and the IGF code based on LNG. Throughout the design process, some adjustment of MSC.1/Circ.1621 has been deemed necessary as there are some significant differences between LNG and methanol. For example the gaseous nature of methane at ambient conditions, whereas methanol is a liquid.

The main principles governing the vessel design for methanol operation are illustrated in Fig. 5.

The main design principle, as for LNG, is that the fuel must always be handled using the double-barrier principle. Any methanol fuel must be protected by a double barrier towards any area where a methanol fuel leak could be ignited. These are areas such as the engine room, cargo space, etc.

This entails that any engine room piping containing methanol has a ventilated outer barrier piping system. Furthermore, equipment to prepare the methanol before injection into the engine must be placed outside the engine room using Ex-classed equipment. Fuel storage tanks must have cofferdams towards any engine room or cargo space.

Any of the barriers and rooms with a risk of methanol leaks is equipped with high-capacity ventilation and gas and leak detection systems.

In addition, all areas with methanol are covered by fire-fighting systems such as CO_2, and alcohol-resistant foam systems capable of handling methanol fires.

Bunkering of methanol

The MSC.1/Circ.1621 guideline also describes bunkering. Fig. 6 shows the guiding layout of a bunker station.

The MSC.1/Circ.1621 guideline defines the use of a dry-disconnect type bunker station equipped with an additional safety dry break-away coupling/self-sealing quick release to reduce risk of any spillages. Maersk has optioned for the NATO standard STANAG 3756 and the tanker standard OCIMF Linked Ship/Shore Emergency Shutdown Systems for Oil and Chemical Transfers 1st Edition 2017 to rely on a ship-to-ship linkage using existing standards as much as possible [6], [7].

Because of the uncertainties related to green methanol fuel supply, and the design of the initial supply or bunker vessel, the bunker station has been designed as an independent unit in terms of requirements for lifting appliances for bunker hose handling, etc.

This means that vessels can bunker methanol from a vessel without using the normal bunker hose crane on the bunker vessel. The bunker station design enables the initial use of a small chemical tanker for bunkering until the supply chain of green methanol has been established.

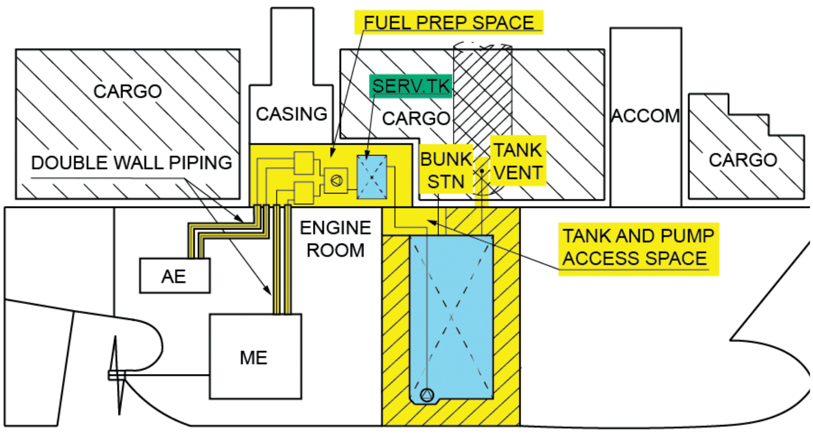


Fig. 5: Vessel design principles

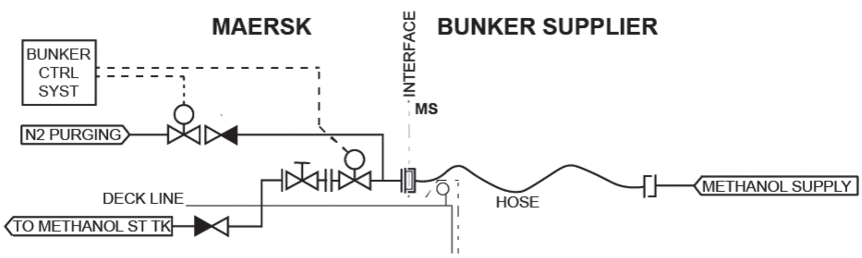


Fig. 6: Bunker station layout

Design challenges

Since the MSC.1/Circ.1621 guideline originates from previous IGC and IGF guidelines characterised by the use of LNG as a fuel, some parts of MSC.1/Circ.1621 would benefit from a further adaption towards methanol.

One important example is the ventilation requirement for hazardous rooms, such as the fuel preparation room, which includes 30 air changes per hour and a gas detection level at 20% of the lower explosion level of methanol, or 10,000 ppm.

These guiding settings in the IGF code are defined for leaking methane gasses from a 300 bar pressurised gas pipe. In comparison, the main supply for the methanol two-stroke engine will be liquid methanol at 13 bar, where a leak will slowly evaporate into a methanol vapour.

Calculations show, that even a very large leak and pool of methanol will not be detected by the guiding settings, and detection levels have therefore been reduced together with a reduction in air change requirements.

Design compliance

IMO requirements towards the technical design capabilities of a ship design have been in place for decades. In relation to the propulsion plant, a regulation towards the manoeuvring capabilities was also introduced. Regulations on NO_x and SO_x emissions came later, and in the past decade the energy efficiency design index (EEDI) saw the light of day.

Everllence B&W two-stroke engines are designed to match and comply with this legislation to attain design compliance. Adjustments are continuously performed to offer shipyards viable engine selections for various phases of the EEDI.

Functionalities like the dynamic limiter function (DLF) [8] and the adverse weather condition (AWC) functionality [9] are examples of development measures taken in response to the EEDI. These ensure that also low-powered, EEDI-compliant ships have sufficient acceleration capabilities, and that they can attain compliance with minimum propulsion power requirements [10] by extending the engine load diagram.

Until now, these regulations have been imposed on a single design level, as illustrated in the left part of Fig. 7. Once verified in the design and demonstrated on sea trial, compliance with these regulations has been in place for the lifetime of the ship. Later, the existing ship energy efficiency design index (EEXI) was introduced to cater for the existing fleet of high-powered ships.

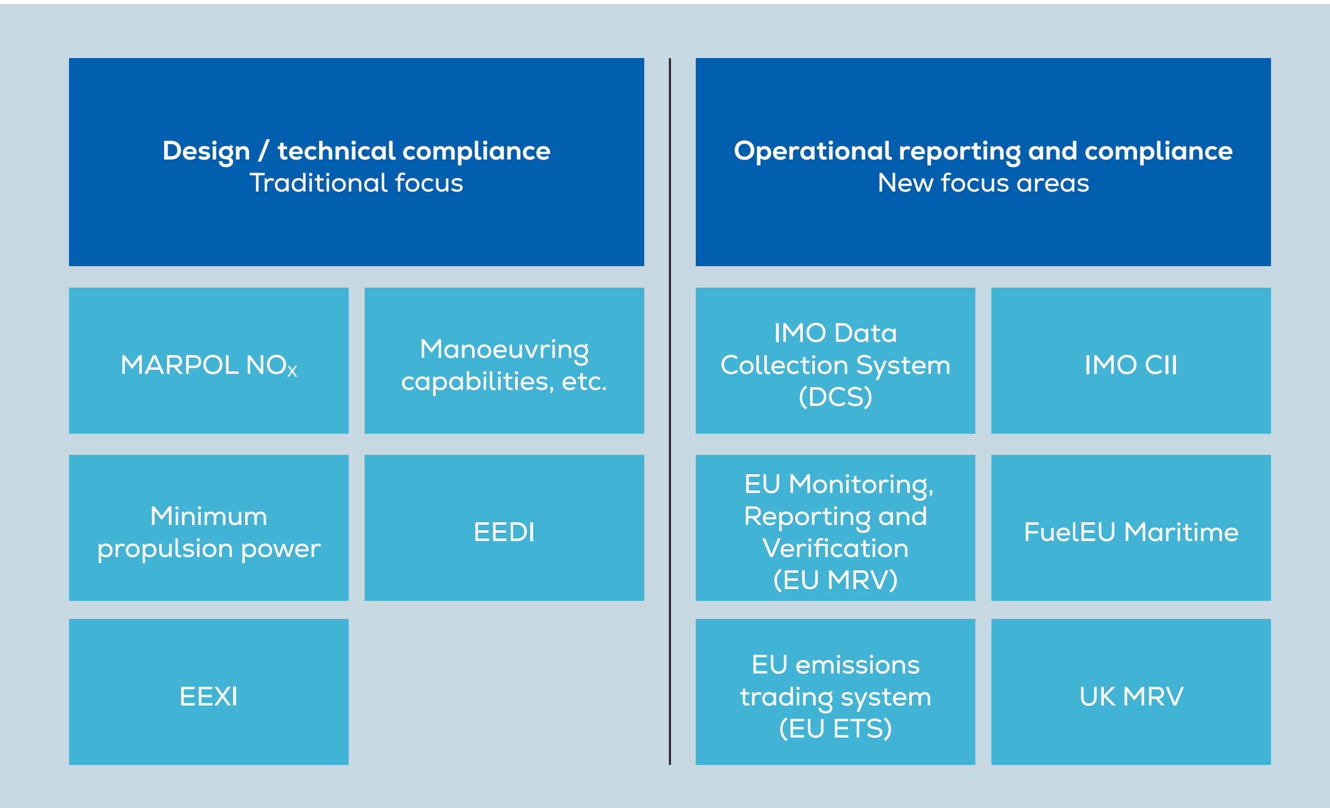


Fig. 7: Design and operational compliance scheme grouped

Operational compliance schemes
To limit the emission of carbon dioxide, the legislation now transitions from considering design compliance only, towards also setting requirements to and evaluating the actual operation of the ship. Both globally for the individual ships, and in some regional cases for a fleet as a whole, as outlined by the three different schemes:

- IMO CII
- EU emissions trading system
- FuelEU Maritime.

IMO CII
The CII [11] is a prime example of a regulation on energy consumption of ships in service. The CII rates ships (Fig. 8) according to the annual carbon dioxide emissions divided by the annual transport work performed, expressed as the deadweight tonnage multiplied by the distance travelled.

Reductions are evaluated by comparing with 2019 as the basis, and tightened by 2% annualy until 2026, after which further reductions are to be decided, see Table 2.

The CII considers emissions on a tank-to-wake basis for the individual ship, see Fig. 9 and Eq. 1.

Hereby, the CII rating expresses the actual fuel consumed, the carbon emitted, and the individual distance travelled. In this scheme, on-board efficiency is important, since a reduction of the fuel consumed directly impacts the rating attained. Likewise, the carbon content of the fuel used has a direct effect on the attained CII.

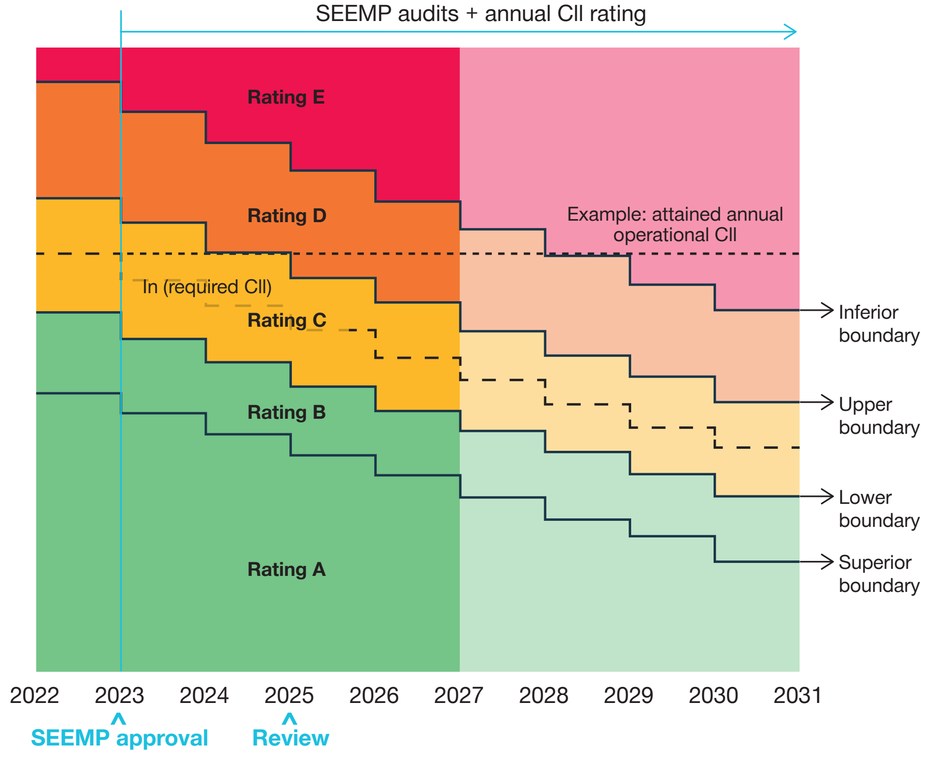


Fig. 8: CII and ratings. Reductions to 2027 agreed, reductions beyond 2027 are to be agreed by the 2025 review (MEPC.338(76))

Year	2023	2024	2025	2026	2027
Reduction from 2019	5%	7%	9%	11%	To be decided

Table 2: CII reduction rates relative to 2019

$$CII = \frac{\text{Annual fuel consumption} \times C}{\text{Annual distance travelled x capacity}} \times \text{Correction factors}$$

Eq. 1: Calculation of the CII

Thus, a strict tank-to-wake approach implies that the CII rating will not improve by operating on biodiesel. A tank-to-wake approach only considers emissions from burning the fuel on board and not any carbon uptake, nor emissions, from the production of the fuel.

However, at its 80th meeting, the IMO MEPC agreed to allow accounting for biofuels in the CII in accordance with the following conditions:

- If the biofuel demonstrates a certifiable GHG saving of minimum 65% compared to fossil MGO, the carbon factor (Cf) of the biofuel can be multiplied by 0.35.
- If the GHG saving is documented to be higher than 65%, the Cf can be reduced accordingly.
- The GHG saving must be certified by a certification scheme recognised by the International Civil Aviation Organization.

This interim guidance for biofuels will be rewoked when IMO has finalised and agreed on guidelines on how to perform life cycle analysis (LCA) of fuels. Establishing a life cycle guideline is part of establishing the IMO mid-term measures, to avoid shifting emissions to other sectors, and these are expected to be in place by 2027.

Low-carbon fuels lower the energy efficiency design index

The Paris Agreement and similar governmental and intergovernmental agreements call for a carbon reduction of crucial industries, like shipping, which paves the way for new fuels. Methanol is an excellent potential alternative. As early as 2013, IMO decided to adopt the EEDI as the mandatory instrument to limit CO_2 emissions for ships built later than January 2013. This has influenced the engine market and the technical solutions faster than anticipated.

Fig. 9: Emission scopes: tank-to-wake, considering on-board emissions, well-to-wake, considering upstream emissions from the production of the fuel as well

To lower the EEDI, alternative low-carbon fuels such as natural gas (LNG), LPG, and methanol are serious candidates to becoming the future fuel. By nature, LNG, LPG, and methanol generate less CO_2 during combustion than fuel oils. Furthermore, methanol is interesting because bio-methanol and e-methanol can be made from a vast variety of biomasses and renewable energy feedstocks, and be mixed with methanol made from fossil fuels.

In October 2020, IMO's intersessional GHG working group introduced short-term measures to address [12-15]:

- Technical (i.e., design): Energy efficiency for existing ships (EEXI) - EEDI applied to existing ships
- Operational: Enhanced ship energy efficiency management plan (SEEMP) with mandatory carbon intensity indicator (CII) rating scheme (A-E) as in Fig. 10
- Measures consolidated into a single package; the outcome is a finely balanced political compromise
- As approved at MEPC 75 in November 2020: Entry into force is expected on 1 January 2023.

Furthermore, IMO will implement the EEXI technical measure, in a goal-based fashion, to ensure that the sector does not miss its targets. In this respect, both requirements and specific guidelines for the calculation of the EEXI will be adopted, see also Fig. 11 [12-15].

Requirements

- All cargo and cruise ships above size thresholds on first annual survey after 1 January 2023 (same ship types and sizes as for EEDI): attained EEXI to be below required EEXI
- Required EEXI is equivalent to EEDI requirements early 2022 (Phase 2/Phase 3) – with some adjustments

Calculating EEXI

- Existing ships determine their EEXI using the same method as for EEDI, with further options available for determining speed
- Goal-based: Operators decide how to achieve target (engine power limit, fuel change, energy saving devices, retrofitting and/or any other options)
- Engine power limit can be overridden: allows for extra power in an emergency.

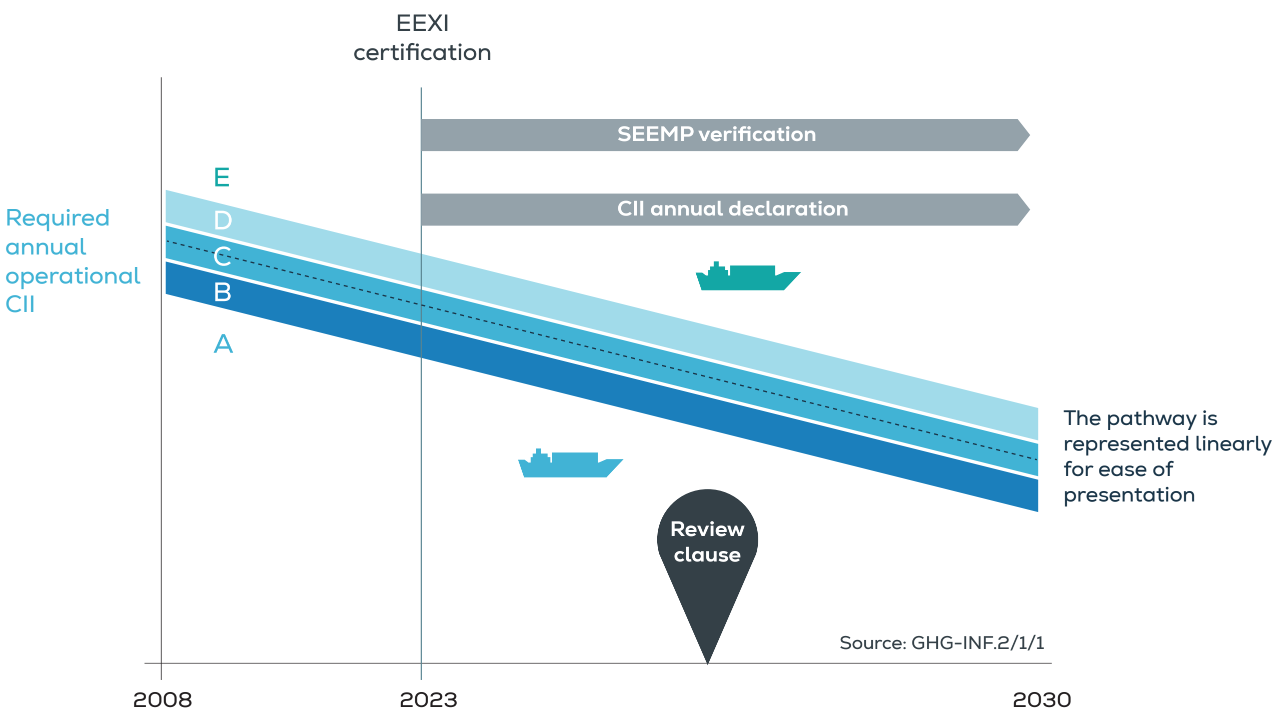
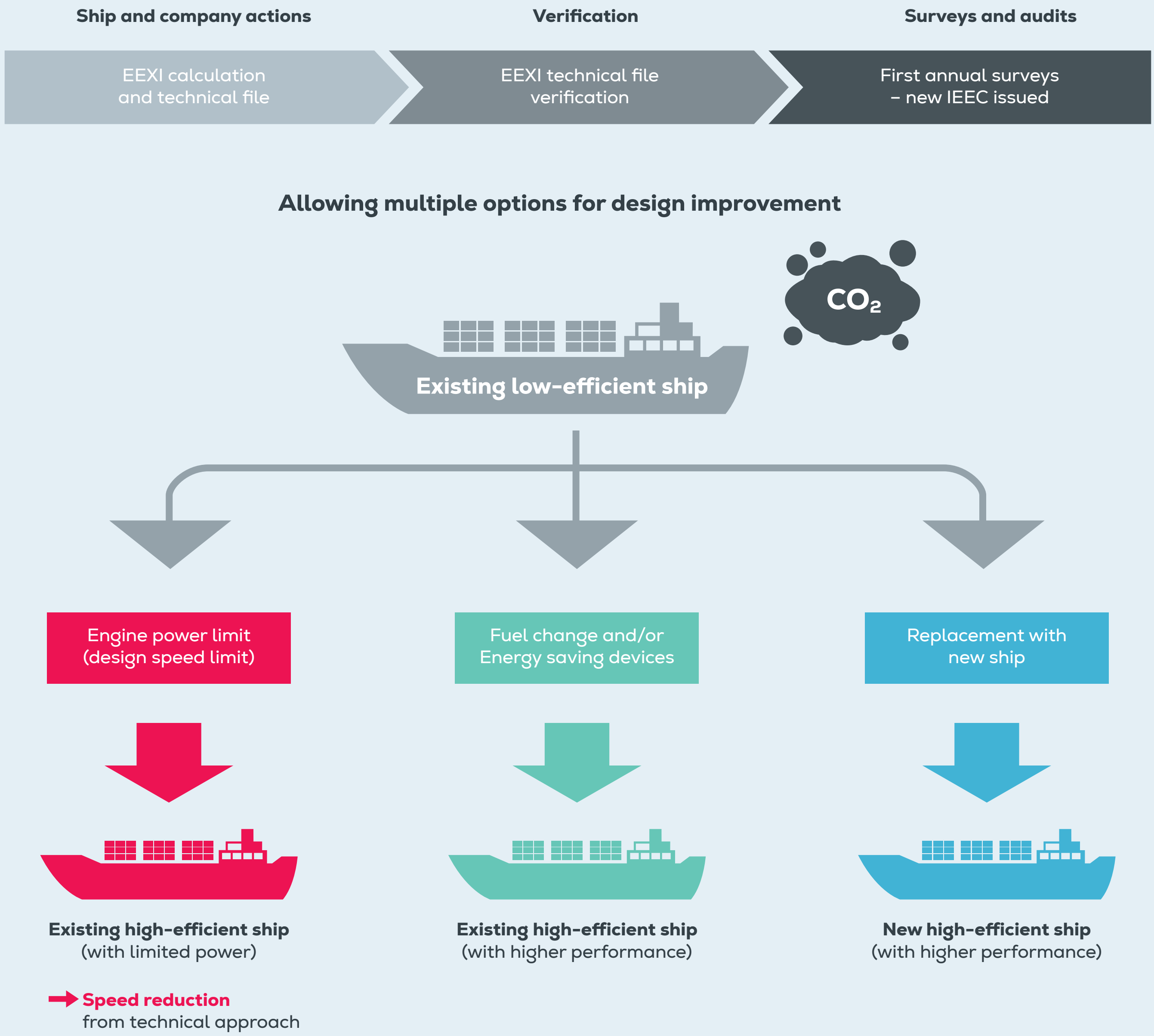


Fig. 10: Enhanced SEEMP with mandatory CII rating scheme (A-E) [12]



Ship type	Required EEXI (Reduction from EEDI reference line)
Bulk carrier	Δ15-20% by size
Tanker	Δ15-20% by size
Container	Δ20-50% by size
General cargo	Δ30%
Gas carrier	Δ20-30% by size
LNG carrier	Δ30%
Reefer	Δ15%
Combo	Δ20%
Ro-ro/ro-pax	Δ5%
Ro-ro (vehicle)	Δ15%
Cruise ship	Δ30%

Fig. 11: EEXI obtained through different design improvement options: engine power limit, fuel change and energy saving devices [12]

5. Latest ME-LGIM engine design considerations

Since the first engine tests made in Copenhagen and at our licensee Mitsui, vessels have been in operation and further developments of the LGIM-engine design have been completed. Furthermore, in line with the frequently used development process, a number of concept verification tests have been carried out at the Research Centre Copenhagen (RCC). In this paper, we will explain the LGIM concept and discuss the verification test results of the ME-LGIM engine.

The ME-LGIM engine has inherited well-known aspects and features of the standard Everllence B&W two-stroke diesel engine, like the ME-GI dual-fuel engine. The LGI and GI concept engines are based on the conventional, electronically controlled ME-C engine with dual-fuel injection integrated as add-on parts. Beneficial features of our standard two-stroke diesel engine have been passed on, including options for: optimising the engine layout for high-load or part-load operation, derating the engine, and combining the engine with power take-off (PTO) and waste heat recovery systems (WHRS).

Fig. 12 highlights components added on the cylinder top for methanol combustion.

The functionalities of the ME-LGIM concept include:

- Unit injectors, the LGI fuel booster injection valves for injection of methanol (FBIVM) into the combustion chamber around the top dead centre (TDC)
- Hydraulic control systems to control the LGI fuel booster valve operation
- Sealing oil supply unit mounted on the engine to ensure that no methanol leakage occurs in the moving parts of the methanol injection system
- Double-walled piping to distribute methanol to the individual cylinders
- Draining and purging system for quick and reliable removal of methanol from the engine
- In addition to the engine control system (ECS), a safety system monitors the methanol injection and combustion, and ensures that the engine reverts to diesel oil operation in case of alarms
- Fuel valve train (FVT) provides a block-and-bleed function between the fuel supply system and the engine
- Fully automated methanol supply system with an embedded purge system.

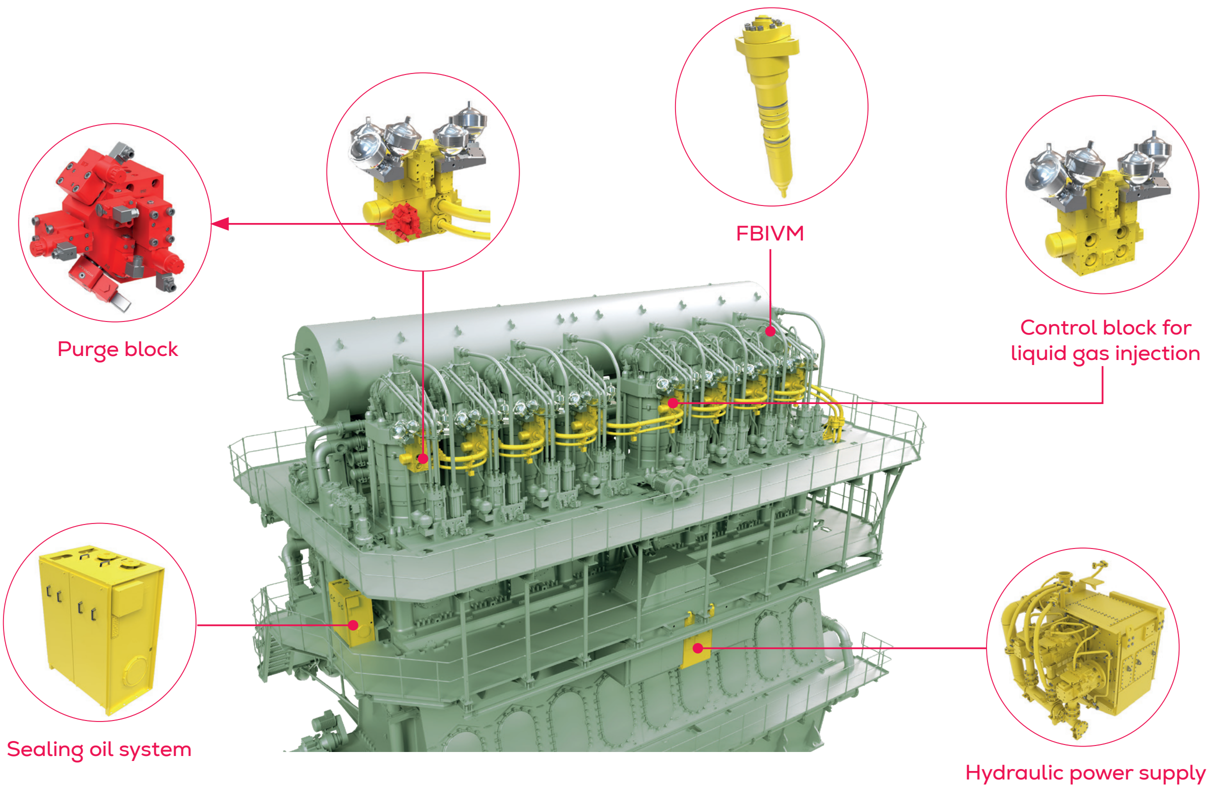


Fig. 12: LGIM engine and the main LGIM system components

The design of the methanol supply pipes in Fig. 12 is based on a double-barrier concept. It means that a second layer encapsulates all methanol piping in the engine room. This outer-piping is ventilated to the outside to eliminate the risk of a methanol leakage to, for example, the engine room and to allow detection of a leakage from the inner pipe with hydrocarbon (HC) sensors.

The diesel fuel system has not been altered significantly on an LGI engine compared to a standard ME engine. As is the case for the ME-GI, the ME-LGI fuel system can change to fuel mode, burning diesel oil or VLSFO from one stroke to the other without any limitation in speed or load.

As the LGI functionality is an add-on to the electronically controlled ME engine, converting an existing diesel engine to a dual-fuel engine capable of using both diesel, VLSFO and, for example, methanol is possible.

Injection system

Fig. 12 shows the ME-LGIM cylinder cover with components for methanol injection (FBIVM, fuel and hydraulic control blocks) and the supply for FBIVM passing through the cylinder cover. Fig. 13 shows the methanol booster injection valve for the ME-LGIM engine.

The FBIV 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 FBIV uses hydraulic pressure to increase the methanol pressure to the required injection pressure of approximately 600 bar. A suction valve (check valve) ensures filling of the pump chamber after each stroke. The methanol supply pressure lies within 13±0.5 bar. A small pilot injection from the diesel fuel system ignites the methanol. In the tests presented in this paper, the fuel injection valves are positioned clockwise from the LGI FBIVs in order to optimise the ignition of the methanol fuel jets.

The ME-LGIM system contains several internal safety features. The fixed pump-chamber-volume design of the FBIV limits the amount of fuel that can enter the cylinder during each stroke, which eliminates the risk of injecting too much fuel.

The parts of the FBIV, where hydraulic oil and methanol could potentially mix, are specifically designed to minimise this risk with sealing oil added at critical points. The drained used sealing oil is recirculated to a separate tank in the sealing oil unit mounted on the engine, which handles a potential methanol contamination in a safe way.

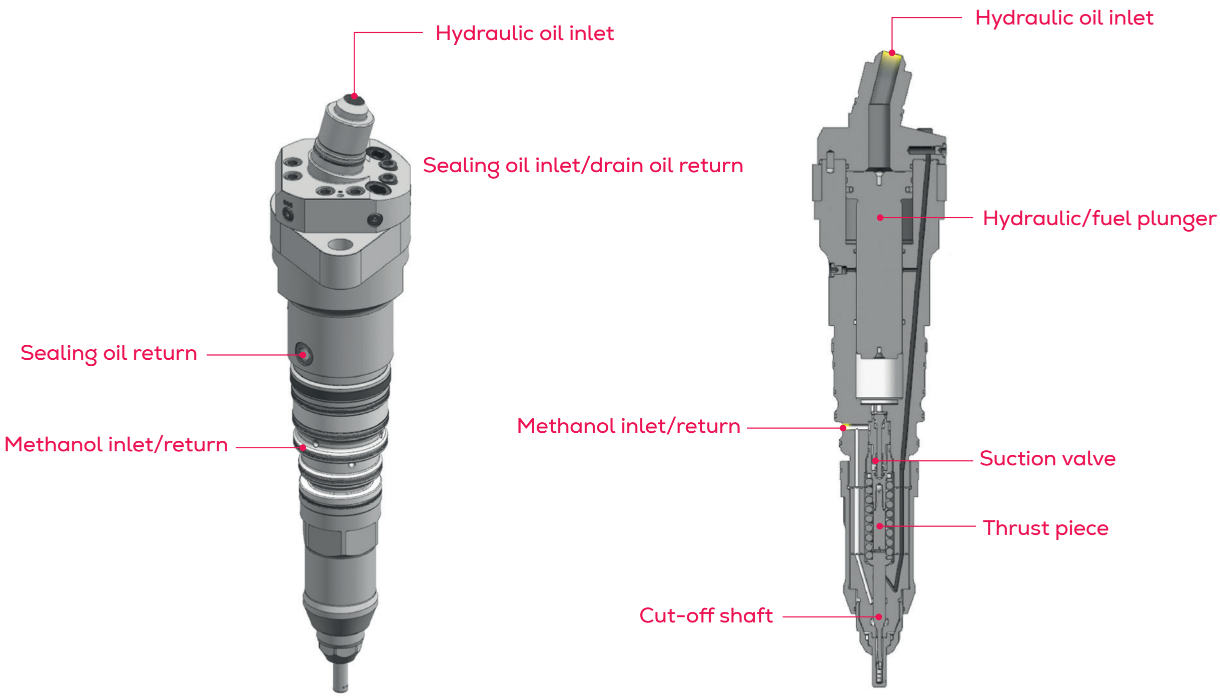


Fig. 13: Graphic (left) and cross-section (right) showing the latest FBIVM design and points of interest

6. Engine auxiliary systems

As part of the responsibility as an engine technology provider, Everllence provides the design specifications for the yards, which consist of requirements for the auxiliary systems of the dual-fuel engines. It is a design based on safety, redundancy, reliability, and safe operation for the crew.

The specifications have been risk assessed in a HAZID/HAZOP process, which is a process involving classification societies, engine builders, yards, and companies providing fuel supply system skids (pumps, filters, valves, etc.).

Methanol is liquid at atmospheric pressure and temperature, and it can be stored in a coated steel tank, as opposed to methane, ethane, LPG, synthetic natural gas (SNG), and ammonia, which need cryogenic conditions.

Fig. 14 shows the complete auxiliary system split in three sections, which can be delivered on skids: tank, low-flashpoint fuel supply system (LFSS), and FVT. The tank section is the simplest of the sections.

Methanol service tank design

Fig. 15 shows the methanol tank design, and the division of the tank in two compartments: a return compartment and a fuel compartment for supply during engine operation.

Methanol returned via the low-pressure return system during flushing and purging of the methanol pipes contains small amounts of sealing oil. The service tank is split to prevent accumulation of sealing oil in the fuel compartment, instead the returned methanol is recovered via the return compartment.

The two compartments are separated by a spill-over bulkhead. Gravity differences separate the returned methanol and sealing oil. The lighter methanol can flow from the return compartment to the fuel compartment with clean methanol.

Typically, the LFSS specifies the inlet requirements to be met by the tank section skid/pump in terms of methanol delivered with an adequate net positive suction head (NPSH). A low-pressure (LP) pump in the tank section is sufficient to meet this requirement.

Low-flashpoint fuel supply system

The LFSS contains high-pressure pump(s), heaters/coolers, and a duplex filter. The purpose of the LFSS is to condition the fuel so it meets the inlet requirements of the engine, which are temperature, pressure and purity. The fuel supply system should be designed to reduce engine downtime when running on a given fuel. Therefore, it is mandatory to integrate a duplex filter in the fuel supply system.

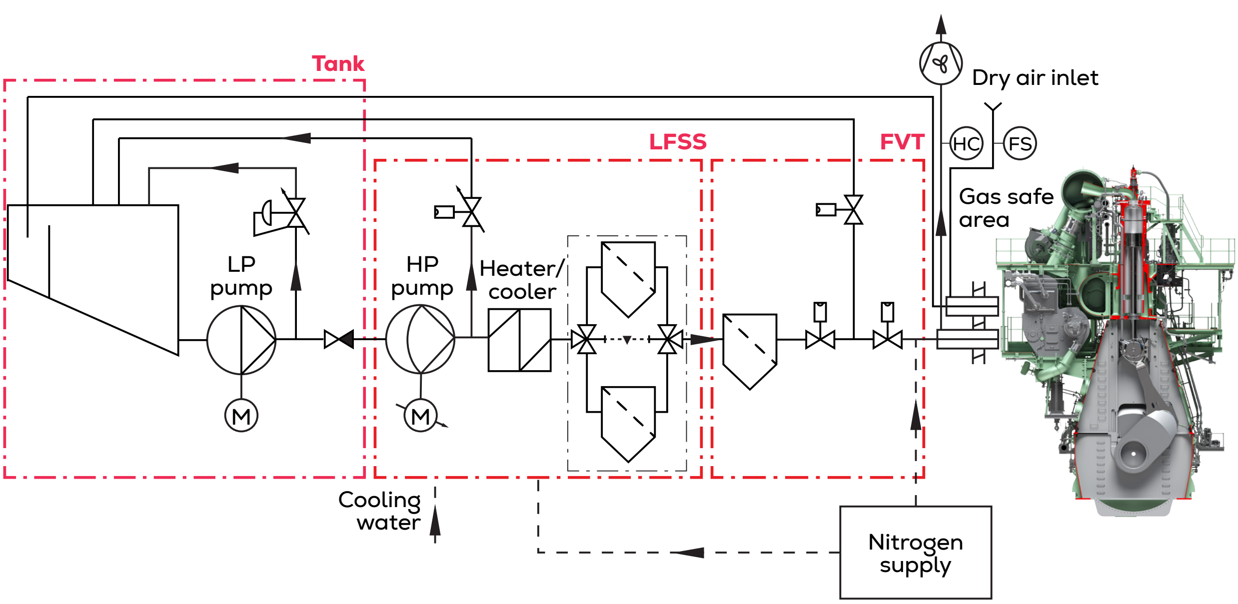


Fig. 14: Methanol fuel supply system divided into three sections

Fuel valve train

The function of the FVT is to separate the fuel supplier (LFSS) from the consumer (main engine) by a double-block-and-bleed arrangement to meet IMO requirements.

The FVT is designed to enable the block valve closest to the fuel supply system to be used as a master valve. Fig. 14 shows that the FVT is also connected to a nitrogen source for purging purposes which is also separated from the methanol line by a double-block-and-bleed configuration (not shown in Fig. 14).

The system contains a nitrogen double-block-and-bleed valve connection in the FVT for purging of the main engine, which is a mandatory part of the main engine safety philosophy. Furthermore, the FVT has a nitrogen double-block-and-bleed connection for purging of the LFSS upstream the FVT.

Sequences and safety

The entire ME-LGIM fuel system, including the FVT, is pressure-tested with nitrogen as part of the start-up procedure. When the conditions for methanol operation have been established, a process controller or the engine control system activates the FVT, and methanol is supplied to the engine.

Air is circulated in the outer piping of the double-walled pipes, while methanol is kept in the inner pipe, throughout the entire fuel supply/return system. If a fuel leakage occurs, a hydrocarbon sensor detects the presence of methanol in the circulated ventilation air and automatically switches the engine from methanol operation to operation on fuel oil, distillate, ULSFO, or VLSFO. When methanol operation terminates, the fuel pipes are purged clean of methanol by applying a sequence of purges using a pressurised flow of nitrogen. When methanol has been returned to the service tank, pulse purging and inerting are conducted in the inner pipe of the double-walled piping system.

A safety procedure is initiated in a hazard situation, and the FVT momentarily shuts off the methanol supply by closing the double-block-and-bleed arrangement. All piping is emptied of methanol and purged, and the ventilation is turned off.

Methanol operation reduces emissions

Compared to the combustion of fossil fuels, methanol operation reduces the average CO_2 content in the exhaust by 10%. In addition, methanol operation reduces particulate matter by approximately 90%, SO_X by 90–97%, and NO_X by 30–50%.

An engine design with exhaust gas recirculation (EGR) is available for methanol engines for Tier III operation. It enables an optimal control of engine performance and exhaust gas emissions.

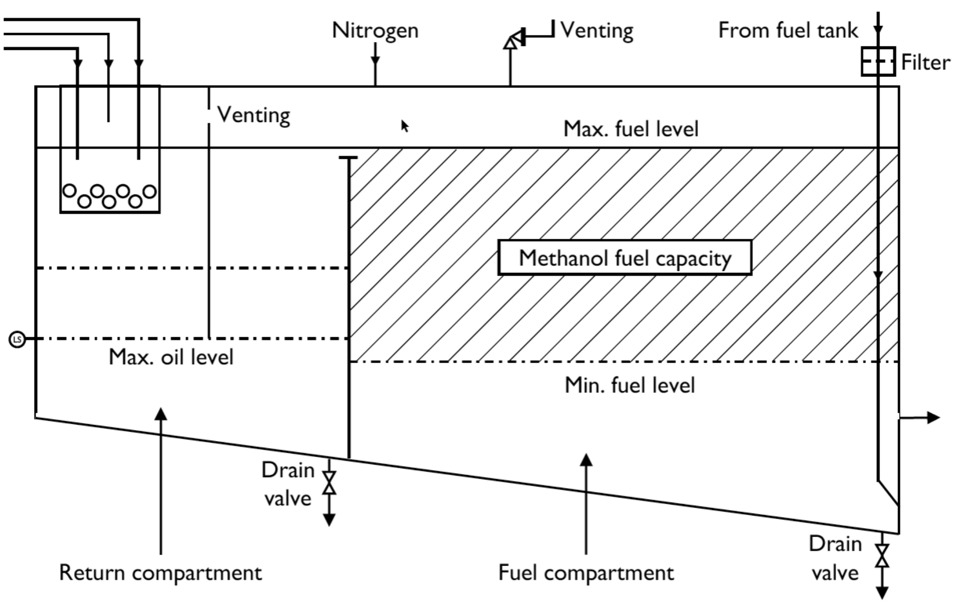


Fig. 15: Methanol tank design

7. Performance results

In the spring of 2015, the first functionality tests of LGI sub-systems and the initial performance tests were conducted on the 4S50ME-T9 test engine at Mitsui's Tamano shipyard in Japan. These tests confirmed the LGIM design applied on the 26 ME-LGIM engines sold as of October 2020.

Fig. 16 shows an ME-LGIM engine installation onboard a vessel.

Injection system layout

Initially, the chosen spray directions of the nozzle holes of the LGI methanol injector were similar to that of the standard diesel injector, and the dimensions of the LGI injector were laid out so that the injection duration of methanol at MCR would be roughly similar to that of the standard diesel layout.

As Table 1 shows, the lower calorific value (LCV) of methanol is as low as 19.9 MJ/kg, which is roughly half that of the ISO standard value 42.7MJ/kg for diesel oil. Furthermore, the methanol injection pump has been designed for a nominal injection pressure of about 600 bar, being somewhat lower than that of the standard fuel oil (MGO/HFO) injection system. Thus, if the initial goal is equal injection durations of methanol and diesel oil, the LGI injector must have more than twice the total nozzle-hole area of the standard diesel injector. However, results from small scale combustion chamber testing indicated that such simple scaling would lead to too large injectors, and in the initial tests, the effective nozzle flow area of the methanol injector was chosen to be roughly twice that of the diesel injector.

Cylinder pressure measurements

The performance diagrams in this section were obtained from the latest ME-LGIM engine that went into service.

Fig. 17 shows the cylinder pressure and the corresponding calculated heat release for 100% load.

Two cases are compared in Fig. 17: the diesel fuel combustion in black and methanol (LGIM) combustion in red. Note that the methanol combustion includes a small diesel pilot oil amount as well. The cylinder pressure traces of the two modes are similar, but with some intentional differences. The methanol injection starts earlier and reaches a slightly higher maximum pressure, while the heat release is also slightly longer due to a longer injection duration. This combination leads to a lower methanol consumption, which has been achieved by actively optimising the methanol mode for this very purpose.

Furthermore, the late cycle heat release rate for methanol decreases faster, indicating that the methanol combustion ends earlier. In theory, this also gives a better thermodynamic efficiency for methanol relative to the diesel reference. The

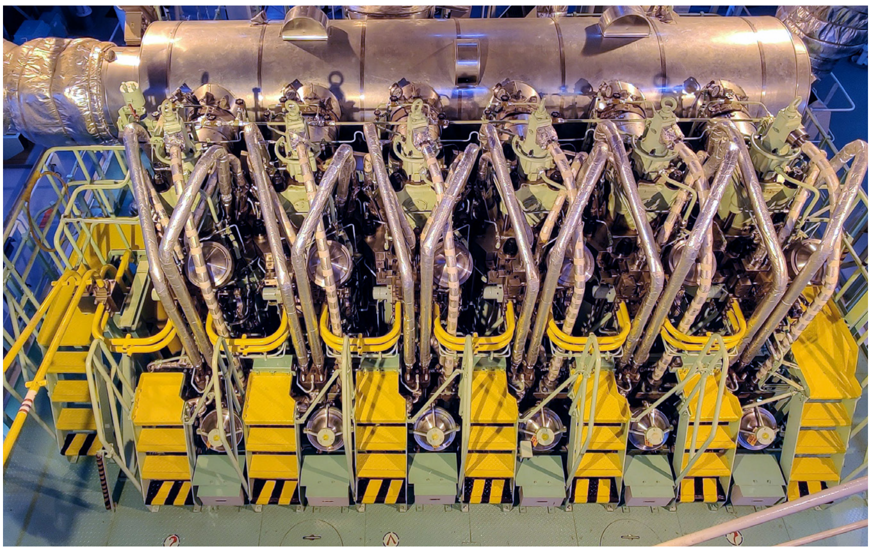
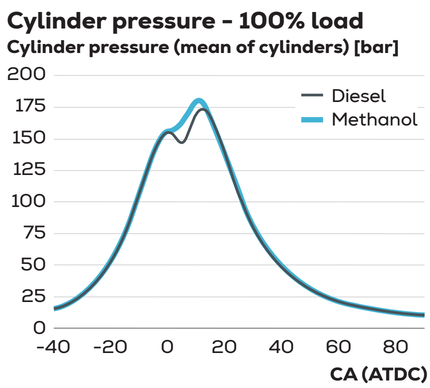


Fig. 16: ME-LGIM engine top



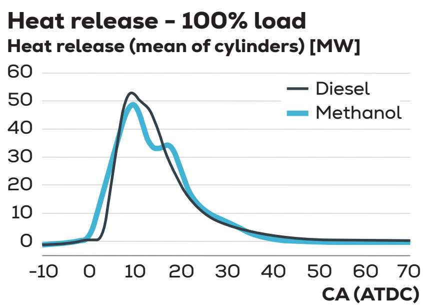


Fig. 17: Cylinder pressure (top) and heat release rate (bottom), both for reference diesel operation (black) and methanol operation (red) at 100% load

first reason that the methanol combustion ends earlier is the larger injected mass of methanol, giving a higher mixing rate. The second reason is the intrinsically high oxygen content in methanol that significantly increases the soot oxidation chemistry in the flame, leading to a faster burn rate in the late flame.

Emissions

Methanol produces around 30% lower NO_x emissions compared to diesel when burned in a two-stroke Everllence B&W engine, provided that the same engine tuning is used.

Fig. 18 clearly indicates that the emission differences in the two modes for both engines are lower than what can be explained by the specific fuel oil consumption (SFOC) optimisation for methanol in Fig. 19.

The fact that NO_x emissions in methanol mode for the G50 are lower than for diesel mode indicates a significant optimisation potential for the combustion layout of this engine.

Pilot oil consumption

The amount of pilot oil is up to 5% of the MCR fuel consumption in diesel oil mode. The amount of pilot oil needed for securing ignition of the injected methanol is very small. It is, however, a technical challenge to design a robust injection system that is large and powerful enough to enable fuel-efficient, high-load operation on fuel oil, while being small and fast enough to be able to inject minute amounts of pilot oil in LGI operation. In fact, the only particulate matter emissions generated from methanol dual fuel vessels is from the pilot fuel.

It is not the requirement for secure ignition of the methanol that sets the lower limit for the pilot oil amount, but the minimum amount of fuel that can be injected reliably by the fuel injection system. In this context, it should be noted that the pilot oil injection is not wasted energy since the oil combustion takes place close to TDC and therefore contributes with maximum thermodynamic efficiency to the engine power output.

In general, the engines showed very good performance with no major component failures during the tests. The engines were operated with the same rating and performance layout regardless of fuel, diesel or methanol, thus demonstrating the robustness of the LGI-engine design.

The tests showed that methanol is a good combustion engine fuel, giving roughly 30% lower NO_x emissions and a slightly better SFOC compared to diesel oil operation when operating with identical thermodynamic operating points.

In conclusion, both NO_x and SFOC targets are easily reached with methanol as fuel.

Technically, the pilot oil can be any renewable hydrocarbon fuel, for example bio-fuel or PtX diesel, thereby making the engine operation CO_2-neutral.

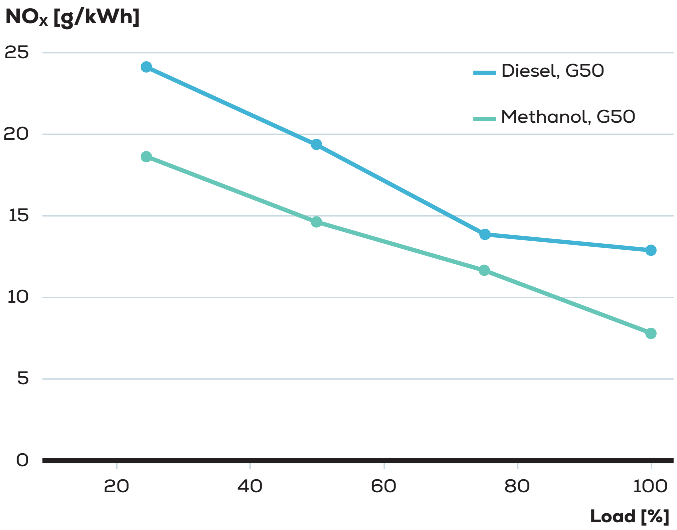


Fig. 18: Specific NO_x emissions as a function of engine load (% of MCR) for G50

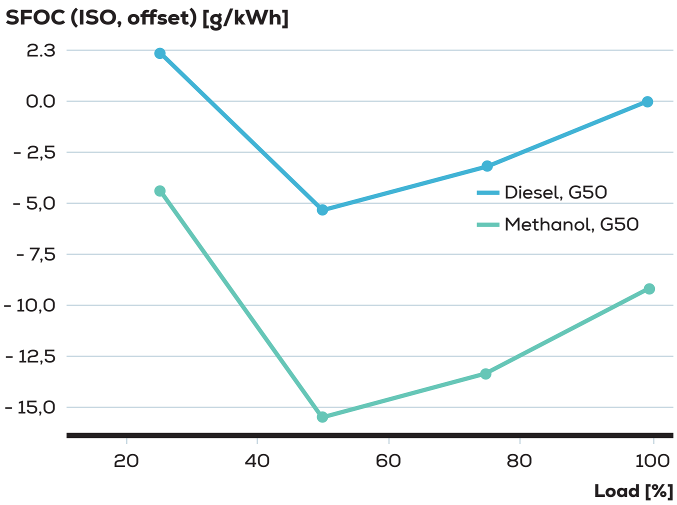


Fig. 19: SFOC measured as a function of engine load (% of MCR) for G50

8. EGR engine performance on methanol

The G95 engine presented in the previous section represents a milestone in many aspects. It is the world's first LGIM engine with an EGR system as the Tier III NO_X reduction system.

Exhaust gas recirculation affects NO_X emissions by reducing the oxygen concentration in the intake air. This reduces the flame temperature, which in turn reduces the NO_X production during the combustion process.

The main issue for engines equipped with EGR systems is that the smoke level can be elevated because of an incomplete combustion. This is also an effect of the reduced oxygen concentration and lower combustion temperature. Since methanol already has a lower flame temperature compared to diesel, it may not be obvious that EGR is a good Tier III solution for LGIM engines.

However, the data presented in this section clearly shows that EGR and methanol are an excellent combination.

Fig. 20 shows NO_X emissions for methanol and Tier II mode (without EGR) and Tier III mode (with EGR). The data is only shown in the load range 75–100% as this is the most critical range for the EGR system layout.

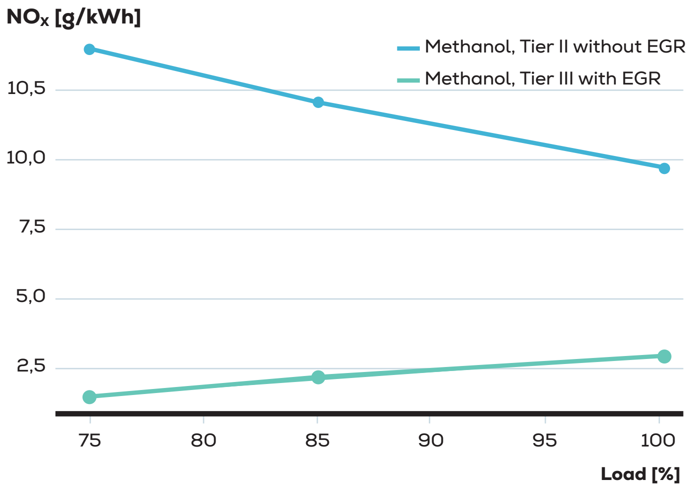


Fig. 20: NO_X emissions for methanol operation in Tier II and Tier III modes using EGR for a G95 LGIM engine

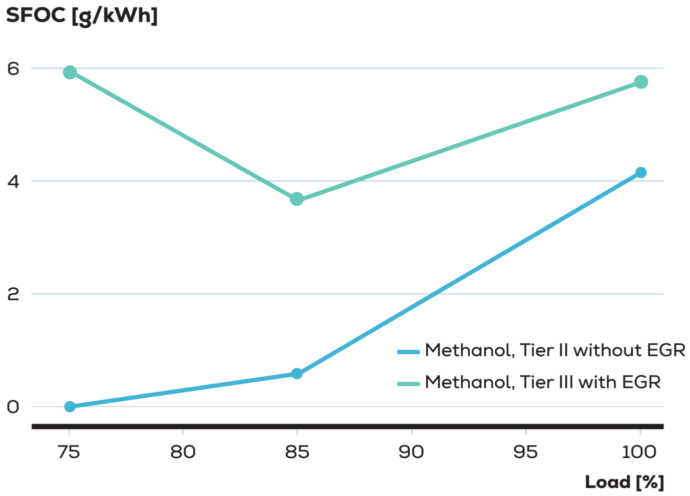


Fig. 21: Difference in specific fuel oil consumption for methanol combustion in Tier II (black) and Tier III (orange) modes using EGR for a G95-LGIM engine

The NO_X emission level complies with Tier III and is clearly below the not-to-exceeed limit of 5.1 g/kWh, and at the required level to get below the cycle average of 3.4 g/kWh. This means that the desired NO_X emission levels can be reached without problems when using methanol and EGR.

Normally, one would expect a lower peak heat release and a significantly higher late cycle heat release when running the engine with EGR. This is only partially the case. It is therefore concluded that the thermodynamic efficiency is not worsened significantly for methanol. This is in stark contrast to diesel operation with EGR, where larger changes are commonly seen. This is also further highlighted in Fig. 21, which shows the measured SFOC.

There is a fuel penalty when adding EGR to the methanol combustion. However, the reduced maximum firing pressure is responsible for most of the penalty.

The conclusion from Fig. 21 is that EGR and methanol are an excellent combination to achieve a NO_X reduction without causing too large a thermodynamic disadvantage for the engine.

Finally comes the question about other emissions that can be aggravated by adding EGR.

Fig. 21 shows the filtered smoke number for these tests.

9. Service experience

The service experience described is based on close to 90,000 running hours. The first generation of ME-LGIM engines, designated Mk. 1.1, have been installed on seven vessels, accumulating more than 80,000 running hours in total. ME-LGIM Mk. 1.2 engines have been installed on four vessels, and they have accumulated more than 8,000 running hours in total.

Mk. 1.1 engines

For vessels with Mk. 1.1 engines, the main issue observed was the tendency of the FBIVM cut-off shaft to stick inside the valve if the engine was running 3 to 4 days on HFO. This was caused by corrosion in the nozzle followed by ingress of exhaust gas. However, with the introduction of a stainless steel nozzle, which is less susceptible to the sticking phenomenon, some vessels have been running a few weeks on HFO without problems. The stainless steel nozzles are now standard for all methanol-powered engines.

After several thousand running hours on methanol, signs of cavitation were observed at the sealing position of the suction valve inside the FBIVM, see Fig. 22a. To avoid future problems, a soft-iron sealing ring was introduced between the suction valve and the FBIVM housing (previously lapped surfaces), see Fig. 22b.

Mk. 1.2 engines

On Mk. 1.2 engines, the external methanol supply pipes on the engine as well as the internal complexity of the FBIVM were reconsidered. By simplifying the design of the FBIVM, it was possible to reduce the amount of external piping and to simplify the sealing oil system, which again led to a reduction in sealing oil consumption.

On these engines, the methanol supply pipes are placed inside the cylinder cover to ease maintenance. The flexible connection visualised in Fig. 23 between the LGI control block and the cylinder cover has shown to be susceptible to the relative movement that caused a seal on the connection to wear out. Our solution will be to tighten the clearances and change from a u-cup type seal to an O-ring seal.

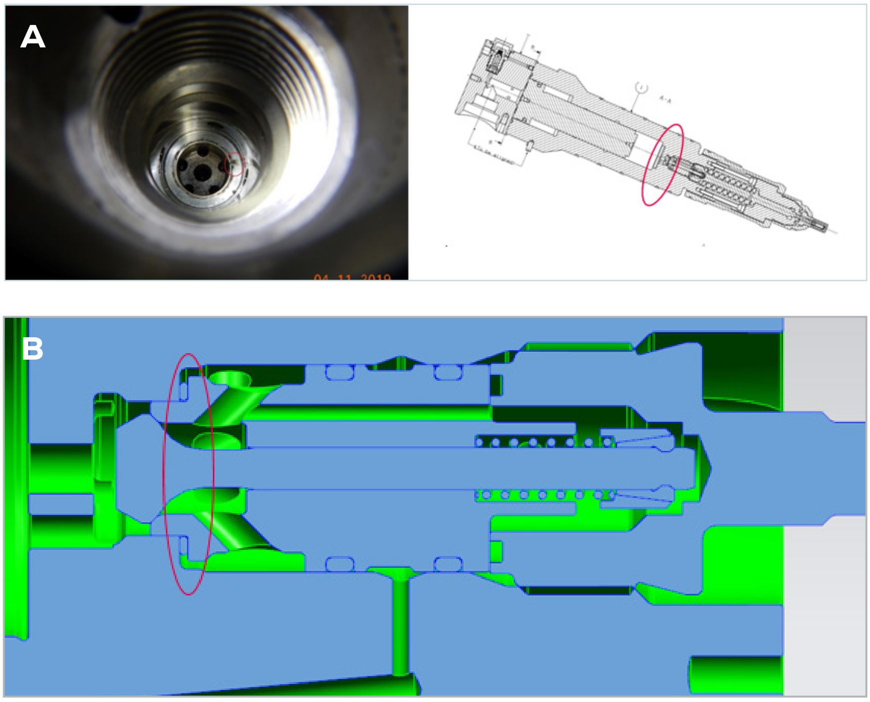


Fig. 22: Cavitation of the suction seat (a) and new design with sealing ring (b)

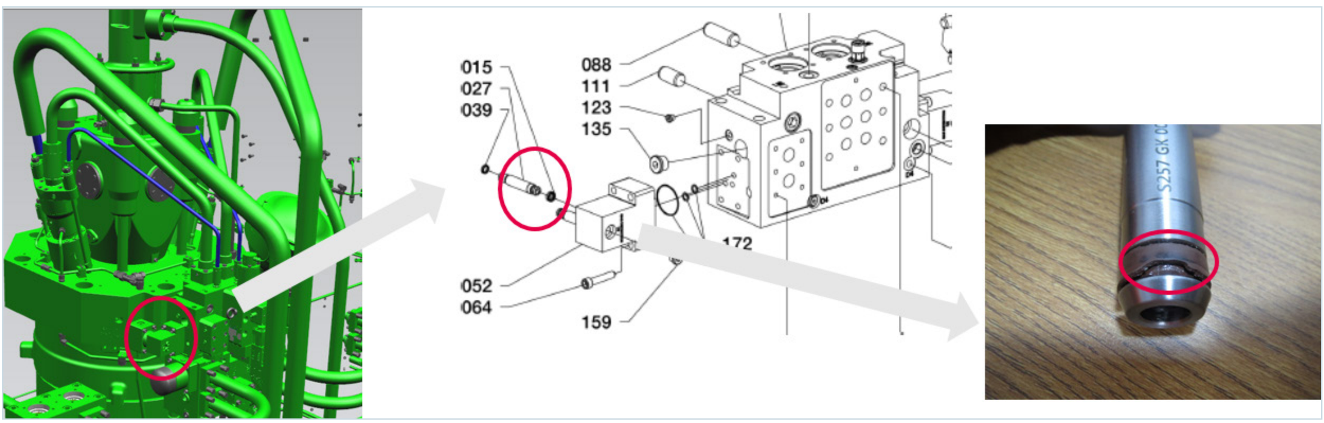


Fig. 23: The flexible connection and a worn-out seal on the connection

Cylinder lubricating oil and combustion chamber conditions

The BN value and the feed rate of the cylinder lubricating oil depend on the sulphur level in the fuel. When running on methanol, the cylinder oil feed rate must be minimum 0.6 g/kWh during normal operation. In the latest cylinder oil guideline, we recommend a low-BN cylinder oil, but as for all engines, it is essential to make a scrape-down analysis to obtain an optimal performance of the compression chamber.

The detergency is often challenged for the BN40 cylinder oils available on the market today. To ensure free movement of the piston rings, the cylinder oil must be able to keep the ring pack clean and prevent deposits from building up, see also Fig. 23.

We therefore distinguish between category I and II cylinder oils, where category II is for the latest high-performing engines. Reference is also made to the Service Letter SL2020-694/JUSV, which is available for download on our homepage [16].

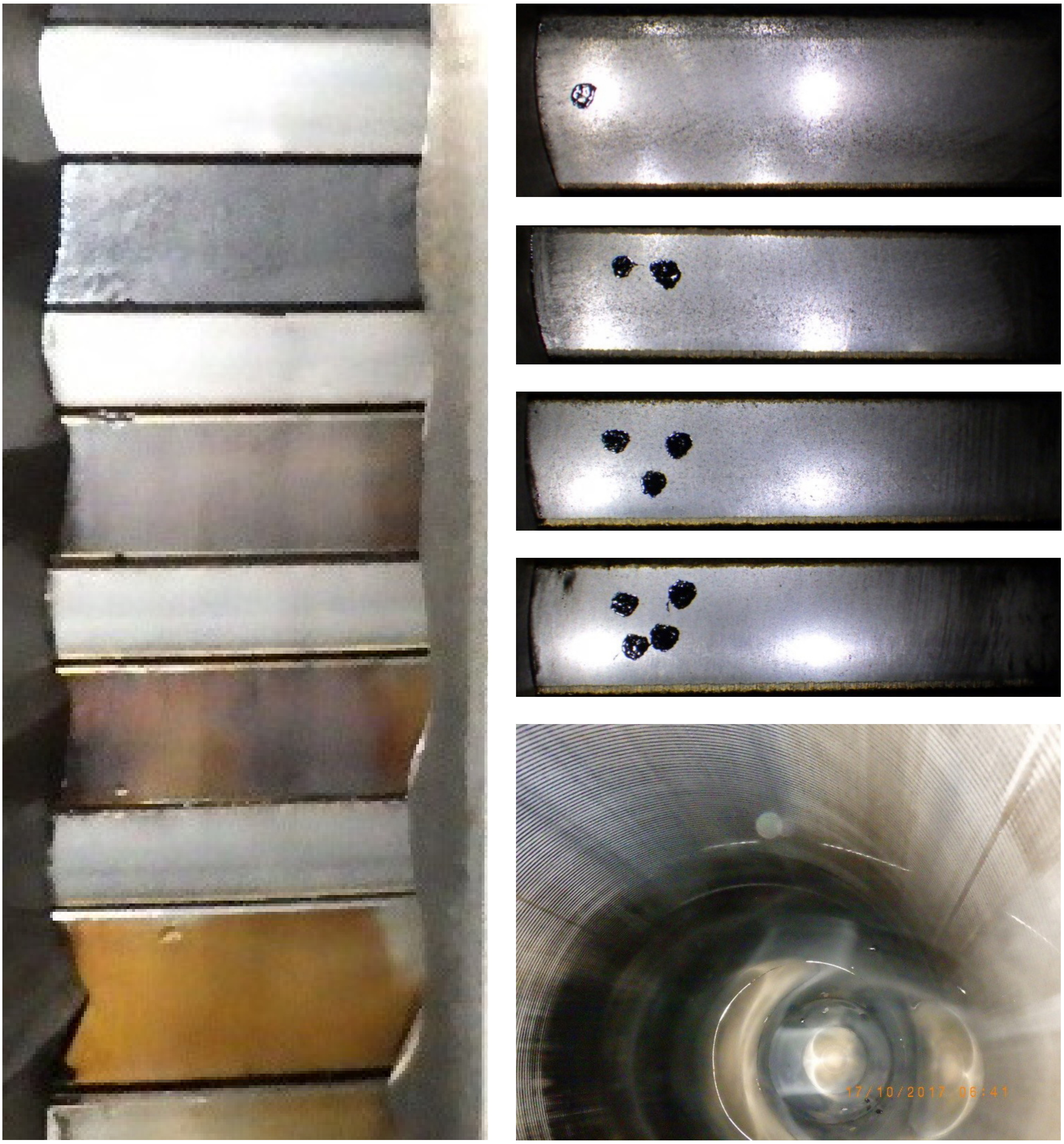


Fig. 24: Ring pack and combustion chamber with visible wave-cut after 7,058 running hours on methanol

10. Future engine programme developments

The engine programme portfolio of Everllence B&W ME-LGIM engines has been expanding rapidly the past two years in response to the significant demand for methanol as a marine fuel for large merchant marine vessels.

The methanol engine portfolio as per July 2023 includes the G45-, S50-, G50, S60-, G60-, G70-, G80-, and G95ME-C.10.5-LGIM engines. These engines cover most large merchant marine vessels, with very few exceptions.

Everllence has very high expectations to methanol as a marine fuel, and foresee that around 21% of all large merchant marine vessels, measured in engine power, will be powered by green methanol by 2050. There is a number of key reasons why methanol is considered one of the most prominent alternative fuels. The engine technology is first of all well proven and optimised based on service experience obtained since 2016. Green methanol is carbon neutral when produced from sustainable energy and biogenic CO_2.

Finally, yet importantly, methanol is very cost efficient from a vessel design perspective. Storage and service tanks can be manufactured from normal steel with the addition of a coating. The auxiliary systems, including the fuel gas supply system, are also relatively simple compared to other alternative fuels. It ultimately means that dual-fuel ships powered by methanol are the most cost-effective ship designs available, resulting in a very competitive capex compared to other alternative fuels with more complex auxiliary systems.

As standard, all ME-LGIM engines have exhaust gas recirculation systems. With over 1,200 EGR engines on order and around 400 of these in service already, the first ones dating back to 2013, the Everllence EGR design is highly proven and cost optimised, and further adds the option of EcoEGR tuning for performance optimisation.

EcoEGR is currently offered for 50-bore ME-LGIM engines, but can in principle be expanded to other bore sizes depending on the market demand. EGR is furthermore the most future-proof Tier III abatement technology for methanol-fuelled engines, especially in terms of potential upcoming emissions regulations for exhaust gasses.

The methanol and water technology for Tier III compliance, designated ME-LGIM-W, has furthermore been applied to 14 ME-LGIM engines. The concept is obtaining crucial and important service experience on board 12 ME-LGIM-W powered vessels for the further maturity of this technology. The next addition to the ME-LGIM engine family is the G70ME-C10.5-LGIM engine, which especially targets 180,000–210,000 dwt bulk carriers, Suezmax tankers, and certain container feeder designs of around 3,500-4,000 teu capacity. The G70ME-C10.5-LGIM engine completes the portfolio of methanol engines for large merchant marine vessel, enabling a fast and continuous uptake of methanol engines based on existing and proven technology.

Around 97% of all large merchant marine vessels can now be specified with an ME-LGIM engine, with the most prominent segments being container vessels and methanol tankers. But also bulk carriers and pure car and truck carriers have ME-LGIM references and many more are expected to come in the future. Everllence continuously monitors the market and is ready to add further ME-LGIM engines to the catalogue, should the market demand call for it.

11. Summary

This paper discusses the latest LGIM-engine development by Everllence .

The engine programme portfolio of Everllence B&W ME-LGIM engines has been expanding rapidly and now includes G45-, S50-, G50, S60-, G60-, G70, G80-, and G95ME-C.10.5-LGIM engines. These engines cover most large merchant marine vessels, with very few exceptions.

This paper highlights the major differences between a regular ME combustion engine and an LGIM methanol engine, such as the methanol fuel supply system and additional engine parts.

The section Perfomance results further highlights the latest LGIM developments by comparing previous G50-LGIM test results with results from the latest G95-LGIM engine. The conclusion is that it has been a great success to transfer knowledge gained from the G50 engines to the larger G95 engines. Furthermore, the section contains performance results from a G95-LGIM engine using EGR. These showed superb performance in Tier III mode, indicating the robustness of the methanol combustion and the ease with which EGR can tune the NO_X emission.

The discussion of and interest in methanol as one of the future fuels has intensified, and many vessel owners believe that it will be one of the future fuels of the decarbonisation. Methanol, as a sulphur-free fuel, is fully compliant with the 2020 IMO low-sulphur regulation. Low-sulphur compliance is not the only beneficial reason for adopting methanol though, as the lower CO_2 formation (up to 7% lower than for HFO) during the combustion process is advantageous. Since the methanol molecule contains no carbon-carbon bonds, it does not produce particulate matter or soot when burned.

The shipping industry has updated its greenhouse gas emissions reduction targets to 20% reduction by 2030, and 70% by 2040, aiming for net-zero emissions by around 2050. The adoption of alternative fuels is emphasised, with a goal to account for at least 5% of the energy use by 2030. Methanol will be playing a massive role in this green transition of the industry. Everllence is determined to work with the industry to ensure that there is access to the latest solutions and technologies in order to contribute to this pathway.

12. Acknowledgements

We would like to thank the Methanol Institute for valuable contributions.

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14. Acronyms and abbreviations

AWC	Adverse weather condition
BN	Base number
CC	Carbon capture
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
Cf	Carbon factor
CII	Carbon Intensity Indicator
DLF	Dynamic limiter function
ECA	Emission control area
ECS	Engine control system
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency for Existing Ships
EGR	Exhaust gas recirculation
EU ETS	EU Emissions Trading System
EU MRV	EU Monitoring, Reporting and Verification
FBIVM	Fuel booster injection valve for methanol
FVT	Fuel valve train
GHG	Greenhouse gas
GI	Gas injection
HAZID	Hazard Identification study
HAZOP	Hazard and Operability study
HC	Hydrocarbon
HP	High pressure
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organization
IMO DCS	IMO Data Collection System
IMPCA	International Methanol Producers & Consumers Association
LCV	Lower calorific value
LFF	Low-flashpoint fuel
LFSS	Low-flashpoint-fuel supply system
LGI	Liquid gas injection
LGIM	Liquid gas injection methanol
LGIM-W	Water as Tier III NO_X compliance measure
LGIP	Liquid gas injection propane
LCA	Life cycle analysis
LNG	Liquefied natural gas
LP	Low pressure
LPG	Liquefied petroleum gas
LT	Low-temperature
MCR	Maximum continuous rating
MFV	Master fuel valve
MSW	Municipal solid waste
NPSH	Net positive suction head
NG	Natural gas
PIFIW	Pilot-oil-ignited fuel in water
PTO	Power take-off
RCC	Research Centre Copenhagen
SCR	Selective catalytic reduction
SEEMP	Ship Energy Efficiency management Plan
SFOC	Specific fuel oil consumption
SNG	Synthetic natural gas

TDC	Top-dead centre
WHRS	Waste heat recovery system

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