ZURICH, MAY 19 – 23, 2025

2025 | 232

Deduction of a customer-oriented methanol four-stroke engine portfolio

New Engine Concepts & Systems

Maximilian Bartholy, MAN Energy Solutions

Dr. Johannes Lauterbach, MAN Energy Solutions
Torsten Dehn, MAN Energy Solutions
Christian Argus, MAN Energy Solutions
Catherina Baptist, MAN Energy Solutions
Dr. Sebastian Kunkel, MAN Energy Solutions

ABSTRACT

To achieve the ambitious goal to reach net-zero greenhouse gas emissions in the maritime industry, methanol is among the most promising fuels to meet the targeted emission reductions.

MAN Energy Solutions as a leader for propulsion technology is committed to support customers in their achievement of this target by providing dedicated products. This paper will address the best suitable options for the utilization of methanol in four-stroke marine engines and the methodologies with which the methanol portfolio strategy was derived.

Serving a broad product portfolio with a different view on market requirements, we developed a targeted product strategy for both high-end and cost-conscious market segments. The transition to a new fuel type has an immense impact on product variance and requires the right focus to maximize synergies and to streamline the overall product portfolio.

Based on a market segmentation for different customer groups, technology concept studies as well as lifecycle cost analyses, MAN Energy Solutions defined the portfolio approach to best fit the individual requirements. The paper will discuss the impact of different methanol combustion technologies such as high-pressure direct injection or low pressure port fuel injection systems on the respective product success factors and provide an insight on the suitability of those technologies for different customers in both newbuilding and retrofit applications.

An outlook on pathways to ensure compliance with the planned regulatory boundaries with methanol will be presented. For this, the results of techno-commercial use case assessments to meet the emission reduction targets for EU regulations in an exemplary customer segment sailing on different international routes will be presented, taking into account the impact of those technologies on invest and operating cost based on real sailing data, fuel cost development and CO2 emission cost through taxation or penalties.

The advantages to ensure emission target achievement in a stepwise approach based on MAN Energy Solutions' class approved methanol ready concept will be presented. This approach enables full flexibility for cost-efficient and reliable operation with the flexibility to operate on alternative fuels once they become locally available. The paper gives advice based on the different customer requirements and circtumstances at the point in time the e-methanol is available, which of the discussed methanol engine technologies is the proper choice for different customer needs. At the end, the paper will name the methanol four-stroke portfolio with methanol ready certification that is available to the market.

1 INTRODUCTION & MOTIVATION

"We cannot solve our problems with the same thinking we used when we created them." (Albert Einstein)

Daring visions and concrete regulations are crucial to phrase and achieve essential targets for a more sustainable future for the maritime industry and the planet.

There are two main cornerstones of regulations:

FuelEU Maritime is a key initiative under the European Union's (EU) ambitious "Fit for 55" climate plan, aiming to decarbonize the maritime sector by promoting the use of sustainable fuels in shipping. Recognizing that maritime transport is responsible for about 3-4% of global greenhouse gas emissions, the FuelEU Maritime regulation seeks to reduce the carbon footprint of ships operating in EU waters. It sets clear targets to increase the share of low-emission and zero-emission fuels in the maritime industry, requiring ships to gradually lower their greenhouse gas intensity from 2025 onwards. Through these measures, FuelEU Maritime supports the EU's overarching goal of reaching climate neutrality by 2050, while also incentivizing innovation in sustainable maritime technologies and fuel alternatives. The FuelEU Maritime regulation supports the transition to more sustainable modes of transport and achieve full decarbonization of the transport sector by 2050. [1]

The key focus areas of the FuelEU Maritime regulation are:

1. Reduction of greenhouse gas (GHG) intensity: the regulation mandates a gradual reduction in the GHG intensity of fuels used by ships, with gradual targets set until 2050.
2. Scope: applies to ships over 5,000 gross tons (GT) visiting EU ports, covering 100% of emissions from voyages within the EU and 50% from voyages between EU and non-EU ports.
3. Onshore Power Supply (OPS): from 2030 containerships and passenger ships must connect to onshore power supply at applicable ports to reduce emissions while docked.
4. Monitoring, Reporting and Verification (MRV): ships must monitor and report the GHG intensity of the energy used on board, with annual compliance verification.
5. Promotion of renewable fuels: encourages the use of renewable and low-carbon fuels.

These focus areas aim to significantly reduce the maritime sector's carbon footprint and promote the use of sustainable fuels.

Second cornerstone is the regulation of the IMO: the 80th session of the International Maritime Organization's Marine Environment Protection Committee (IMO MEPC 80) adopted a revised strategy to significantly reduce GHG emissions from international shipping. Here are some key points:

1. Net-zero target: the revised strategy aims to achieve net-zero GHG emissions from international shipping by or around 2050.
2. Interim targets: includes a 20% reduction in emissions by 2030 and a 70% reduction by 2040, compared to 2008 levels.
3. Alternative fuels: commitment to ensure the uptake of alternative zero and near-zero GHG fuels by 2030.
4. Lifecycle assessment guidelines: adoption of guidelines for the lifecycle assessment of marine fuels, allowing for a Well-to-Wake calculation of total GHG emissions.
5. Data Collection System (DCS): approval of amendments requiring more detailed data on fuel consumption.

IMO Secretary-General Kitack Lim emphasized the importance of this strategy, stating:

"The adoption of the 2023 IMO Greenhouse Gas Strategy is a monumental development for IMO and opens a new chapter towards maritime decarbonization. However, it is not the end goal; it is in many ways a starting point for the work that needs to intensify even more over the years and decades ahead of us."

These measures are crucial for the maritime industry's transition towards sustainability and the global effort to combat climate change. [2]

Because of nowadays growing need of a massive CO2 reduction to protect our planet and to ensure desirable living in the future, we need to achieve the ambitious goal to reach Net-zero Greenhouse gas emissions in the Maritime industry. There are different approaches to do so: exhaust and efficiency measures as well as alternative fuels. There are several exhaust measures that can be implemented, e.g. CCS (Carbon Capture and Storage), EGR (Exhaust Gas Recirculation) and SCR (Selective Catalytic Reduction). Another smart approach to reduce fuel consumption and emissions is improving engine efficiency e.g. through variable speed and battery support.

In this paper we take some first steps on the exciting path of future fuels (in particular methanol (MeOH)). You will not only find a comparison of the different technologies, but also insight into interesting customer cases on the different solutions.

2 PORTFOLIO VIEW

MAN Energy Solutions as a leader for propulsion and power generation technology is committed to support their customers in the achievement of this target by providing dedicated engine products. We are capable of developing both ecologically and economically optimized technical solutions for a more environmentally conscious generation.

Following our decarbonization strategy and with these new marine emission legislations put in place, our product strategy had to be fundamentally reviewed and updated, calling also for deep-dive engine portfolio and future fuel technology concept evaluations [3]. Due to different potential customer routes ahead, with step-by-step emission limit level enforcement over the next two decades, however, significant market uncertainties prevail not only as regards the right choice of low emission fuel, but also in terms of the most competitive and adequate injection technology [4]. IMO and EU fleet emission compensation rules additionally impede straight forward approaches. Another significant challenge represent alternative emission reduction choices, leading to questions such as whether fossil fuel engines might be still preferred from customers in specific segments or whether engines are going to be replaced by other technologies. For this reason, a comprehensive business assessment had to be conducted.

2.1 Systematic Assessment Approach

A cross-functional project team was implemented to assess marine emission requirements, segment compliance implications, future fuel characteristics, combustion technology alternatives, engine design alteration scopes (and costs), competitor portfolio activities, substitute technology options, alternative approach options, segmental market preferences and to elaborate MAN ES' general future fuel 4-stroke engine portfolio and R&D roadmap strategy [5].

2.1.1 Initial Future Portfolio Questions

Since vessels usually operate for roughly 20 years, customers ask for long-term emission compliance solutions. This has to come at reasonable costs in order to maintain the customers competitiveness. Within this business context, some initial questions had for the general assessment to be raised:

- Which alternative fuel will most likely take-off in the near future, mid term or long term? What about the future fuel costs, fuel availability and required infrastructure?
- What options will our customers pursue within the different market segments? How to remain compliant w/o changing the engine design? How does a fleet-oriented regulation support?
- Are ship and engine conversions adequate to reach general compliance? What is the scope of conversions and what are associated costs? Is it advantageous for existing ships to go for biofuels or fuel blends w/o any need for engine modifications?
- How will major competitors meet these future requirements? How will they develop their portfolio? Which combustion / injection technology will be applied for the variety of future fuels?
- Which segments are front runners, which the followers? Which benefits might provide any future fuel readiness package? What are later conversion costs?
- Could it still be beneficial to continue with Heavy Fuel Oil (HFO) and pay penalties? Are there promising ship optimization or aftertreatment options? What about alternative technologies?

2.1.2 Defined Work Task Approaches

As starting point served our previous market arena categorizations, segmental product success factor ratings, R&D project roadmap programs as well as our general long-term engine portfolio plan [3]. This documentation constituted the basis to following listed assessment work tasks:

- Market research and regular exchanges with key customers regarding general concerns, marine trends etc. [3], [6]
- Emission reduction market implications (take-off timeframe, ship exceptions, fleet renewals).
- Customer compliance option evaluations also referring to non-engine technologies e.g. fuel cells, batteries, shaft generator, aftertreatment.
- Customer compliance Total Cost of Ownership (TCO) case studies including future fuel costs, taxation and penalties.
- Competitor roadmap and benchmark studies with continuous tracking of all major competitor R&D activities. [3]

- Alternative fuel options assessment including characteristics, safety concepts, infrastructure and fuels availability.
- Combustion technology fuel match evaluations including basic future fuel engine performance investigations.
- Integration of findings from public-funded MAN ES future fuel research projects; conduct of future fuel single cylinder injection and combustion tests.

Moreover, PESTEL (Political, Economic, Social, Ecological, Legal) and SWOT (Strengths, Weaknesses, Opportunities, Threats) assessments have been conducted also investigating first mover – fast follower – late follower market entrance options with general consideration of ongoing and already planned R&D roadmap projects. Besides, at a later stage, MAN ES business cases have been calculated for shortlisted potential future fuel engine types in alignment with roadmap synergy and development capacity clarifications. [3] [4] Figure 1 depicts the overall assessment approach.

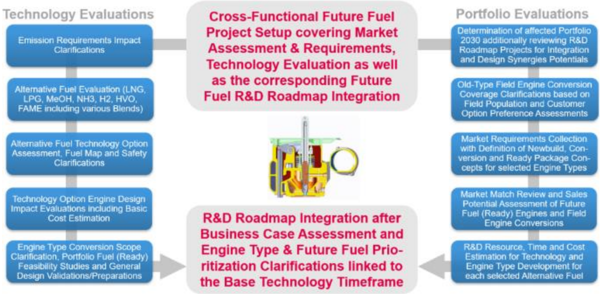

Figure 1. Design technology and engine portfolio future fuel assessment project approach

2.2 Engine Portfolio Implications

MAN ES continuously strives to realize new technological synergies across the entire engine portfolio as well as family design that reflect standardized and modularized future fuel variants. The target is primarily to achieve long-term product costs competitiveness. Such mass customization portfolio strategies often require more effort in upfront design or roadmap clarifications. [3]

Portfolio technology alignment is further considered beneficial for the streamlining of supply chains and customer services, usually resulting in operational excellence. And yet, as new engine type variants require profound real world prototype validation and corresponding class approvals, the future fuel features cannot just simply be transferred to our entire portfolio but rather call for some kind of validated type selection.

What else matters is the advice to not blindly apply future fuel or other major technologies across the entire portfolio, as there might be space, pressure, slip or flow restrictions causing large design issues. Specific high-end or low-end technologies might be also in contrast to segmental market requirements. One interesting aspect in this context, nonetheless, is the question of how the product success factors change in cases future fuel engines are requested.

2.2.1 Product Success Factors Impact

Figure 2 depicts the engine success factor rating for the 3X cruise segment with eight crucial factors been defined: CapEx €/kW reflecting the engine first costs (Capital Expenditures); OpEx (Operational Expenditures) efficiency referring to engine fuel and lube oil consumption while OpEx maintenance addressing spare part and service costs; engine performance linked to general operation features and capabilities; availability + TBO comprising parts exchange intervals and global spares availability; dimensions covering engine space requirements whereas delivery time goes for the engine's lead time; fuel flexibility comprises fuel type, load step, fuel map, fuel switch or other operation restrictions. [4] [7]

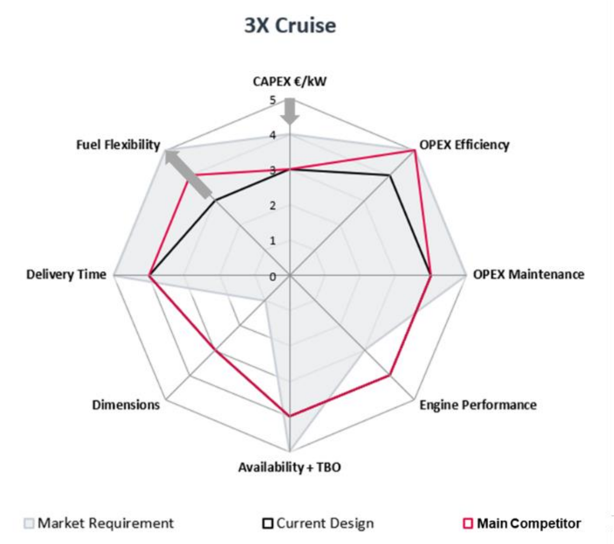

Figure 2. Exemplary future fuel success factor rating adjustment for 3X cruise segment

As indicated in the graphic, going for additional fuel options generally leads to a higher rating increasing from 4 to 5. Since customers expect a price tag for this extra flexibility, the CapEx €/kW requirement is down from 5 to 4. All other ratings remained unchanged, due to the fact that no compromises are accepted concerning OpEx maintenance and OpEx efficiency. Parts availability + TBO are also critical to our customers operating their high invest cruise vessels all over the world, whereas engine performance and dimensions are less of a headache within this specific segment. In order to meet the 3X cruise market requirements, MAN ES decided to mainly develop corresponding MeOH engines, which will be probably seen in the market by 2027.

This 3X development decision, however, was not only based on the above graphic. The factor rating is just one piece to the puzzle from the described in-depth business and portfolio assessment equally requiring market potential, product profitability and technological feasibility approval.

2.2.2 Roll-Out of Future Fuel Portfolio

Serving a broad product portfolio with various views on market requirements, we developed a targeted product and portfolio strategy for both high-end and cost-conscious market segments [6]. The transition to new fuel types has thereby an immense impact on our product variance and requires the right focus to maximize synergies and to streamline the overall engine portfolio. Based on identified emission and future fuel requirements, long-term related marine market trends, engine type business potentials, technology concept studies as well as lifecycle cost analyses, MAN ES defined its future fuel engine and portfolio approach to best fit individual customer and market segment requirements. [3] [4] [9]

Figure 3 below indicates general portfolio analysis efforts, evaluating 65 engine types in total within a project timeframe of approximately 18 months due to further technological development, additional market and customer insights. Since markets and technologies continuously develop with potential changes also to be expected within the next few years, adjustments might be necessary and MAN ES as its competitors being forced to regularly observe these markets for latest trends or major shifts. As of today, consensus was achieved to select nine out of 32 active propulsion as well as seven out of 16 active auxiliary engine types. Decision was further made to immediately design port fuel injection (PFI) conversion packages covering four engine types.

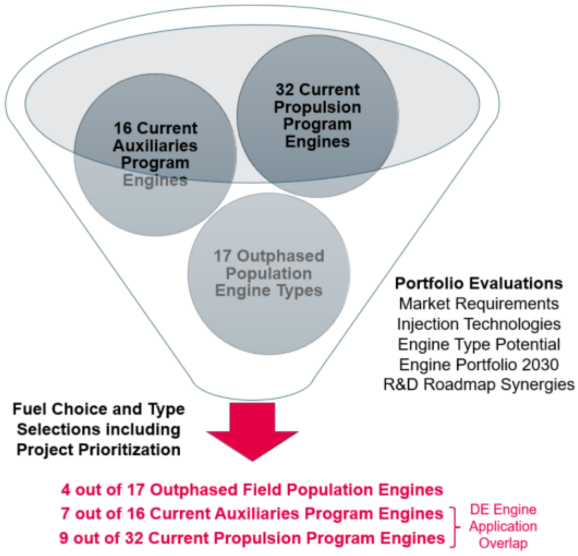

Figure 3. Future fuel application marine engines portfolio roll-out approach and outcome

With 13 MeOH L+V 4-stroke engine types (9x PFI, 4x HPDI (high pressure direct injection)) listed on our Research & Development (R&D) roadmap or already being part of the current engine program, MAN ES is able to cover the power output spectrum reaching from 1 MW to 18 MW within all relevant marine segments. Ammonia (NH_3) and hydrogen (H_2) development projects have further been initiated (not reflected in Figure 3) to equally serve these potential upcoming markets in due time. [3]

3 MARKET SEGMENTATION AND TECHNOLOGY OVERVIEW

In the maritime world, the choice of the right technology plays a crucial role in the success and efficiency of ships. Given the increasing demands for decarbonization and cost-effectiveness. [3] [9] It is essential that ships are equipped with engines that are not only powerful but also sustainable and efficient. The right engine technology can make the difference between a competitive vessel and one that does not meet market requirements.

The technical solutions for MeOH engines must meet specific requirements depending on the application, customer and market. These include success factors such as fuel efficiency, cost effectiveness, emission reduction and reliability under various conditions.

When selecting the technology for MeOH engines, it is essential to consider not only new builds, but also the potential for retrofitting existing vessels. This dual approach ensures that both new and existing ships can meet evolving regulatory, environmental and operational requirements.

This chapter examines the importance of different technologies for MeOH engines and analyzes how the technology impacts the success factors of the respective applications, customers and markets. The core message is that the "right" technology must fit the market.

3.1 Analysis of Key Segments and Target Requirements

The marine market can be broadly divided into two main areas: the high specification market and the low specification market (Figure 4). [8]

Figure 4. Market classification of applications

3.1.1 High Specification Market

The high specification market primarily includes ships that are typically built in Europe. Common applications in this segment are cruise ships, ferries and navy vessels. These ships are characterized by their advanced technical requirements and specialized equipment.

For the high specification market, the following target requirements are essential:

- Efficiency (OpEx): maximizing operational efficiency to reduce ongoing operating costs.
- Multi-fuel capability: utilizing multi-fuel systems to ensure flexibility and environmental sustainability.
- Competitive price (OpEx / CapEx): balancing investment and operating costs to remain competitive in the market.

3.1.2 Low Specification Market

In contrast, the low specification market consists of ships that are typically built in Asia. Common applications in this segment include auxiliary gensets. These ships have lower technical requirements and are often more cost-effective to manufacture.

For the low specification market, the following target requirements are crucial:

- Capital Expenditures (CapEx): minimizing investment costs to maximize economic efficiency.
- Multi-fuel capability: flexibility in using various fuels to reduce operating costs and comply with environmental regulations.
- Size / dimensions / complexity: optimizing ship size and complexity to reduce construction and operational costs.

3.1.3 In-Between Market

There are also applications such as fishing vessels, wind turbine installation vessels (WTIV), tankers and cargo ships that can fall into either the high or low specification market, depending on the owner and shipping company. These markets are served selectively based on specific requirements and economic considerations of the clients.

3.2 Combustion Technology and Potential Solutions

Combustion processes can fundamentally be divided into otto and diesel combustion methods. This distinction is crucial for understanding the different technologies available for methanol fuel readiness.

3.2.1 Technologies for Methanol Combustion

3.2.1.1 Methanol Ready Engines

- Optimized single-fuel diesel engine: this technology leverages all the advantages of an optimized single-fuel diesel engine, providing high efficiency and reliability.
- MeOH-ready concept: the term "ready" refers to the availability of concepts for future retrofitting. This involves the design and development of these concepts to ensure they can be applied later with minimal effort. This readiness applies to both PFI and HPDI systems.

3.2.1.2 High Pressure Direct Injection

- Diesel combustion process with HPDI for MeOH and diesel**:** this method uses a high pressure injector to introduce MeOH and diesel into the combustion chamber with one main injector (Figure 5).

- Engine based on diesel engine**:** The engine is fundamentally a diesel engine but adapted for MeOH use.

- Ignition using diesel fuel: the ignition process is initiated using diesel fuel through the common-rail diesel main injection system, which is capable for minimum quantities to ensure a reliable combustion.

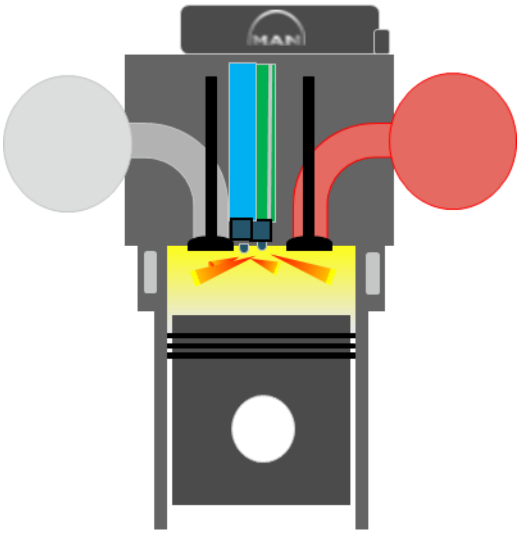

Figure 5. Cylinder layout with HPDI-injector

3.2.1.3 Low Pressure Port Fuel Injection

- Pre-mixed (otto) combustion: this method involves pre-mixing the methanol with air before it enters the combustion chamber. The main diesel fuel can be injected via a common rail injection system as well as a conventional injection system (Figure 6).

- Injection into charge air manifold: methanol is injected into the charge air manifold and a diesel main or pilot injector is used to initiate the ignition by using diesel fuel. This can be executed in both simplified and advanced versions:

  - Simplified**:** without separate pilot fuel injector for diesel fuel

  - Advanced**:** with separate pilot fuel injector for diesel fuel

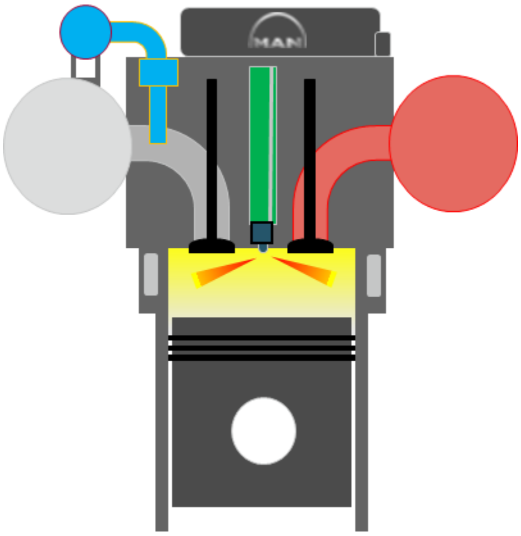

Figure 6. Cylinder layout with PFI-injector

3.2.2 Consequences of Technology Choice or Advantages of Technology Choice

3.2.2.1 Methanol-Ready Concept: Optimal Choice for Uncertainties in the Future

The methanol-ready concept is an optimal choice when there is uncertainty regarding the future availability of green methanol or the need for methanol operation in the distant future. This approach ensures that the engine is prepared for future fuel transitions without immediate execution and has several benefits: the methanol-ready engine is designed to achieve optimal specific fuel oil consumption (SFOC). Utilizing only one injection system simplifies maintenance and operation, leading to lower OpEx and CapEx. This streamlined approach enhances the overall efficiency and reliability of the engine. [3] [9]

Operation

The solution has a standard diesel map with all the advantages in terms of dynamics.

Retrofit

A retrofit can be optimally combined with a major maintenance event, minimizing both the time and financial investment required. This strategic planning ensures that the retrofit process is efficient and cost-effective, aligned with the vessel's maintenance schedule.

In summary, the methanol-ready technology provides a flexible and future-proof solution for marine engines, balancing efficiency, costs and adaptability to future methanol requirements. This approach ensures that shipowners can make decisions that optimize both current and future operational performance.

3.2.2.2 High Pressure Direct Injection Concept for Methanol

Operation

The HPDI technology preserves the performance characteristics of a traditional diesel engine. This means that the engine retains its high power output, responsiveness and reliability, ensuring that the best of both worlds can be achieved: superior engine dynamics and the flexibility to use methanol as a fuel, all without sacrificing performance.

One of the key benefits of the HPDI system is its ability to operate with very low quantities of pilot diesel fuel for ignition. This not only reduces fuel consumption but also minimizes emissions, contributing to a more environmentally friendly operation.

The engine equipped with a HPDI system can operate on diesel fuel from 0% to 110% Maximum Continuous Rating (MCR) and on methanol fuel from 10% to 100%. This wide operational range provides flexibility and ensures that the engine can perform efficiently under various load conditions, see Figure 7.

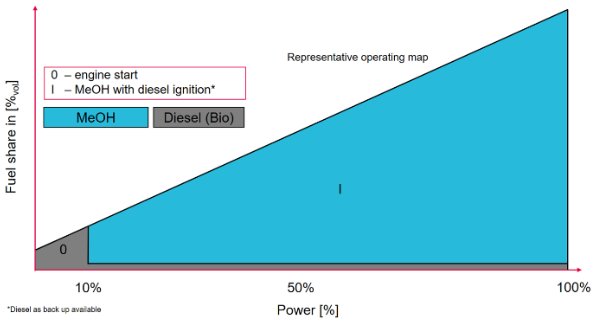

Figure 7. Engine operation map with HPDI-injector

The HPDI system ensures high combustion stability across different operating conditions. This stability is crucial for maintaining consistent engine performance and preventing issues such as knocking or misfiring, which can affect engine longevity and efficiency.

The HPDI system is specifically optimized for methanol operation, achieving high efficiency when using methanol as a fuel. This optimization allows for a seamless transition to methanol, providing an effective solution for meeting future environmental regulations and reducing greenhouse gas emissions.

In total, the HPDI system combines the robust performance of traditional diesel engines with the flexibility and efficiency of methanol operation. Its low pilot fuel requirement, wide operational range, high combustion stability and optimization for methanol make it an ideal choice for modern marine engines.

Retrofit and Maintenance

A retrofit is possible if the methanol-ready concept is considered during the diesel engine's development. This ensures that future upgrades can be implemented with minimal effort and costs.

The maintenance costs for the respective injection systems are comparable to conventional common rail (CR) diesel injection systems. However, HPDI systems are more complex due to the integration of two systems in one, leading to higher maintenance requirements compared to a single diesel fuel system.

Viewed in its entirety, the HPDI technology is relevant for the high specification market, where advanced performance and efficiency are the main success factors.

3.2.2.3 Low Pressure Port Fuel Injection Technology for Methanol

The PFI system enables dual-fuel operation, which closely resembles traditional diesel engine operation. This system has a smaller impact on the engine setup, making it an optimal choice for retrofitting and dedicated operation conditions. The PFI system incorporates a second low-pressure injection system for methanol, offering several advantages. The low-pressure system is easier to integrate into existing engine designs and it is more cost-effective compared to high-pressure systems.

In general, there are two possible configurations of PFI systems:

- Simplified Configuration: in this setup, there is no separate pilot injector. The pilot injection is managed through the main injection system, simplifying the engine design and reducing costs. The configuration is especially suitable for engines with bores smaller than 30 cm. The corresponding operation map can be seen in Figure 8.

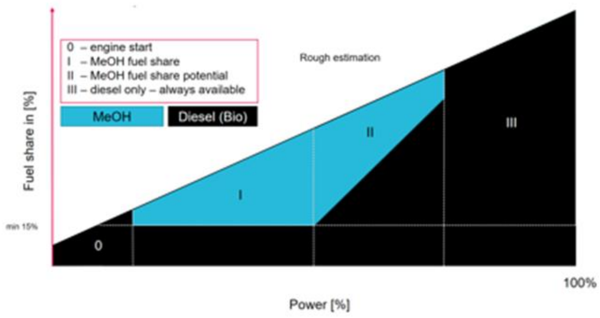

Figure 8. Engine operation map with PFI-injector in the simplified configuration

Advanced configuration: this setup includes a dual-fuel pilot injector that enables a wider methanol operating map, as shown in Figure 9.

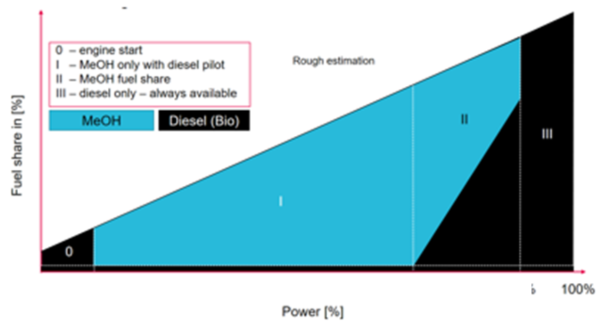

Figure 9. Engine operation map with PFI-injector in the advanced configuration

Operation

Both configurations ensure 100% diesel capability in all cases, providing maximum operational flexibility and with a similar efficiency as typical dual-fuel gas engines.

Retrofit

Compared to the HPDI system, the PFI system is conceptually simpler to retrofit. This simplicity reduces both the CapEx and maintenance costs, making it a more economical option for upgrading existing engines.

In summary, the PFI system offers a practical and cost-effective solution for methanol operation, with the flexibility to maintain diesel performance. Its ease of integration, lower costs and suitability for retrofitting make it an attractive choice for customers, where cost-effectiveness and ease of integration are critical factors.

4 CUSTOMER PERSPECTIVE: CASE STUDY

EU and IMO (likely) follow a technology open approach, avoiding predetermining market behavior, but creating a large tree of decision options for investments to reach the final target. For potential ship owners, a variety of decision options is being created that requires the evaluation and subsequent selection and execution of best fitting action options under significant levels of insecurity.

Aside from the obvious fuel choice and readiness thereof, also the structure of economic evaluation for individual ships or fleets as a whole drives the complexity of the investment decision. Each option comes with individual pros and cons. Obviously, aside from mere commercial aspects, shipping, application and vessel specific requirements may and will have a significant effect on actual technology selection.

Due to large numbers of options, modelling can only tackle a limited number and thus must follow a rational and pragmatic selection based on real life restraints and requirements.

This chapter will provide a commercial case study for a typical ferry operating exclusively in EU waters (Table 1). It is equipped with four main propulsion engines and has an operation profile of approx. 20% port calls, 70% voyage and 10% maneuvering, which results in an annual total energy demand of ~675 TJ.

Table 1: Ferry use case operational assumptions

Ferry Use Case

First Year of Operation	2025
Lifetime	2025 - 2050
Area of Operation	100% within EU
Annual Energy Demand at Sea in Port	674.400 GJ (15.790 t MGO eq.) 659.400 GJ (15.445 t MGO eq.) 15.000 GJ (345 t MGO eq.)

Three scenarios will be evaluated:

1 Operation on fossil MGO (Marine Gasoil)

2 Blend-in of e-methanol in order to ensure compliance with the increasing GHG intensity targets

3 Operation on solely e-methanol resulting in an overcompliance of the vessel

Since this paper is focused on methanol as a fuel, neither fuels like LNG (liquefied natural gas) or ammonia will be considered nor other efficiency improvement measures like hull lubrication, wind assisted propulsion, shore power or others.

Globally influencing factors account for the greatest uncertainty in the assessment. Especially the following have a significant impact on the calculation: fuel availability and especially pricing and related the benefit of selling overcompliance within the fleet with price forecast ranges being so widely varying that a substantial prognosis remains a challenge. Table 2 gives an overview of the considered assumptions for the assessed scenarios:

Table 1: Case study commercial assumptions

Overview of Main Commercial Assumptions

MGO Price	580 EUR/t 13,6 EUR/GJ
MGO GHG Intensity	
Well-to-Wake	90,77 gCO_2eq/MJ
Tank-to-Wake	76,37 gCO_2eq/MJ
EU ETS Allowance	100 EUR/tCO_2eq (Scope: Tank-to-Wake)
e-Methanol Price	1000 EUR/t 50,2 EUR/GJ
e-Methanol GHG Intensity	
Well-to-Wake	4,75 gCO_2eq/MJ
Tank-to-Wake	Not considered for EU ETS
Additional CapEx for Methanol Capability	10 mEUR (7% Interest Rate, 25 Years Paydown Time)

Scenario A: Fossil MGO

The base scenario A (Figure 10) will consider a single fuel design of the vessel, operating solely on fossil MGO. Consequentially the vessel will not comply with the increasing GHG intensity targets and the operator will have to pay both EU Emission Trading System (ETS) allowances and penalties throughout the vessel's lifetime.

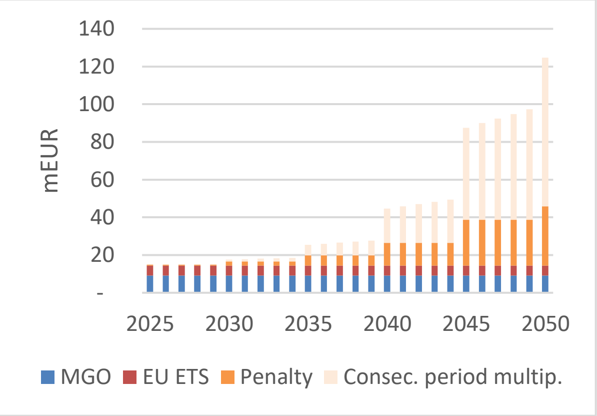

Figure 10: Scenario A: annual expenses in mEUR

This scenario results clearly in the lowest annual fuel costs (~9 mEUR) and provides the lowest initial CapEx. Until 2035, the resulting EU ETS payments for the tank-to-wake CO2eq emissions remain higher than the penalty payments.

The penalty payments in this scenario are illustrated in two categories: the general penalty payments (rising from 0.6 mEUR to 31.5 mEUR in 2050) and the additional penalty resulting through the consecutive period multiplier (see equation (1)). This multiplier increases the penalty by 10% for each consecutive period in which the vessel does not comply with the GHG intensity targets. [10] This effect dominates the development of the penalty payments in the later years.

$$\text{Penalty } [€] = \frac{(\text{Req. GHG int.} - \text{act. GHG int.}) \times \sum \text{Energy used}}{\text{act. GHG int.}} \times \frac{2.400€/\text{tVLSFOeq}}{41.000 \frac{\text{MJ}}{\text{tVLSFOeq}}} \times \left(1 + \frac{\text{Consecutive periods} - 1}{10}\right) \quad (1)$$

In 2035, the penalty payments including the consecutive period penalty are higher than the fuel costs and remain the highest cost factor for the following years.

Scenario B: Blend in e-Methanol

Scenario B targets to avoid penalty payments by using sufficient e-methanol to reach GHG intensity targets of the FuelEU Maritime (Figure 11).

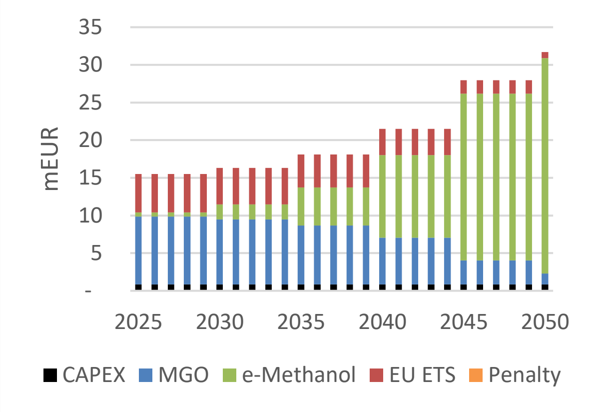

Figure 11: Scenario B: annual expenses in mEUR

To reach the required GHG intensity targets, the share of e-methanol in the vessel fuel split would need to increase from below 2% in 2025 to 84.3% in 2050 [Note: the available reward factor for the utilization of Renewable Fuels of Non-Biological Origin (RFNBO) until 2033 was not considered in this scenario]. With the rising e-methanol share, the total fuel costs increase from 9.5 mEUR in 2025 to 30 mEUR in 2050.

The EU ETS costs gradually decrease compared to Scenario A, since for e-methanol operation with a REDII compliant pilot fuel, no EU ETS payments are considered.

Scenario C: Maximum e-Methanol

This scenario reflects a vessel operation on e-methanol only (Figure 12).

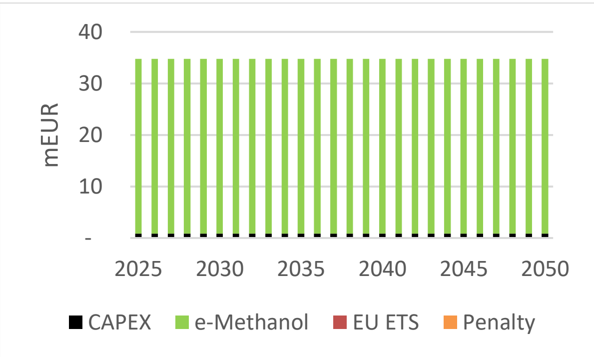

Figure 12: Scenario C: annual expenses in mEUR

This scenario results in the highest fuel costs of ~34 mEUR per year. No additional costs for EU ETS or penalties occur.

This fuel utilization results in a significant over-achievement of the GHG intensity targets. This over-achievement can be utilized in the FuelEU pooling mechanism to compensate the non-compliant GHG intensity of other vessels. The following Table 3 shows the number of similar vessels operating on MGO according Scenario A, which could avoid paying penalties if they pool their GHG intensity with one vessel operating on 100% e-methanol according to scenario C.

Number of Fossil MGO Vessels	
2025-2029	59
2030-2034	15
2035-2039	5
2040-2044	2
2045-2049	0

Table 2: Number of similar fossil MGO vessels compensated by one vessel operating on e-methanol in compliance pool

A price for selling a vessel's GHG intensity over-achievement in a compliance pool will depend on multiple factors like alternative fuel prices, costs for other efficiency improvements and in general the demand for GHG intensity compensation by other vessels not achieving their target values. A maximum selling price could be defined by the GHG intensity penalties a vessel owner would have to pay according to the FuelEU Maritime. Considering the penalty in 2025 for a vessel in scenario A (~0.6 mEUR), the potential income of such a pooling mechanism might result in up to ~36 mEUR income, compensating all e-methanol fuel costs by selling the over-achievement to other vessels.

The following Table 4 shows the cumulated annual expenses for all scenarios over the vessel's lifetime.

[mEUR]	Scenario A: Fossil MGO	Scenario B: Blend in e-Methanol	Scenario C: Maximum e-Methanol
Until 2030	75	77	174
Until 2035	166	159	347
Until 2040	299	250	521
Until 2045	534	357	695
Until 2050	996	497	869

Table 3: Overview of cumulated annual expenses

A vessel operating on fossil MGO will initially have a cost advantage compared to methanol capable vessels. However already within the first five years, blending e-methanol to the required amount provides comparable cumulated costs as scenario A. Operating fully on e-methanol from 2025 on results in the highest fuel costs, but might be a commercially attractive option where pooling demand can be addressed. These results are corresponding to other comparable studies, like a recent white paper of DNV evaluating a broad spectrum of fuel types and efficiency measures to comply with the FuelEU Maritime. [10]

Methanol oriented decarbonization strategies will encompass two options which have to be carefully weighted based on the individual availability of green fuel, with the supply chain of these posing the greatest investment risks.

- The establishment of a fully multi-fuel capable installation, at the benefit of being able to commission the vessel, prove and market the full set of abilities

  or

- The provision of a vessel with necessary structures, space provisions and safety setups, but not the full setup to operate on methanol (ready concept)

The methanol ready concept offers the advantage to ensure emission target achievement in a stepwise approach based on MAN ES' class approved concept. It enables full flexibility for cost-efficient and reliable operation with the flexibility to operate on alternative fuels once they become locally available.

Choosing the methanol ready approach gives owners benefits in initial CapEx and OpEx according to scenario A in the period until the fuel switch, while an additional retrofit investment is required when the fuel switch is executed.

On top of this, a modern single fuel engine usually operates with a higher overall efficiency than the currently available 4-stroke methanol engines in diesel-mode. In case no sufficient green fuel is available, this higher efficiency results in overall lower GHG emissions for a single fuel engine compared to a methanol engine having to run on fossil MGO, benefiting again GHG related costs like EU ETS and penalty payments.

In case no sufficient green fuel should be available to an owner in the first years, the accumulated savings through higher efficiency, reduced fuel and emission costs and reduced maintenance efforts for a single fuel engine, will enable to finance the later retrofit expenses. MAN ES supports the customers considering on how to handle this challenge in the best possible way within their fleet.

5 SUMMARY AND STRATEGIC CONCLUSION

Getting our planet green is one of the major missions our generation has to fulfill, guided by steadily increasing regulations. MAN Energy Solutions is seeking to do this in the best possible way with its large product portfolio regarding technical requirements as well as optimizing total cost for their customers. Therefore the entire MAN ES 4-stroke product range was systematically assessed how to decarbonize in the best possible way out of the customers perspective, technologically and commercially. For methanol as the most promising future marine climate neutral fuel the main requirements (CapEx, OpEx efficiency, OpEx maintenance, engine performance, fuel flexibility, availability & TBO, dimensions, delivery time) were derived and compared to regular single fuel diesel engines and the main competitors. With all these results the entire MAN ES marine engine portfolio was streamlined to optimize effort and R&D spent for decarbonizing it. As basis for choosing the proper engine technologies, the market was structured into two segments: the "high" specification market with high requirements regarding engine performance (e.g. efficiency, load range and load behavior) and the "low" specification market focused on optimized first costs. The different possible engine technologies HPDI and PFI for using methanol in a medium speed engine were described with their properties incl. possible engine map and retrofitability concluding their suitability for the two market segments respectively. As a key result the readiness approach is explained, operating the engine on conventional diesel with superior efficiency while preparing it for easy retrofit for the point in time it will operate on methanol. Three possible pathways (diesel operation, blend-in e-methanol and maximum e-methanol) to handle the emission regulations are investigated regarding their financial results based on real sailing data of a typical ferry operating in EU waters. In this simulation the stepwise increasing penalties coming into force by legislation are included.

The conclusion is, that there is no one fits all solution for all vessels. The overall optimum is to operate with a methanol ready pure diesel engine with best in class efficiency thus emitting lowest possible GHG emission at lowest costs as long as methanol is not yet available on the specific routes of the vessel. By the time the fuel is available, it has to be investigated specifically for each vessel in the context of the owners fleet, which technology fits best. This is depending on fuel price, penalties in force plus considering possible incentives as well as the operating profile of the vessel at that time. Furthermore the current status within the product lifecycle has to be taken into account to estimate the remaining time in use. The longer the engine will operate at higher loads and / or with high dynamic requirements or with a high operating window demanded in methanol, the more likely it is that HPDI will be the right choice for the retrofit. For vessels that only justify a lower effort for the retrofit from the aspects mentioned, a PFI solution will be the right choice. MAN ES offers amongst others the 175D, 32/44CR and 49/60 as methanol ready products already today in addition to several individual retrofit solutions and the first methanol capable engines 21/31DF-M and 27/38DF-M.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

CapEx = Capital Expenditures

CCS = Carbon Capture and Storage

CR = Common Rail

DCS = Data Collection System

DE = Diesel-Electric (Propulsion)

DF = Dual Fuel

EGR = Exhaust Gas Recirculation

ETS = Emission Trading System

EU = European Union

FAME = Fatty Acid Methyl Ester

GHG = Greenhouse Gas

GT = Gross Tonnes

H2 = Hydrogen

HFO = Heavy Fuel Oil

HPDI = High Pressure Direct Injection

HVO = Hydrotreated Vegetable Oil

IMO = International Maritime Organization

IMO MEPC = International Maritime Organization's Marine Environment Protection Committee

LNG = Liquefied Natural Gas

LPG = Liquefied Petroleum Gas

MAN ES = MAN Energy Solutions

MCR = Maximum Continuous Rating

MeOH = Methanol

MGO = Marine Gasoil

MRV = Monitoring, Reporting and Verification

MW = Megawatt

NH3 = Ammonia

OPS = Offshore Power Supply

OpEx = Operational Expenditures

PESTEL = Political, Economic, Social, Ecological, Legal

PFI = Port Fuel Injection

R&D = Research & Development

RED II = Renewable Energy Directive II

RFNBO = Renewable Fuel of Non-Biological Origin

SCR = Selective Catalytic Reduction

SFOC = Specific Fuel Oil Consumption

SWOT = Strengths, Weaknesses, Opportunities, Threats

TBO = Time Between Overhaul

TCO = Total Cost of Ownership

WTIV = Wind Turbine Installation Vessel

VLSFO = Very Low Sulphur Fuel Oil

7 REFERENCES AND BIBLIOGRAPHY

[1] European Union. 2023. *Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance)*. Official Journal of the European Union, L 234, 22.9.2023, pp. 48–100. Available at: EUR-Lex.

[2] International Maritime Organization. 2023. *Marine Environment Protection Committee (MEPC) 80th session, 3-7 July 2023: Revised strategy on reduction of GHG emissions from ships*. Available at: IMO

[3] Annachhino, M.A. 2003. *New Product Development – From Initial Idea to Product Management*, 1st ed., Butterworth-Heinemann, Burlington, VT, USA.

[4] Hooley, G., Piercy, N.F. and Nicoulaud, B. 2008. *Marketing Strategy and Competitive Positioning*, 4th ed., Pearson Education, Harlow, UK.

[5] Ernst, H. 2002. Success factors of new product development – A review of the empirical literature, *International Journal of Management Reviews*, 4(1): 1-40

[6] Enkel, E., Perez-Freije, J. and Gassmann, O. 2005. Minimizing market risks through customer integration in new product development – Learning from bad practice, *Creativity and Innovation Management*, 14(4): 425-437

[7] Saatweber, J. 2011. *Kundenorientierung durch Quality Function Deployment*, 3rd ed., Symposium Publishing, Düsseldorf, Germany.

[8] Kumar, D., Chen, W. and Simpson, T.W. 2009. A market-driven approach to family design, *International Journal of Production Research*, 47(1):71-104

[9] Barclay, I., Dann, Z. and Holroyd, P. 2000. *New Product Development – A Practical Workbook for Improving Performance*, 1st ed., Butterworth-Heinemann, Oxford, UK.

[10] DNV. 2025. *FuelEU Maritime – Requirements, compliance strategies, and commercial impacts*. DNV. Available at DNV.com.