GREEN MARITIME METHANOL

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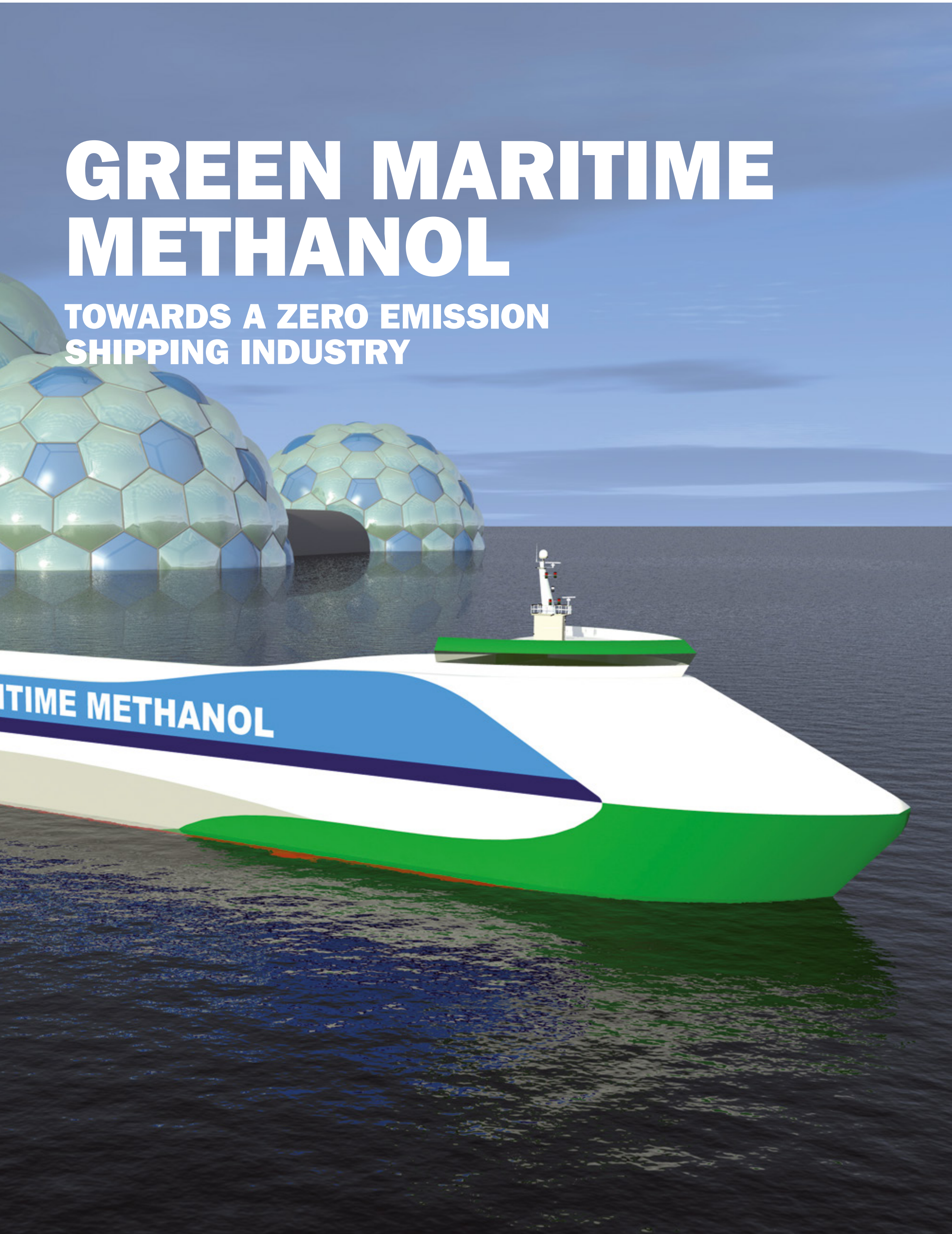
TOWARDS A ZERO EMISSION SHIPPING INDUSTRY



INTRODUCTION

The maritime sector is facing a major challenge. Whilst a globally growing economy leads to greater demand for the transport of goods, the goals from the Paris Climate Agreement and the subsequent agreement of the IMO requires a 50% reduction of CO_2-emissions from maritime transport by 2050 compared to the level of 2008. Several stakeholders (including policy makers, engine manufacturers, ship building companies and research institutes) are working on the development of new alternative fuels and energy carriers for shipping, such as methanol, hydrogen, various biofuels and battery-electric systems. There remains significant uncertainty as to which are the best options for the short as well as the longer term, and what the best options are for different ship segments (e.g. short sea or intercontinental freight transport, naval vessels or passenger ships). Solutions for shipping segments for the short term should contribute to a significant reduction in CO_2-emissions, but also should be compliant with regulations on air pollutants such as the 2020 Global Sulphur Cap and NO_x Emission regulations.

In literature, the use of methanol as an alternative energy carrier for maritime shipping is considered to be a promising option for implementation in the short to medium term, based on its availability, emission reduction potential and energy density. However, in order to assess the feasibility of methanol in different shipping markets and make the next step towards implementation, knowledge needed to be developed in several areas. The following topics for applying methanol as an energy carrier for shipping have been identified:

- Overall technical and operational requirements:
  - Investigation of different options for applying methanol in a ship engine,
  - Safe storage and handling of methanol on board, and
  - Bunkering safety and operations.
- Economic and environmental viability:
  - Overall market potential of application of methanol,
  - Investigation of different production and supply chain routes, and
  - Effect of different production routes on emissions,
- Translation of these overall results into different shipping markets:
  - Detailed ship design based on the specific technical layout and operational profile for different vessel types, and
  - Business Case for applying methanol for these different vessels.

In the Green Maritime Methanol project, a consortium of leading Dutch and international maritime companies and knowledge institutes have joined forces to investigate these topics. The consortium brought together a wide set of stakeholders in order to bring extensive experience and knowledge for the different topics. The following 30 partners participated actively in the consortium:

- Major *shipowners* Boskalis, The Royal Netherlands Navy, Rijksrederij, DEME, Arklow Shipping, Van Oord, Wagenborg Shipping and the associate carrier organization KVNR,
- *Shipbuilding companies*, Damen Shipyards, Feadship, Royal IHC,
- Major *marine engine manufacturers* Pon Power, MTU and Wärtsilä together with their trade association VIV,

- Specialized *marine systems design and equipment supplier* Marine Service Noord and *maritime service provider* C-Job Naval Architects,
- *Class societies* Bureau Veritas and Lloyd's Register,
- The Netherlands' two largest *ports* of Rotterdam and Amsterdam,
- *Methanol suppliers* BioMCN and Helm Proman and *trade organisation* The Methanol Institute, and
- *Research Institutes* TNO, TU Delft, NLDA, MARIN and Ghent University, supported by the Maritime Knowledge Centre.

The Green Maritime Methanol project was supported by TKI Maritime and the Netherlands Ministry of Economic Affairs and has been completed in two years.

Figure 1: Overview of the Green Maritime Methanol consortium

This report presents a high-level summary of the 10 deliverables of the project. These deliverables can be found via greenmaritimemethanol.nl.

PROPERTIES OF METHANOL

Methanol is a fuel that has sometimes been overlooked in policy and industry discussions despite having many attributes that make it an attractive marine fuel. It is compliant with the strictest emissions standards, plentiful and available globally, could be manufactured from a wide variety of fossil and renewable feed-stocks, and its properties are well-known because it has been shipped, handled and used globally for a wide variety of uses for more than 100 years. Moreover, it is similar to current marine fuels in that it is a liquid.

Methanol is an alcohol and alcohols have deviating properties compared to conventional hydrocarbon fuels such as marine diesel oil. The following table provides the chemical properties of methanol and compares this to the properties of Marine Diesel Oil (F76)

Table 1: Technical characteristics of different fuel types

Properties	Diesel Oil	Methanol	Hydrogen	Ammonia	LNG
Chemical structure	$C_{12}H_{26}–C_{14}H_{30}$	CH_3OH	H_2	NH_3	C_nHN
Molecular weight	190–220	32.042	2.02	17	16
Density (kg/m^3) liquid	830	790	73,22 (20K)	680 (20k)	419
Density (kg/m^3) gas	-	-	0.084	0.73	0.83
Boiling point (°C)	180-360	65	-253 (20K)	-33	-161.4
Lower heating value (MJ/kg)	42.6	19.9	120.2	18.6	48 - 50
Flammability limits (vol)	1.85-8.2	6.7-36	4.1 - 74	15-28	5-15
Flash point (C)	78	11	-	-	-136

Some conclusions from this table are:

- The energy density (lower heating value) of methanol is about half of the value of regular diesel oil; however, the density is much higher than that of liquefied hydrogen (LH_2),
- Methanol is in a liquid phase at room temperature and ambient pressure, offering the possibility to use existing diesel storage systems with a few relatively small adaptations compared to other alternative fuels, notably those that are a gas at room temperature, and
- Methanol is a low-flash-point fuel and the design of ships using such fuels are to meet the safety objectives and functional requirements of Part A of the IGF Code. The provisions of Part A1 are limited to ships using LNG, whereas the recently approved MSC.1/Circ 1621 gives provisions for ships using methanol as fuel.

The energy density of a fuel is an important factor for its applicability. The the higher the density, the less storage space is required for normal operation of the vessel. The figure below summarizes results for different fuel types and shows the energy density expressed in MJ per m^3 for the fuel itself as well as the density including packaging (size of the storage tanks including secondary barriers and cofferdams). Diesel, MDO and HFO, as reference fuels, have a relatively high energy density compared to the alternative fuel types. Methanol has a significantly lower density than diesel, but higher than the other fuels in the comparison, especially when taking packaging into account.

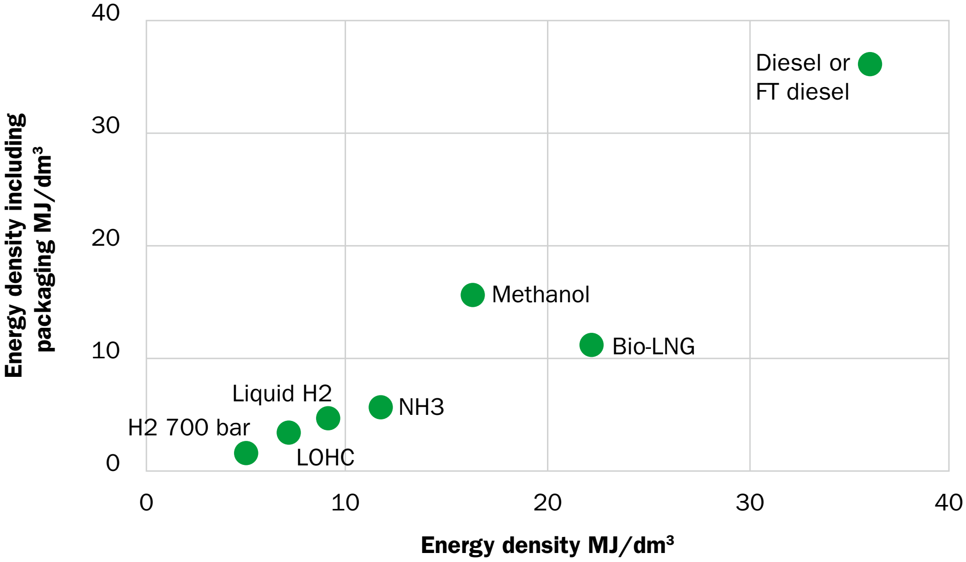


Figure 2: Energy density of different fuel types

PERFORMANCE IN THE SHIP’S ENGINE

Because the chemical properties of methanol differ from various diesel types, methanol cannot be injected directly in a compression ignited internal compression engine (CI-ICE). There have been some demonstration projects where methanol has been implemented as a maritime fuel. Stena Germanica, a passenger ferry, employs medium-speed four stroke marine engines by Wärtsilä running on (separate) directly injected methanol and marine gas oil as pilot fuel. Furthermore, tankers by Waterfront Shipping operate with MAN low-speed two-stroke engines, again using separate direct injection of methanol and a pilot fuel (MGO). Measurement and engine performance data on these engines is limited, with only information showcasing emission regulations compliance and diesel-like efficiencies being available by manufacturers. In recent years, there were additional demonstration projects that have been initiated for maritime applications such as LeanShips, MethaShip, GreenPilot and SUMMETH. However, research and publications on combustion and engine performance by application of methanol in marine engines is scarce.

Figure 3: Converted tugboat in the GreenPilot

There are several options to inject and ignite methanol in an internal combustion engine. Within the project, engine tests were performed for two of these concepts. This section describes the different types of engine options and the results of tests performed within the project.

PORT-FUEL INJECTION IN A SPARK IGNITED ENGINE

A first option is the **port-fuel injection in a spark ignited engine**. After the exhaust stroke when the exhaust valve has closed, the inlet valve opens and the (partly evaporated) methanol – air mixture enters the cylinder. Near the end of the inlet stroke, the inlet vale closes and during the compression stroke pressure and temperature build up. The remainder of the fluid methanol evaporates. Around 20° BTDC a spark is given (the optimum moment is one of the research questions) and the air-methanol mixture ignites resulting in a steep increase of the pressure. After this the work stroke follows.

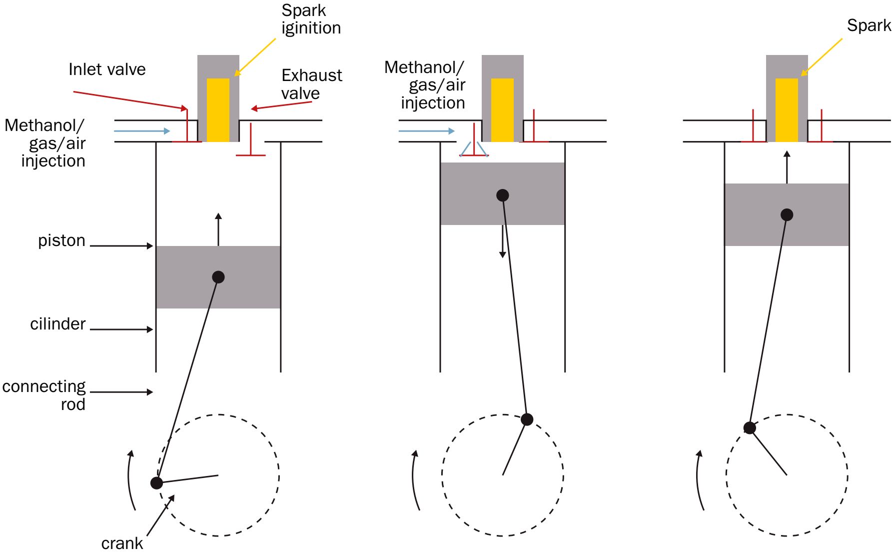


Figure 4: Schematic overview of the port-fuel injection and spark ignition process

As part of the project, engine tests were performed with a Cat 3508G-SI engine at PON in Papendrecht. The engine is a turbocharged spark-ignited natural gas (NG) engine with 8 cylinders and a rated power of 500 kWe at 1500 rpm. Significant modifications have been made to the engine for safe operations and measurements with 100% methanol. This included system changes such as modification to the fuel system, air cooling system and the control system, safety measures and measurement equipment.

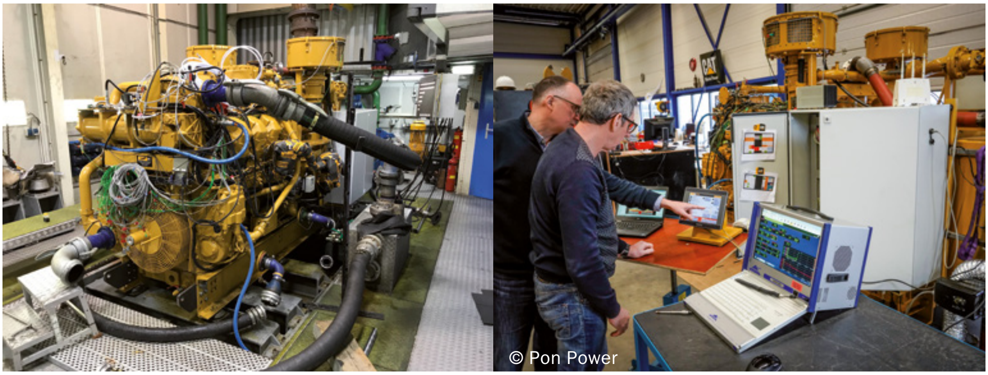


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Figure 5: Test setup in Papendrecht

Tests with stable engine operation were achieved with 100% methanol at 25%, 50%, and 75% engine loading and a constant engine speed of 1500 rpm. In this research, experiments and modelling have been performed to study combustion using 100% PFI methanol. Measurements were realized with varying ignition timings, NO_x emission settings, and manifold temperatures. The measurement data have been used to validate a developed methanol engine model and to optimize the engine performance for further experimental runs and better understanding the use of methanol as a fuel. The engine operates stably on methanol at 50% and 75% load within ignition timings of 16-24 °CA BTDC, but less stable than with Natural Gas. Heat release indicates a shorter combustion duration is shown for methanol. Also with methanol, the crank angle where 50% of fuel is burnt (CA50) is shown earlier compared to Natural gas. The faster premixed combustion, combined with a better fuel consumption operating point, resulted in higher efficiencies for methanol (37.7%) compared to NG (36.5%) for the tested 50% and 75% load at comparable operating conditions.

Results with the spark ignited engine are very hopeful. We could run on 100 % methanol and efficiency even slightly improve with indications of decreased NO_x emissions.
We recommend to perform future research with the SI engine focusing on:

- Impact of increased air temperatures on the evaporation of methanol before entering the cylinder,
- Impact of evaporated methanol percentage on the combustion process,
- Impact of ignition timing on the combustion process,
- Maximizing engine performance, and
- Pilot projects in order to show results in real-life operations.

METHANOL-PILOT-FUEL MIXTURE IN A COMPRESSION IGNITED INTERNAL COMBUSTION ENGINE

A second option is direct injection of a **methanol-pilot-fuel mixture in a compression ignited Internal Combustion Engine (ICE)**. In this option, a mixture of methanol and pilot fuel (in this case diesel) is injected directly in the cylinder. The injection process is that of a classical compression ignition engine. Ignition is started by the auto-ignition of the pilot fuel and after the pilot fuel ignites, the methanol / air mixture follows. As part of the Green Maritime Methanol project, an analysis was made on the use of emulsifiers in order to keep the methanol-pilot fuel stable and experiments were performed with a 4-stroke compression ignited engine.

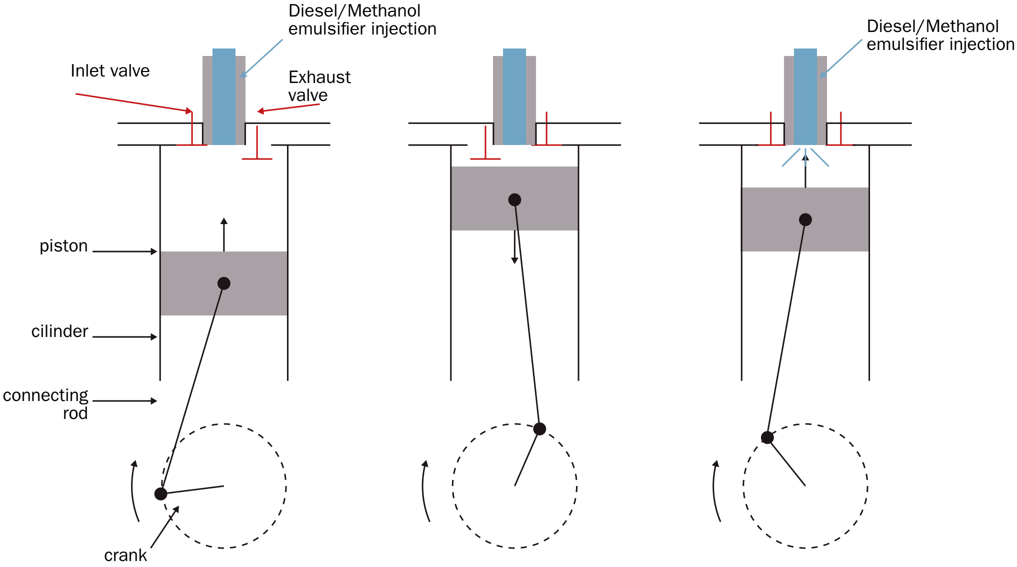

Figure 6: Schematic overview of the direct injection of a methanol-pilot fuel mixture

Dissolving methanol in diesel has as a main advantage that only minimum of adaptations to the engine would be necessary. In order to keep this process stable, the pilot fuel concentration in methanol (or methanol concentration in the pilot fuel) cannot fluctuate much. This imposes strict requirements to the mixture, and preferably we aim for dissolving one fuel in the other. The prime pilot fuel that is deemed to be suitable in this process is F76. However, methanol and F76 will separate in time as result of four degradation processes: Ostwald ripening, aggregation processes, phase separation, and phase inversion. Analyses were performed in order to slow down these processes to obtain a solution that remains stable for 8 hours or longer. A few emulsifiers were tested to observe stabilization time. The tests show that a stable emulsion appears when *Hypermer B246-SO-(MV) (0.3 w/v%)* is used. This mixture remained stable for more than 10 hours. This emulsifier is also the only one that could accomplish this result. Due to the small amount of emulsifier Hypermer B246-SO- (MV) required, it appears to be quite effective.

In this research, tests were performed in the lab facilities of NLDA in Den Helder using a MAN 4L20/27 compression ignited test engine. A methanol-diesel mixture was directly injected in the cylinder and ignited by compression. Just as for the testing with the spark-ignited engine, significant modifications were made to the fuel system of the engine and safety precautions were made in order to ensure safe operations. Tests were performed using three different methanol/ diesel blends:

- 100 % diesel pilot fuel (F76),
- A blend where 10 % of the energy was supplied by methanol, and
- A blend where 20 % of the energy was supplied by methanol (about 37,5% volumetric of methanol).

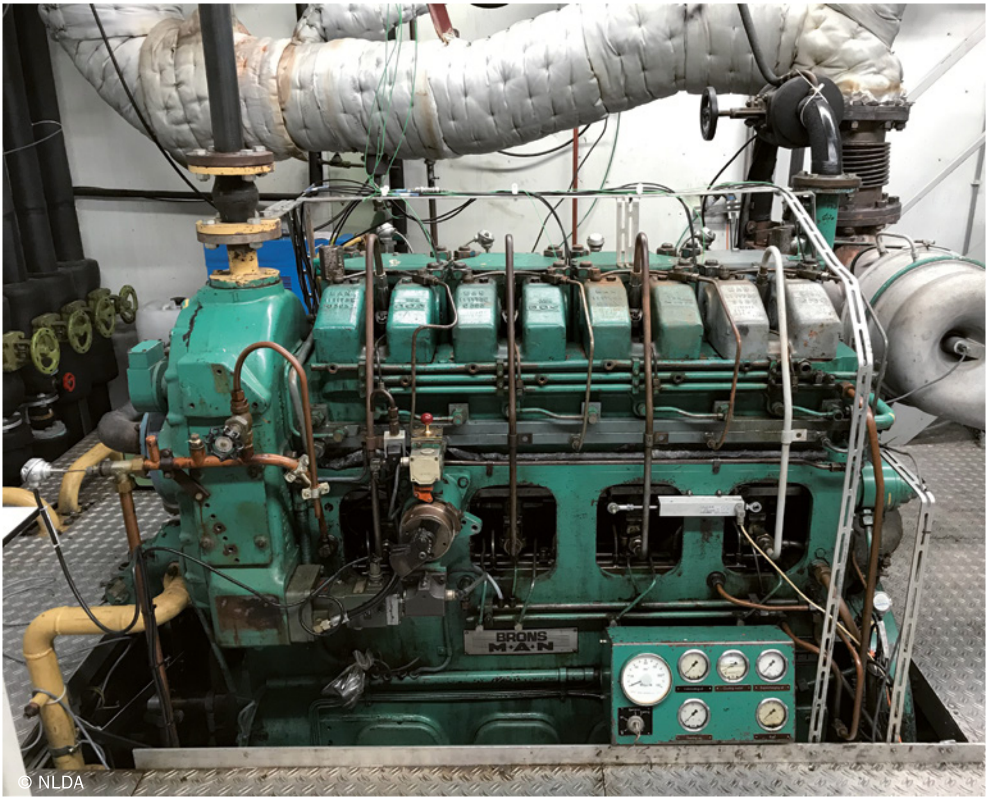

Figure 7: Test setup in Den Helder

During the experiments, the engine was not able to maintain its operation envelope from a methanol ratio of 20 [% energetic]. At low loads, the engines temperature seems to be too low in order to vaporize the methanol in the engine. Operation below 153 kW resulted in an engine failure due to failed ignition in the cylinders. For direct injection in the cylinder this phenomenon can be countered by decreasing droplet size (decreased opening of the injection needle and increased injection pressure) and by earlier injection of methanol. Overall, combustion process stability decreased with increasing methanol content.

NO_x emissions decreased between 2.9% and 14.2% by using methanol compared to 100% diesel F76. We assume the short combustion time and the cooling effect caused by evaporation of methanol are responsible for this difference.

Extrapolating these results to a full-scale situation on board of a ship does not give hopeful results. It is quite an issue to keep methanol and diesel mixed in a tank. In our lab setup we could keep both fluids well mixed by permanently mixing. The day-to-day practice on a ship is less controlled than a lab situation. It is easy to make mistakes, and this could lead to a completely separated diesel/ methanol mixture in the day-tank. As a result, sooner or later pure methanol will be injected in the engine, which doubtlessly leads to engine failure. In our view, future research should focus on injecting methanol and a pilot fuel separately in an internal combustion engine.

OTHER ADVANCED METHANOL ENGINE CONCEPTS

The **direct separated methanol pilot fuel injection** allows separate injection of methanol and a pilot fuel. During the first phases of the compression stroke methanol is directly injected in the cylinder. This gives the methanol some time to evaporate and mix well with the air in the cylinder. Near the end of the compression stroke an explosive air/methanol mixture has formed in the cylinder that only needs an excuse to ignite. At that moment a small amount of pilot fuel is injected and ignites, enabling combustion of the methanol/air mixture. This method requires a significant reconstruction of existing engines or even a complete redesign. Smaller engines may not have sufficient space in the cylinder head for the two required injection needles for pilot fuel and methanol.

Another possibility is a **methanol port fuel injection direct injected pilot fuel method**. The method is a copy of the method shown in Figure 8 but now ignition is started by a pilot fuel directly injected in the cylinder.

No engine tests have been performed with these two concepts as part of the Green Maritime Methanol project. This would be an important topic for further research.

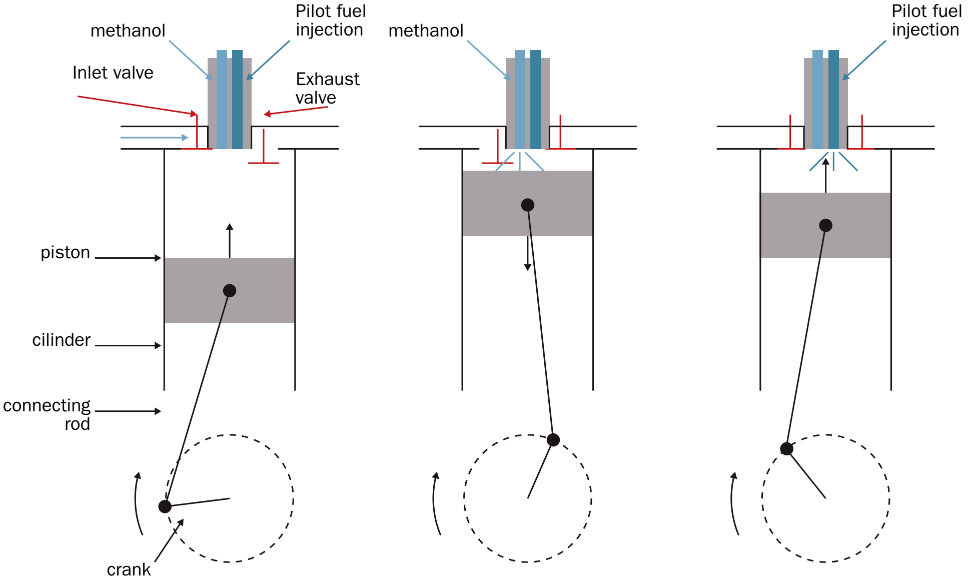

Figure 8: Schematic overview of the direct injection of methanol and separate pilot fuel

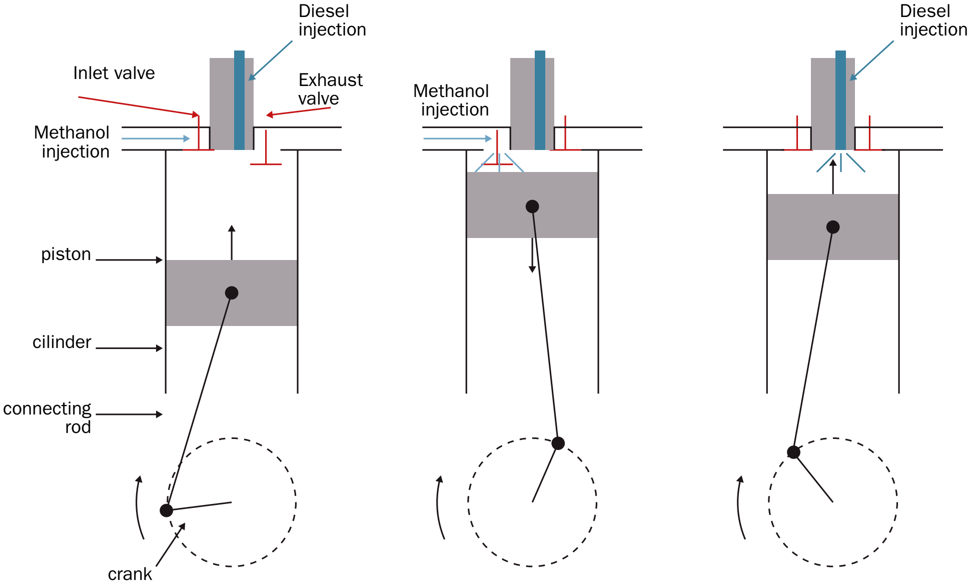

Figure 9: Schematic overview of the port fuel injection of methanol in a pilot fuel ignited ICE

SAFE STORAGE AND HANDLING ON BOARD

Demonstrating that novel technologies are possible at a safety level ‘equivalent’ to existing technologies serving a similar purpose, can be done in a convenient way by applying the concept of risk-based design. A practical way of comparing the safety/ risk of a novel fuel to existing fuels is by listing typical precautionary measures of both in a table and stating the associated hazard mechanisms alongside the precaution. In addition, the specific toxic, chemical and thermodynamic data of the fuels need to be compared. Throughout such comparative analyses the hazards, typical to people, the ship and the environment are the three focal points.

The process of making such a comparison is straight forward but requires a considerable effort. However, the result is rewarding because it allows for a consistent and rational comparison between risks introduced by the new fuel and risks of a fuel with which the community is familiar.

In the project the equivalent safety of methanol was compared to that of Marine Gasoil (MGO). The detailed findings of this analysis can be found in the WP3 safety report. The analysis demonstrates that through additional measures methanol bunker fuel can be *designed into* the tolerable risk region. Methanol fuel is therefore now in the same risk category as MGO and Heavy Fuel Oil (HFO). Thus, risk equivalence is demonstrated. There are however some safety issues that need to be addressed further.

A first aspect is the mechanism of vented methanol vapors entering the spaces in the ship. The source of vented or leaked methanol needs to be clear as it defines the behavior of this hazard. For example, liquid methanol will possibly spray or cause pools, depending on the pressure and flow, and evaporate to form toxic or flammable mixture if not sufficiently ventilated or drained. Regulations related to flammability limits state minimum distances between venting outlets and space entrances/ air intakes (IEC 60079-10). Ventilation requirements should be determined on a site-specific basis, but the ultimate target is to ensure that methanol concentrations in air do not reach or exceed 200 ppm. Technical evidence supporting the choice of the actual distances is difficult to generate. It would probably require CFD calculations and physical testing, either in a wind tunnel or full scale. Current safety zone distances are derived from IBC Code and IGF Code and reflect good practice in other applications. These minimum distances pose severe restriction on the ship design. It may be attractive to further investigate these because a better understanding of air/ vapor flows may give opportunities to alleviate these very restrictive distances.

Another mechanism which needs to be addressed further is tank leakage. Above the ballast water line, a safe distance between tank and ship shell is required, while below the ballast waterline there is no such requirement (CCC6 5.3.2). Here also it is not straight forward to generate supporting technical evidence. Leakage below the ballast waterline is regarded as not so hazardous because methanol is not toxic to aquatic life (H411 in SDS). Moreover, since methanol has a density of 0.8 ton/m^3, sea water will enter the tank rather than methanol escaping the tank, depending on the pressure of the nitrogen blanket on the methanol and possibly on how far the tank is below the waterline. Above the ballast water line however, methanol will escape from the tank and a pool will develop on the waterline. Above this pool, a vapor/air mixture will develop causing a flammability, asphyxiation and intoxication hazard. It is worthwhile to further investigate the actual mechanisms associated with methanol escaping above the water line. It may very well be the case that the pool dissolves quickly in the water while any vapor disperses rapidly. If it can be demonstrated that after a methanol egress a hazardous situation exists only for a (very?) short period, it might be considered to lift the safe distance above the ballast water line. This again would substantially increase the design flexibility for the naval architect.

BUNKERING SAFETY AND OPERATIONS

Today, there are three main bunker transfer methods being applied. In mature bunker markets, ship-to-ship bunkering is the dominant method, certainly in terms of volume. Truck-to-ship bunkering is being used for vessels with low demand and offers flexibility and control over the delivered quantity and specs. Shore-to-ship bunkering is often being applied by smaller vessels such as tugs, inland shipping vessels (floating installation), utility vessels, fishing boats, and patrol and inspection vessels (coast guard). Lloyd's Register together with Methanol Institute developed a Technical Reference which provides operational safety management protocols for bunkering.

Since methanol is a liquid just as oil, most of these methods can and will be applied to methanol as well. Methanol is being treated as a hazardous liquid, so it requires some additional safety measures. However, infrastructure adjustments are marginal, contrary to LNG bunker facilities. The additional measures include among others specific safety equipment, training and certification. The IAPH audit and accreditation tool helps ports to issue a license to operate methanol bunkering in their port area. In truck-to-ship bunkering, interpretation of the safety regulations on the quay (applicability of environmental permit regimes of terminals) may differ between countries, this needs further elaboration when aiming for a European level playing field.

In the transition phase, it is expected that in the pilot phase truck-to-ship will be mainly used, but when adoption of methanol further increases the larger ports will soon facilitate ship-to-ship bunkering and shore-to-ship for the local fleet. This might require additional safety measures since vessels carrying methanol are marked with two blue cones. In terms of bunker vessels, the total market will grow, the lower energy density simply requires more frequent bunkering. However, the ports do not foresee any serious capacity or safe navigation issues.

MARKET SIZE AND PRODUCTION ROUTES

POTENTIAL SIZE OF THE METHANOL SHIPPING MARKET IN THE ARA REGION

The potential market for which methanol is applicable for marine propulsion is considerable. Based on data analysis of vessel arrival data in the ports of Rotterdam and Amsterdam, sailing on methanol seems applicable for most midrange shipping markets. The often over-dimensioned tank capacity allows them to bunker methanol without serious adjustments to the bunker frequency, sailing pattern, or tank capacity/ship design. This is particularly the case for shortsea shipping markets and shipping markets with point-to-point sailing patterns. Moreover, inland shipping looks also promising for methanol, whereas ultra large container ships are being built with expanded tank capacity. The methanol applicability heatmap is shown below.

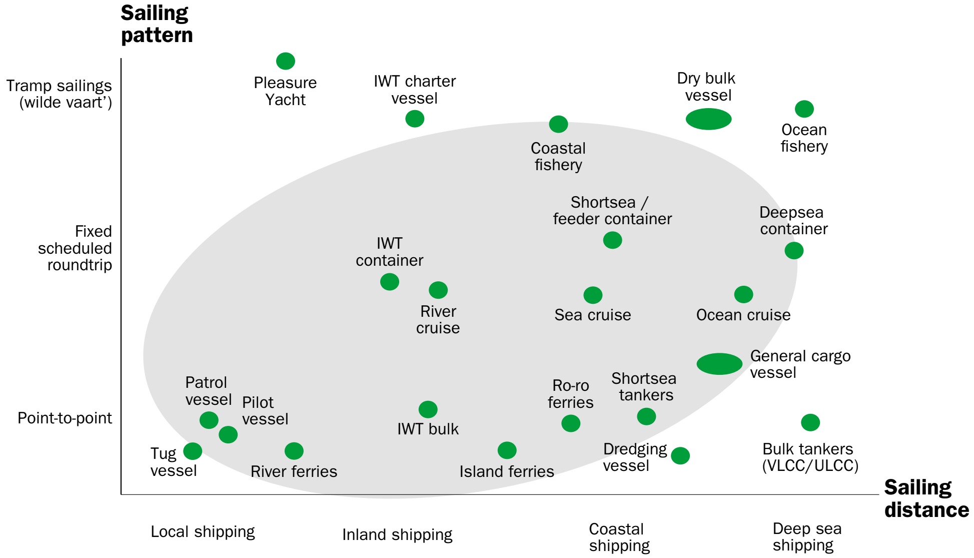

Figure 10: Heatmap of methanol-applicability of shipping segments

The global bunker demand is estimated at around 300 million metric tons fuel per year (in 2012). Container vessels constitute of 6% of the world fleet but consume 22% of total yearly bunker volume. Together with dry bulk carriers, oil and chemical tankers consume almost 60% of the global bunker demand. Bunkering in Europe is concentrated in a limited number of ports. The ARA-region (Rotterdam, Antwerp and Amsterdam) handles 20 million Mt, covering 40% of the European market. HFO represents 80%, biofuels and LNG are still marginal in volume, but rapidly increase their share in the modal split. A scenario analysis, taking into account the methanol applicability heatmap, results in an estimated methanol bunker volume in the range of 0.6 to 2.6 million m^3 for Rotterdam and 1.1 to 5.0 million m^3 for the whole ARA-region (5% to 22% of the total bunkering market).

METHANOL PRODUCTION ROUTES

There are four possible production routes for methanol. This section will briefly introduce them and will provide insights on the impact of these routes on possible emission reduction of the maritime sector and on the availability and possible pricing of these different routes.

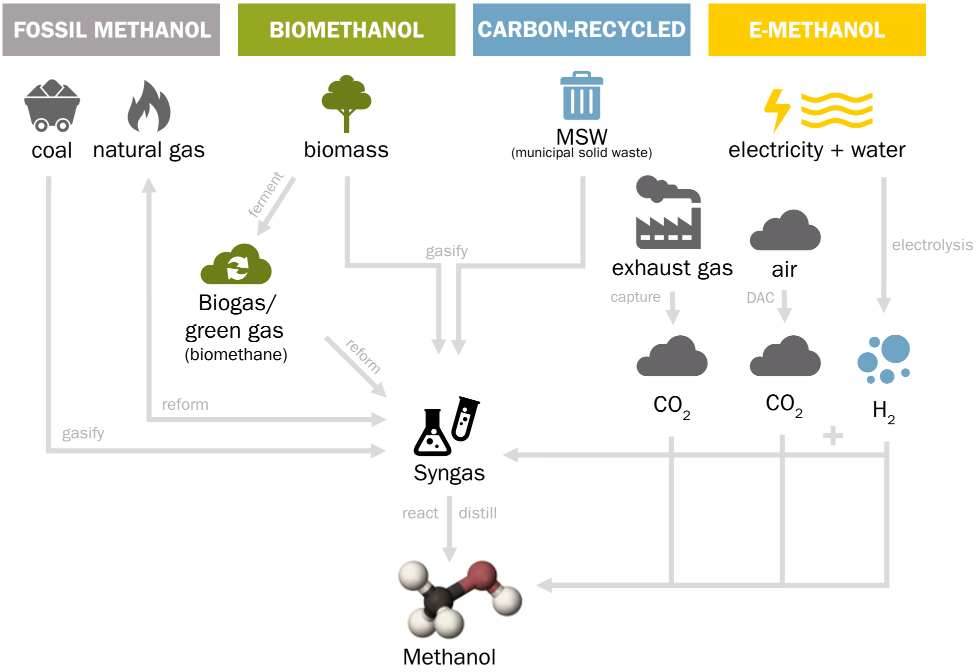

Figure 11: Schematic overview of different production routes for methanol

Typically, the production of methanol uses fossil fuels **(fossil methanol)**. It takes place by reforming of natural gas to produce synthesis gas (syngas), or from coal gasification to produce syngas (predominant in China). From syngas, methanol can be produced by CO or CO_2 hydrogenation with an energy efficiency of roughly 80%. Fossil methanol is a well-established market in Europe. Currently around 1.5 Mt is produced in EU27 and around 7.5 Mt is being consumed. Globally, production is around 100 Mt. Significant amounts of the European methanol demand get imported from Trinidad, Venezuela, Equatorial Guinea, the United States and Russia. The Netherlands is an important hub for the current import and European distribution of methanol imported from outside Europe. The Netherlands can consequently also serve as hub for the distribution of green methanol from production locations outside Europe.

Biomethanol is a renewable energy source. Its feedstock is biomass, which includes agricultural and forestry products such as wood pellets, black liquor (a waste product from paper production or sugar beet processing waste), animal waste products (manure) and organic fraction of municipal solid waste and sewage sludge. Biomass can directly be gasified to syngas or fermented to biogas in a process called anaerobic digestion. The biogas can then act as a precursor to produce either syngas or biomethane. Biomethane is biogas that is purified to natural gas quality. It has the advantage that it can be fed into the existing natural gas network, which greatly facilitates its distribution as a feedstock for methanol production. The two options of fermentation and gasification allow for very heterogeneous types of biomass. If produced from biogenic waste as listed in the Renewable Energy – Recast to 2030 (RED II), biomethanol qualifies as an advanced biofuel.

The production of **carbon-recycled methanol** makes use of a similar gasification technology as dry biomass. Waste streams that are otherwise non-recyclable can be gasified and thereby used as a feedstock for methanol production.

To produce **e-methanol** or **power-to-fuel methanol**, hydrogen (H_2) is produced by water electrolysis, either with electricity from fossil fuels or by using renewable electricity. Carbon dioxide (CO_2) can be captured from industrial exhaust gases, from biomass, or by direct air capture (DAC). Together, hydrogen and CO_2 can be combined to either produce syngas, or to directly react to form methanol.

AVAILABILITY AND PRICES OF DIFFERENT FEEDSTOCK ROUTES ARE UNCERTAIN

Future price developments of fossil methanol will be in line with that of the natural gas market. The price development for the long term will depend on several factors like economic growth, the oil and gas supply and to a significant extent to development of environmental policy measures such as CO_2 allowance fees.

European production for biomethanol or carbon-recycled methanol is currently at significantly lower production capacities than their grey counterparts. The attention and demand for these production routes is vastly growing, and with that also the supply is expected to increase continuously. Future biomethanol prices show a wide range and will be influenced by several factors, including biofeedstock supply, technological development of production, the demand from different sectors, as well as national and international policies. The same considerations and price uncertainties also apply to other biofuels such as biodiesel or LBG.

E-methanol is currently at a lower technology readiness level as the other feedstocks. Availability and prices depend a lot on the increase in capacity of green electricity (driving the hydrogen price) and the price of sustainable CO_2-source (DAC).

The cost ranges of grey, bio- and e-methanol, and their depencies on feedstock prices are summarised below.

Table 2: Cost range for fossil, bio- and e-methanol, and their dependencies on feedstock costs

Methanol type	Cost range	Cost dependent on
Fossil methanol	€ 9-22/GJ	Policy, Natural gas price
Biomethanol	€ 11-33/GJ	Policy, Biomass & green gas price
E-methanol	€ 27-68/GJ	Sustainable electricity and CO_2 costs

IMPACT ON EMISSIONS

GREENHOUSE GAS EMISSIONS

The feedstock that is used for the production of methanol has a significant impact on the Greenhouse gas emissions. The well-to-propeller CO_{2eq} emissions of different feedstocks of methanol were compared with that of diesel and LNG These values deviate slightly from the values in the more detailed analysis in the previous sections. The well-to-propeller GHG emissions are graphically shown in Figure 12. Based on fossil fuels, the GHG emissions of methanol and LNG are a bit higher than for diesel fuel. This is respectively 5%-10% (methanol) and 5% (LNG) higher. It is therefore important to switch directly to a sustainable methanol source in order to reduce CO_2-emissions. Based on biofuels; methanol has lower GHG emissions than the other energy carriers. Biodiesel shows a broad range depending on feedstock and production method.

In case of synthetic production via green electricity and hydrogen, the GHG emissions will likely be low for all three fuels. For both production routes, emissions of LNG are higher than methanol, due to the usual engine methane emission.

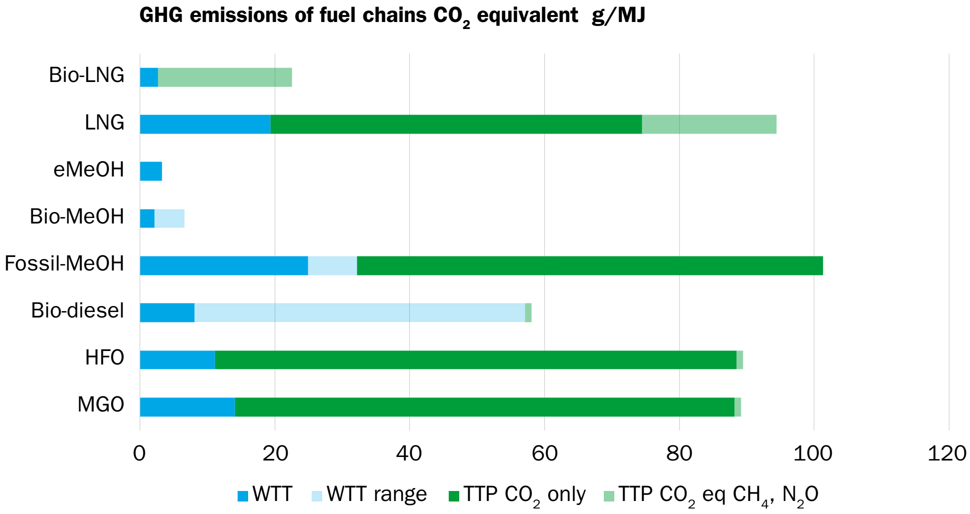

Figure 12: Well-to-propeller CO_2-equivalent emissions for different energy carriers with 100-year Global Warming Potential, GWP (CO_{2eq} g/MJ).

AIR POLLUTANTS

The following table shows the tank-to propeller pollutant emissions for respectively Nitrogen oxide (NO_x), Sulphur (SO_x) and particulate matter (PM) in gram per kWh mechanical work (engine output). The SO_x and PM emissions for methanol and LNG are very low. The SO_x emissions are primarily based on the sulphur in the diesel pilot. A diesel pilot of 2% on energy basis is assumed (plus in addition ~5 ppm S within the LNG). MGO and methanol need additional NO_x emission control technologies to meet Tier III NO_x emission level. For MGO this will be SCR aftertreatment or EGR (Exhaust Gas Recirculation). For methanol, the most likely technologies are SCR aftertreatment or application of a methanol-water fuel mixture.

Table 3: Tank-to-propeller pollutant emissions for MGO, methanol and LNG in gram per kWh mechanical work (engine output).

g/kWh	HFO 0.5% S	MGO 0.1% S Tier II	MGO 0.1% S Tier III	Methanol Tier II	Methanol Tier III	LNG Tier III
NO_x	12.8	9	2-3	5	2.2	2
SO_x	2.0	0.36	0.36	0.007	0.007	0.009
PM_{10}	0.74	0.23	0.23	0.034	0.034	0.02

Compliance with current and future emission legislation can be met with all three fuels. However, for LNG and methanol, NO_x emission control for Tier III will be easier. Also, SO_x and PM emissions will be some 75% lower than for diesel fuel (MGO and HFO). Lower SO_x and PM emissions with diesel fuel are also possible, but then almost all Sulphur needs to be taken out of the fuel, or a biofuel could be used.

VIABILITY FOR DIFFERENT SHIP MARKETS

Knowledge found in the Green Maritime Methanol project has been translated into six practical ship designs. These designs were evaluated with regard to safety, technical and economic feasibility in view of future pilot projects. These designs were developed by smaller working groups within the consortium consisting of a vessel owner/ carrier, a ship design company, complemented by other members such as engine and component manufacturers and knowledge institutes.

The selected real-life vessels in this work package are shown below. Based on several design considerations, such as availability of methanol engine and space issues for methanol tanks, methanol is likely a more suitable fuel for some of the ships than for others.

Figure 13: Ship types evaluated in detail for methanol solutions

SHORT SEA SHIPPING CONTAINER VESSEL

© Wagenborg Shipping

Built:	2009
Builder:	Koninklijke Niestern Sander
Length overall:	137.9 m
Breadth overall:	15.87 m
Draught design approx:	7.98 m
Deadweight tonnage:	11,300 ton
Total bunker capacity:	850 m^3 HFO 70 m^3 MGO
Power:	4500 kW Wärtsilä 9L32C engines
Speed:	11.2 knots

The Wagenborg E-borg series comprises of seven bulk freight carrying vessels that operate both on coastal and transatlantic routes within and outside Emission Control Areas (ECA).

Concept design for methanol

In the researched conversion of the Wagenborg E-series, methanol will be used for the propulsion of the vessel. For the propulsion system, intention is to keep the current principle of a geared drive, using the engine driving the propeller via a gearbox. The gensets are intended to keep running on MGO. In case the engine conversion or replacement is being considered as a major conversion under MARPOL, it has to be discussed with Class if the gensets need to become Tier III compliant as well. Sufficient methanol storage capacity will be created as necessary for fueling the engine during ECA operations. The rest of the tanks remain MGO tanks, in order:

- To accommodate long distance voyages outside Emission Control Areas, and
- To have sufficient bunker capacity for the situation that methanol is not available, or that methanol is more expensive (on energy basis) than MGO.

To be able to safely use and store methanol on board, the vessel needs to be equipped with a couple of dedicated systems: a methanol bunker system, a methanol transfer system and a nitrogen blanketing system.

In the current bunker storage system, about two-third of the HFO bunker capacity is stored in three tanks located in the cross-bunker section. Another part of the HFO tanks and all the MGO tanks are located in the engine room. The cross-bunker section is the construction halfway the length of the vessel separating the holds. This section is selected for the storage of the methanol tanks, because it intrinsically has a high volume, part of which is already used for storing fuel and the section is relatively easy accessible, an advantage from the perspective of conversion.

Based on the operational profile of 2018, the minimum required methanol storage capacity was set to the equivalent of 140 MT MGO plus a margin of 10%. This is equivalent to a methanol storage capacity of 330 MT. For sailing outside ECA and in case of unavailability of methanol the rest of the fuel tanks will be MGO tanks (377 m^3).

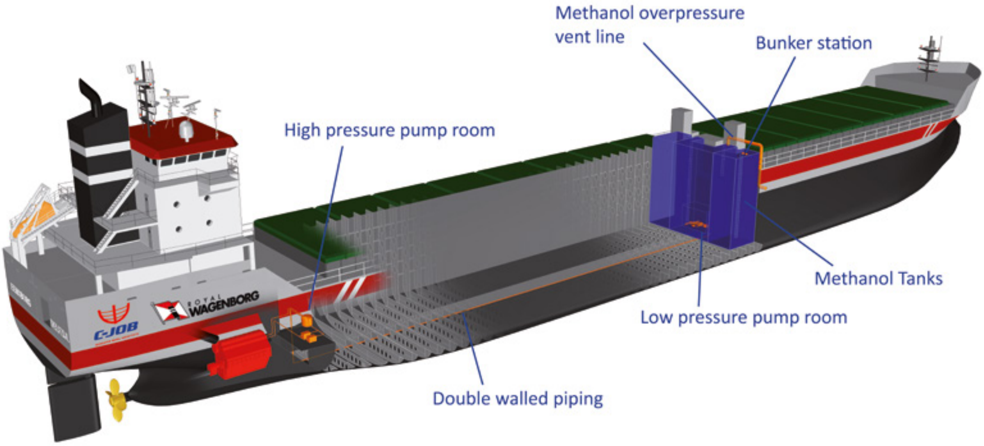

Figure 14: Cross bunker section with methanol cross bunker storages, low pressure pump room and methanol overflow tank.

For the minimum required methanol storage capacity of 330 MT an effective storage space of 418 m^3 is required. The combined capacity of the three current HFO tanks in the cross-bunker section is 550 m^3. Sufficient tank capacity for storing the methanol is available this way.
To fulfil the safety requirements set in IGF code for methanol storage in the cross-bunker section the following solutions were applied:

- Two cofferdam-bulkheads were applied in front and aft of the cross-bunker section, with a distance of 600 mm.
- Bulkhead penetrations for hold entrance and ventilation were lengthened with a distance of 600 mm.

HAZID - Regulations and classification

In order to identify and mitigate the risks existing in the design of the system and which are not covered by prescriptive regulations, a HAZID has been performed which is worked out in a separate HAZID report by C-Job.

The HAZID sessions gave a lot of insight into the risks involved when using methanol on board a vessel. The end result is that a methanol system is technically feasible for the Wagenborg E-borg series, but there are some unknowns left to explore in future research:

- The behavior of methanol vapor when released in ambient conditions and what this means for placement of vent masts. If the vent masts are placed above the deck area and methanol vapor drops, this results in a hazardous situation. Therefore, the position of the vent mast can be on the vessels side in the hull. Since it is unclear how methanol vapor disperses, this requires further research before vent masts can be placed,
- The effect of water blending of methanol. Blending could make storage less dangerous. A SCR might not be needed when water blending is used to comply with Tier III of the IMO,
- Capabilities and limitations of methanol specific equipment,
- Type of ship to shore link,
- Desired extent of redundancy for sensors and other components, and
- Access to high pressure pump room by airlock in the engine room or directly from open deck.

Findings of the case

A practical ship design is made with compliant methanol systems. Knowledge of other work packages on safety items, regulations, operational aspects and environmental footprint analyses are put into a conceptual conversion of the E-series.

DREDGING VESSEL


© Boskalis

Built:	2010
Builder:	IHC Dredgers
Length over all:	144 m
Breadth moulded:	28 m
Depth to upper deck:	13.5 m
Max. draught dredging:	10.0 m
Displacement:	34 000 tons (approx.)
Hopper capacity	12 000 m^3
Total bunker capacity:	1,585 ton HFO/MDO (incl. service tanks)
Main Power:	12,000 KW (2x Wärtsilä 12V32)

The dredging case was based on the (existing) vessel Willem van Oranje. The option was investigated for retrofitting of this dredger to be able to use methanol as fuel.

The Willem van Oranje distinguishes three (main) operational profiles: dredging and pump ashore, dredging and dumping, and transit. The dredging profiles each have a different impact on the overall power usage. In principle, the vessel is being used 24/7 and projects can be executed all over the world. For this reason, this case will consider a dual fuel solution, in order to be able to execute tasks in areas where no methanol is available.

Concept design for methanol
The design concept for retrofitting considered redesign of the engine, the bunkering tank arrangement and the engine room configuration.

The existing engines are deemed suitable for reconfiguration into a system with dual fuel injectors (direct separated methanol pilot fuel injection, see Figure 8 on page 13). Modification of the cylinder heads is required.

Originally the Willem van Oranje was designed with several HFO tanks and MDO tanks. The HFO tanks are currently situated in the midship along the hopper with a total capacity of 1585 m^3. The tanks are adjacent to the longitudinal hopper bulkhead, but not adjacent to the ship's side shell due to fuel outflow regulations (MEPC.141(54)). The MDO tanks are situated in the aft ship on Port side and have a smaller capacity (100 m^3).

To convert the actual tank arrangement into a suitable methanol tank arrangement, the starting points must be clear. In the case of this hopper dredger, it is the intention to be able to switch between a methanol/(low sulphur) MGO combination and single-fuel (low sulphur) MGO given the operational circumstances. Furthermore, if the same autonomy must be maintained as the current layout, the capacity of the tanks must become 2.5 times bigger. This seemed impossible to realize in an existing ship. Thus, it was decided that two weeks dredging and (preferably) one large transit must be possible. Considering this condition, it could be concluded that the current tank arrangement has overcapacity.

Based on this information, changes were made to the tank arrangement. Methanol tanks may be adjacent to the side deck below the lowest draught of the vessel. However, because the vessel must be able to sail on MGO, it was no option to extend the tanks to the ship's side shell and bottom. It was decided to make additional methanol tanks under the existing tanks. Between the methanol tank bulkhead and the longitudinal hopper bulkhead, cofferdams were required. The spaces under the hopper currently contain equipment such as cable trays, valves, bilge lines and hydraulic installation. These spaces would be adjacent to the methanol tanks if no cofferdam is in between. This would mean that these spaces are hazardous zones which is not allowed. Cofferdams reduce the tank capacity significantly and are not easy to manufacture because of the narrow space (Cofferdams of 60cm wide are not easy accessibly for welders.).

A set of layouts were created that enabled changing a tank arrangement of an existing ship for methanol and the ability to run on MGO only.

It was found that a methanol fuel preparation room could not be situated in the existing lay-out of the engine room. So, space must be found in the midship on the cost of bunker capacity. On top of that it was found that the initial width of the cofferdams (600 mm) was too small. A minimum width of 800 mm is required to be able to manufacture it. So, a new search was done for additional tank capacity. This additional capacity was found by extending the SB-side methanol bunkers in the aft part of the midship through transverse bulkhead of the pump room. In the fuel preparation room, a service tank can be located and the double bottom tank can be extended under the fuel preparation room, see the figure below.

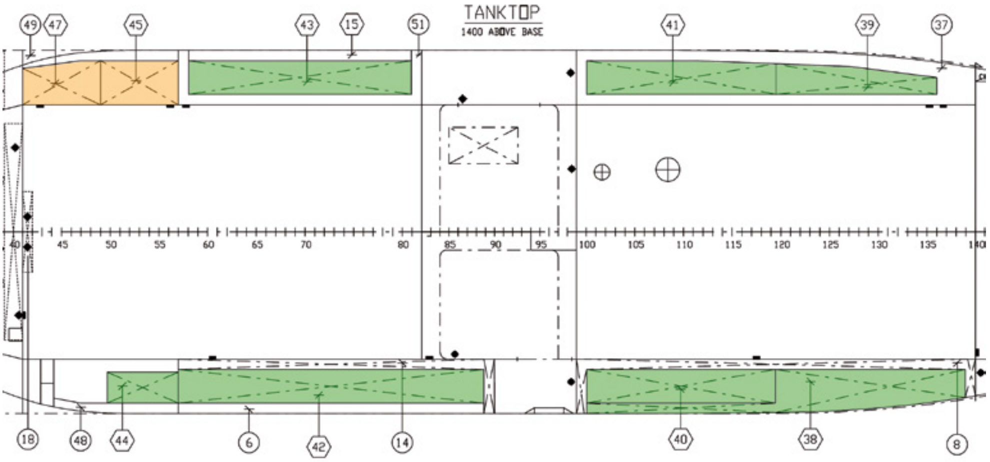

Figure 15: Modified methanol tank arrangement for the dredging vessel

The final methanol capacity in this layout is now 1337 m^3 (green in Figure 15) together with 231 m^3 pilot fuel (orange), and in MGO mode the total capacity is 1012 m^3 (green and orange). Although not according to what was preferred, this seems to be the maximum which can be achieved reasonably. The autonomy for the resulting methanol and MGO capacity, taking into account the energy density of methanol and MGO and a daily consumption of 45 m^3 MGO, is summarized in the next table.

Table 4: Bunker capacity and autonomy for the dredging vessel in the current situation and for the methanol/ MGO dual fuel option

Fuel type	**Volumetric capacity**			**Autonomy[1]**		
	Current (HFO/MDO) vessel [m^3]	**Methanol mode [m^3]**	**MGO mode [m^3]**	**Current (HFO/MDO) vessel [days]**	**Methanol mode [days]**	**MGO mode [days]**
MGO	1,585	231	1012	33		21
Methanol	-	1,337			16	

From this table it can be concluded that 2 weeks dredging is feasible for the achieved methanol capacity. However, the preferred 20% pilot fuel is not achieved. Furthermore, due to additional construction weight, ballast, and weight of fuel the max. carrying capacity is reduced with 2.5%.

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[1] The autonomy is based on 95% volumetric tank capacity

Findings of the case

The subject of the study was to check if it was feasible to use methanol as an alternative fuel for the Willem van Oranje using a dual fuel system. During the study it appeared that a big challenge is the bunker capacity in relation to sufficient autonomy (time between bunkering, trans-ocean crossing). The choice for dual fuel complicated this case even more.

Tanks for methanol need cofferdams above the water line and where they are adjacent to other (accessible) areas (inside the ship). Tanks used for MDO need cofferdams when they are adjacent to the hull. Using tanks for both methanol and MDO means that quite some space is used for cofferdams thus reducing the bunker capacity considerably. The main conclusion is that in a retrofit case the tanks cannot be optimized completely. In case of new building a better optimization can be found.

Autonomy reduced from approx. 33 days to approx. 16 days. This means more frequent bunkering stops while executing a project. Due to additional construction weight, ballast, and weight of fuel the max. carrying capacity is reduced with 2.5%.

It is roughly estimated that due to the additional investment for conversion the weekly cost will increase approx. 5%. In total based on items investigated the cost price per m^3 is increasing with approx. 10 - 12%.

In case it is assumed that not on all future projects the conversion will be rewarded by the client (either no interest or no methanol available) the increase in cost price (for projects in which the client is willing to reward the use of methanol) will be more. This is still without increased price of methanol over MDO.

CABLE LAYING VESSEL


© Van Oord

Built:	2014
Length over all:	122.68 m
Breadth moulded:	27.45 m
Max. draught dredging:	5.82 m
DWT:	8,398 tons
Cable carousel	5,000 tons
Total bunker capacity:	1,678 m^3 (incl. service tanks)
Main Power:	10,948 kW (Total Power installed)
Speed:	12.4 knots

The purpose of the project was to convert the existing cable laying vessel Nexus of Van Oord in order to reduce the CO_2-footprint of the vessel by 50%. Air pollutants of the redesigned vessel should comply with IMO Tier III.

For the analysis of the operational profile of the vessel, the energy consumption for both short- and long-range operations was evaluated. The average current fuel consumption is approx. 25 m^3 MGO per day for cruising (part 1 of the long-range mission operations). For short range operations the approx. fuel consumption is 15 m^3. For these typical mission profiles, the vessel needs approximately 1,000 m^3 of methanol tank volume and approx. 500 m^3 of MGO tank volume. In the short-range mission profile of two weeks the objective of 50% reduction of CO_2-emissions can easily be met. In the long-range mission profile of four weeks, only 22% of CO_2-emissions can be reduced.

Table 5: Fuel consumption and CO_2-emissions for the cable laying vessel for different mission profiles

Fuel consumption and CO_2 emissions	**Fuel**			**CO_2–emissions**		
	Type	**Energy [GJ]**	**Volume [m^3]**	**Weight [Tons]**	**Tons1)**	**Reduction %**
Short range mission profile (two weeks autonomy)	MeOH	8,05	517	409	262	54%
	MGO pilot2)	403	10	9	29	
	Total	8,453	527	418	291	
	MGO only	8,453	230	198	634	0%
Long range mission profile (four weeks autonomy)	MeOH	8,05	517	409	262	22%
	MGO pilot2)	403	10	9	29	
	MGO	12,1	329	283	906	
	Total	20,553	856	701	1,197	
	MGO only	20,553	559	481	1,539	0%

Concept design for methanol

For this use case, Damen made a conceptual design of the engine room systems for the new situation. The analysis shows that a rebuild towards methanol engines on the ship design is a major conversion, but that it's feasible to modify the vessel to an engine room with DF MeOH-MGO engines in the generator sets, complying with the additional Rules and Regulation for safe operations with MeOH. The following figure presents the 3D model of the concept design (taking into account the results of the HAZID).

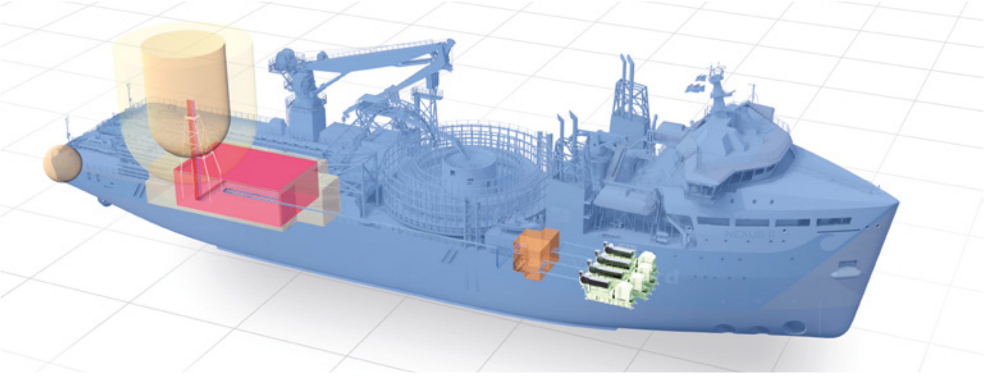

Figure 16: 3D model of the concept design for a methanol cable laying vessel

For modification of the engines, two configurations were considered. The first configuration was to modify the current engines on a MeOH-MGO blend (minor modification). Based on the results of the engine in this project, this option was not deemed feasible. A new DF MeOH-MGO engine concept has to be developed (major modification) based on a direct separated methanol pilot fuel injection (see Figure 8 on page 13). In order to meet the IMO Tier III emissions requirements, most likely an SCR unit needs to be added.

HAZID - Regulations and classification

Also for this use case, a HAZID has been performed. The hazardous zone plan has been made by Marin in consultation with Lloyds Register and Van Oord. A detailed overview of the findings is presented in the WP5 report. An important aspect that came forward in the process is that the ventilation outlets of tanks and spaces should be positioned so that hazardous zones are as far away from working areas as reasonably possible. The use case therefore recommends to investigate application of underwater tank ventilation outlets in future research.

Findings of the case

Using methanol in combination with MGO is a suitable option for the cable laying vessel. For short term missions, the required 50% CO_2-reduction objective can be reached. The impact for rebuilding the vessel towards methanol is extensive. As a further step, a concept design of the ship's hull and superstructure, the ships arrangement and the ship systems needs to be made as well as further tests and development of a new methanol engine with a separate injector.

HYDROGRAPHIC SURVEY VESSEL


© DMO

Built:	2003
Length over all:	75 m
Breadth moulded:	13.1 m
Draught:	4.0 m
Displacement:	1.750 tons (approx.)
Total bunker capacity:	435 m^3
Main Power:	1,500 kW (Diesel-electric drive)

The Netherlands Ministry of Defense aims to reduce its dependency on fossil fuels by at least 20% by the year 2030 and 70% by the year 2050 (compared to 2010). Two Hydrographic Survey Vessels are approaching their end of life, presenting an opportunity to introduce an alternative fuel source and begin the journey towards reduced fossil fuel dependency. In this Case Study, a methanol design of the existing *Zr.Ms. Snellius* and *Zr.Ms. Luymes* was compared to an updated re-design, both complying to the latest standards and regulations.

The operational profile of the vessels is summarized below:

- Days at sea: 150
- Distance sailed: 26.000 nautical miles
- Total Fuel Consumption: 830 m^3
- Average Daily Fuel Consumption: 5-6 m^3
- Typical duration between fueling: 2 - 4 weeks
- Average amount fuel embarked: 93 m^3 (21% of total 435 m^3 capacity included RAS tank)
- Target amount fuel held onboard at any one time: 95%
- Minimum amount fuel held onboard at any one time: 60%

Concept design for methanol

As starting points, the following parameters were defined for the methanol re-design of the vessel.

- 2-5 diesel/methanol generators (single fuel - pure methanol or methanol with a small quantity of diesel 8-10%),
- Each generator capable of developing in the range of 400-1000kW,
- Range of 4300nm @ 12 knots,
- As a starting point, the design will be based on the requirements of the IGF code, in particular the IMO “draft interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel”, approved in November 2020 as MSC.1/Circ 1621 Interim Guidelines.

The methanol power system will be used to supply electrical power to the ship's network from the main generators. Since the methanol power system is the single source of propulsion power on board, redundancy shall be built into all subsystems to assure that the system will not fail or fully shut down in a single incident scenario, other than a single incident incapacitating the engine room (like an engine room fire or engine room collision). A fully independent diesel fueled emergency generator is installed as per conventional regulations. No additional tanks have been introduced in the methanol design – the existing diesel tanks are repurposed to hold a total embarked volume of 435 m^3 of methanol. Owing to the hydrophilic nature of methanol there is no requirement for double-hulled tanks; however, the tanks are surrounded by a safety zone in the form of cofferdams. In addition to the fuel tanks, the methanol storage subsystem consists of several auxiliary components needed for fueling and system safety such as pressure relief devices (PRD), (main) shut-off valves and a nitrogen blanketing and purging system. The subsystem will be located in two physically separate and segregated fuel preparation spaces adjacent to the engine room. The inclusion of two separate fuel preparation spaces, outside of the engine room ensures that if there is a problem with one, the other can safely maintain provision of fuel to the combustion engines.

The Main Generators shall be installed in the Engine Room at mid-ship Tank deck / Lower Deck, next to the methanol fuel preparation spaces. The Main Generators shall be driven by specially designed methanol fuel engines, derived from type approved gas-safe engines - considered intrinsically safe and therefore remove the requirement for the engine room to be considered a hazardous zone.

The “Main Generator subsystem” consists of several auxiliary components needed for the effective and efficient operation. These components include such items as injectors and injector pumps, exhaust treatment systems, engine monitoring and control systems, sensors, et cetera.

The engines are supplied with fuel via double walled piping. The fuel is routed directly from the Main Storage Tanks to the engines via the Fuel Supply Pumps in the Fuel Preparation Rooms. It is assumed that the engines are designed in such a matter, that a methanol leakage in the engine room can never occur. In this way, the engine room can be labelled “gas safe” and thus can be equipped in the same way as a normal engine room and negating the requirement for a gas tight enclosure and dedicated ventilation system for each engine. For this project, 5 retrofitted combustion ignited (CI) ScandiNAOS engines, each capable of delivering 375kWe are chosen, with mechanical output expected at 390ekW (96% alternator efficiency).
These engines run on methanol with a 2-3% ignition improver and are IMO Tier III compliant.
A cost calculation was made for the new design. The cost price was found to be 7.3% higher than a regular diesel fueled setup. The technical solutions on which the cost price calculation was based, is focused on the methanol fuel system and its safety aspects. Additional attention regarding the electrical power and distribution system has not been considered and further work may be required for optimal performance.

HAZID - Regulations and classification
For this use case a HAZID was performed. The outcome from this process was a risk matrix which highlighted the technical challenges to the introduction of methanol and a number of areas of uncertainty where additional research is required to fully understand the technical implications. Recommendations were given on several topics, including fuel distribution,

installation of cofferdams around bunker tanks, inclusion of two separate fuel preparation spaces and safety measures to deal with methanol vapor dispersion.

Findings of the case

The design shows that methanol is a suitable option for the Hydrographic Survey vessel. Several design challenges have been identified in the design study and additional work is recommended at certain safety topics such as vapor dispersion. The overall cost price of the system is slightly higher than a regular diesel system.

PORT PATROL VESSEL

© Port of Amsterdam

Built:	2013
Builder:	Damen Shipyards
Length over all:	19,64 m
Breadth moulded:	7.94 m
Depth to upper deck:	3.39 m
Draught design approx.:	2.49 m
Displacement:	176 tons
Total bunker capacity:	14 tons MGO
Power:	896 kW (2x Caterpillar C18, 425 kW, 1800 rpm)
Speed:	11.2 knots

The Port patrol Vessel was brought in by the Port of Amsterdam. On an annual basis port patrol vessel Castor will operate in the Amsterdam Port area for 315 days with on average 16 hours of operating time per day. The total operating time for Castor is estimated at 5,040 hours per year. The average speed during patrols is limited to 5.4 knots

Concept design for methanol

The concept design for methanol was based upon the conversion of one main engine to methanol while the other engine would still be running on marine gasoil (MGO), with regard to system redundancy leading to the following concept design. In this concept design only the port side engine is converted to methanol, also the port side bunker tank is converted for methanol storage and includes cofferdams for safety issues. On the port side also a dry disconnect bunker connection for methanol is installed, as well a pressure vacuum (P/V) valve at waterline level for safety venting.

The starboard side engine and auxiliary engine as well as the starboard bunkering tank are designed to continue operating on marine gasoil. The methanol pumps are located in a separately ventilated space in the engine room. The aft peak foam tank will be used as a tank for alcohol resistant foam. On the work deck behind the wheelhouse, space is reserved for a Nitrogen tank inerting system and an extra CO_2 firefighting system for the engine room.

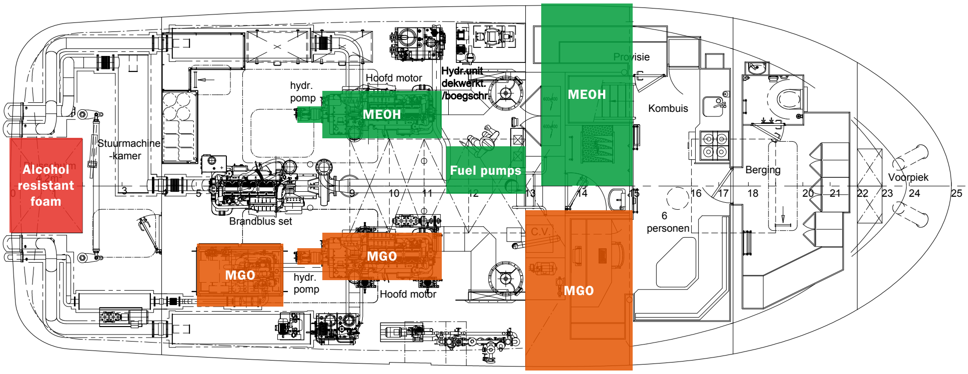

Figure 17: Port Patrol Vessel Castor – Below deck

In this concept, methanol is stored in the port bunker tank, with cofferdams near the center line of the vessel and the engine room bulkhead. The cofferdam at the center line is installed at the expense of the MGO bunker space and the one near the engine room bulkhead at the expense of the methanol bunkering space. The impact on bunkering capacity is dependent on the minimum required size of the cofferdam (900 mm vs 500 mm).

There is no conversion package available for converting the current engine towards methanol and in the power range for the vessel there are currently no methanol engines available. The only experimental methanol engines available are produced by Scandinaos and are converted Scania MD98 13L engines (350 kW) or Weichai SI 12L engines (313kW). However, the output power of these engines is too little with regard to operational requirements of the Port of Amsterdam.

Regulations and classification - HAZID

At present there are no rules and regulations available for inland vessels that want to use methanol as a transport fuel. For methane as a transport fuel there is a temporary regime for inland vessels using methane issued by the CCR. It is to be noted that for the use of low flashpoint fuels (<55C) in inland waterways, ESTRIN 2019 only has specific provisions for methane gas (Annex 8 Section 1). For the use of other fuels, a derogation from the requirements is to be requested and supported by engineering analysis and risk assessment (ESTRIN Chapter 30 refers). Systems would require class approval even for vessels that do not require classification (such as dry cargo vessels). It is expected that additional regulations are written in the course of 2021 addressing fuel cells, hydrogen and methanol. When included in ESTRIN 2023 these regulations could be applicable from 1 Jan 2024. Until that a derogation procedure needs to be followed with Class and Flag. Due to Dutch and EU objectives towards zero emissions, it is generally anticipated that derogations are granted, provided sound engineering and risk analysis can demonstrate safe design. Port of Antwerp is in the process of converting existing tug to methanol duel fuel concept.

A HAZID was not yet executed in this phase. In case of a future design, it must be noted that ESTRIN Chapter 30 Section 5 specifies the need for such a risk assessment for low flash point fuel applications.

Findings of the case and solutions for design challenges
Port of Amsterdam concluded that in the current situation a retrofit of this vessel is not feasible yet. The existing vessel is built very compact and there is little room for extra bunker capacity and the additional safety measures that come with a retrofit towards methanol. Methanol requires new fuel tanks and piping on board which would be a major and costly conversion for the vessel. Therefore, a retrofit was not regarded as a sustainable option for this patrol vessel.

For future decision-making regarding newbuilding, methanol will be taken into consideration as a clean fuel for the vessels of the Port of Amsterdam. However, several issues still need further attention and research.

INLAND PATROL VESSEL

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Built:	1998
Builder:	Damen Shipyards
Length over all:	18.47 m
Breadth moulded:	5.00 m
Depth to upper deck:	2.49 m
Draught design approx.:	1.35 m
Displacement:	66 tons
Total bunker capacity:	3 tons MGO
Power:	1040 kW (2x MAN D2840 LE401, 520 kW)
Speed:	16.6 knots

The inland patrol vessel is operated by the executive agency of the Ministry of Infrastructure and Water Management, Rijkswaterstaat. The ship is under management of the Governmental Carrier organization Rijksrederij. On an annual basis patrol vessel RWS 88 will operate on inland canals and (small) rivers for about 1,500 hours per year. The current maximum speed of 16.6 knots is not really required and the current maximum engine power of 1,040 kW can be reduced to approximately 700 kW.

Concept design for methanol

The concept design for methanol was based upon the conversion of both main engines to methanol and the auxiliary engine continues to operate on MGO.

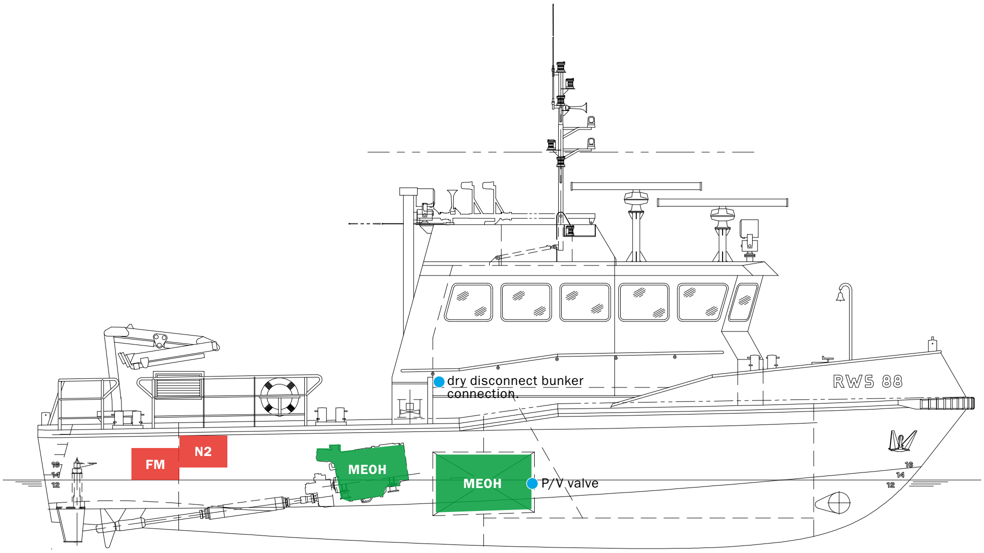


Figure 18: Patrol Vessel RWS 88 – Side view

Due to the use of cofferdams the methanol bunkering capacity is reduced from 2 x 1,500 liters of MGO to an estimated 2 x 500 liters of methanol. This reduces the operating range of the vessel with 67%. The plan is to operate the RWS 88 after conversion on inland canals and (small) rivers for about 1,500 hours per year. Estimated fuel consumption on methanol is approximately 90,000 liters per year. This implies a fuel consumption of approx. 2,000 liters of methanol per running week and means bunkering two times a week. For this pilot project that is deemed acceptable.

The location of the bunkering tank is in the midships, which hardly influences the stability of te vessel. However, some of the port and starboard bunker tanks are located above the lowest waterline of the vessel. Although a nitrogen blanket system is used for the bunker tanks. this might pose problems regarding evaporation of the methanol when exposed to the sun burning on the sides of the vessel. This issue should be further investigated in co-operation with IL&T and classification societies.

There is no conversion package available for converting the current engines towards methanol and in the power range for the vessel there are currently no methanol engines available. The only experimental methanol engines available are produced by Scandinaos and are converted Scania MD98 13L engines (350 kW) or Weichai SI 12L engines (313kW). Although the output power of the Scandinaos engines is significantly smaller than the current MAN engines, they could be used on board of the RWS 88 since the required maximum output power of the vessel is reduced from 1,040 kW to approximately 700 kW. Another option would be the conversion to two Scania 16L V8 compression ignited engines that run on MD97 which is 97% methanol and 3% ignition enhancer. The ignition enhancer makes it possible to operate the engines compression ignited, which gives superior fuel efficiency (in particular on part load) and identical drive characteristics as a conventional diesel engine (torque, response etc.).

HAZID - Regulations and classification

As mentioned before in the case of the Port Patrol Vessel, for methanol no provisions have yet been made in ESTRIN 2019. No HAZID has been performed for this vessel yet.

Findings of the case

Although the RWS 88 is a relatively small vessel, it can probably be converted to a full methanol vessel. However, discussion on the regulatory framework and/or exemptions with the Ministry of Infrastructure and Water management, and probably also with classification societies is required in order to design and built inland vessels using methanol as a fuel.

Although methanol engines are told to be available on short notices (within 6 months), in practice these engines are still in an experimental stage and it is not easy to receive any detail information about these engines.

OVERALL FINDINGS OF THE USE CASES

CONVERSION VERSUS NEWBUILDING

For existing vessels, it is more complicated and costlier to execute a conversion from HFO or MGO towards methanol. For some of the vessels these complications proved to be a show-stopper for the conversion towards methanol. When requirements for methanol as a transport fuel are included at the beginning of the ship's design process, cost for implementation of a methanol system including tanks and safety systems are significantly lower compared to the conversion process.

However, in view of the average lifespan of about thirty years for commercial vessels, the low replacement rate of 3.3% per year of an entire fleet continues to justify the search for cost reduction of ship conversions in order to meet future emission targets. Modular design of vessels will be an important step in reducing costs for possible future conversions.

MAJOR CONVERSION VERSUS MINOR CONVERSION

In this study a major conversion is defined as a conversion where the vessel is enlarged with several frames in order to accommodate the methanol system on board, or a significant change in the operational profile is required. A minor conversion is a conversion where enlargement of the existing vessel is not required.

For several of the studied vessels a major conversion is required in order to realize the methanol fuel system on board. The tailor-made design of these vessels simply does not allow for modifications of tanks, bulkheads and inclusion of cofferdams or double walled piping. This is the case for the Dredging Vessel, the Hydrographic Survey Vessel and the Port Patrol Vessel. Furthermore, the operational range of all ships researched is decreased considerably due to the reduced energy density of methanol. For some vessels this would require an elongation in order to obtain the required bunker volumes. However, for other vessels a minor conversion suffices. This is the case for the Short Sea Shipping Container vessel, the Cable Laying Vessel and the Inland Patrol Vessel. No elongation is required since lower bunker tank capacities can be compensated with higher bunker frequencies and there is sufficient room for system modifications towards methanol below deck and in the engine room in particular. From a technical point of view, the conversion of existing vessels towards methanol is feasible. However, the financial implications of such a conversion might not always warrant such a decision. Especially for older vessels near the end of life, the investment for a major or minor conversion cannot be justified based on economic principles.

NEW ENGINES VERSUS RETROFIT ENGINES

At present only few new engines are available for methanol. MAN is the only engine supplier who delivers two stroke engines for methanol tankers that can run on their own fuel. Wärtsilä has executed a conversion of a conventional diesel engine towards methanol on the Stena Germanica, but there are no standard retrofit packages yet. The demand for retrofit packages towards methanol engines is currently too small, mainly due to the price gap between MGO and (green) methanol. Scandinaos has converted Scania engines towards spark ignited and compression ignited methanol engines for smaller vessels and power ranges up to 400 kW. Although these developments are in an early stage it is hopeful that there are some pioneers that take steps toward the introduction of methanol engines in the marine market. In the European FASTWATER project which recently started, ABC will take the initiative to convert one of her engines towards methanol.

Many engine manufacturers have expressed interest in the Green Maritime Methanol project over the last two years. However, it is quite a large step for most of them to start the production of conversion packages towards methanol engines (in case this is anyhow possible) or to start producing methanol engines in larger amounts. Apart from the larger two stoke engines of MAN the market demand for these engines seems presently too low. Issues on what kind of engines should be developed first (single fuel, dual fuel, compression ignited, spark ignited), needs to be addressed before production on a larger scale can start to take place.

DEDICATED VERSUS FLEXI FUEL TANKS

For dual fuel engines fuel flexibility is of great importance. (Sustainable) Methanol might not be available in every port around the globe. This means that fuel tanks for diesel should be able to be used for methanol and vice versa. This is an operational challenge regarding contaminations and cleaning of the fuel tanks. This subject requires further study and also development of clear and unambiguous rules.

VENTING ON DECK VERSUS VENTING NEAR THE WATERLINE

Finally, it is concluded that venting methanol a certain distance above deck might pose a challenge based on e.g. the ambient temperatures during venting, pressures, the amounts of vented air/methanol and the people working in that deck area. Rules have been implemented, but verification of the behavior of methanol fumes in various circumstances should be a subject of further detailed study.

BUSINESS CASE CALCULATIONS

Based on the analysis of the developed price scenarios of methanol for feedstocks and the specific inputs of the six ship design use cases, the Total Cost of Ownership (TCO) was calculated for the different vessel types.

In the TCO calculations, the total costs of the powertrain, consisting of both the capital and operational costs, were calculated over a lifespan of 15 years. In these calculations different fuel options were elaborated:

- Two reference scenarios in which HFO or MGO (fossil diesel fuel) were used (Grey and brown lines in the subsequent figures),
- A scenario with 100% fossil methanol (yellow line),
- A dual fuel option in which 30% MGO and 70% sustainable Methanol (based on a bio-feedstock) were used (in light blue).
- An option in which 80% sustainable and 20% fossil methanol are combined (in dark blue). This use case was chosen to consider the possible effects of reduced availability of sustainable methanol,
- An option in which 100% sustainable methanol (based on a bio-feedstock) was used (green line).

There are significant uncertainties with respect to fuel price development in the coming years. Therefore, for each of the options, different price levels were considered (low, medium and high range of the prices presented in Table 2 on page 19). In the figures, this is shown through the light-colored intervals which show the costs in high and low fuel price scenarios.

Figures 19 and 20 show the TCO results of the different options for the short sea container vessel and the inland patrol vessel. The results do not include any CO_2-emission taxation (current situation) or application of HBEs which are currently applicable for biofuels. Under this scenario, it is clear that the cumulative total costs over the years for 100% sustainable methanol concept is significantly higher than in the reference. This is especially the case for the short sea container vessel, which is due to high share of the operating costs in the total TCO. However, also the capital expenses for this case are higher due to retrofit expenses. Note that the prices used in the cost calculations are based on generic market values, real world costs may vary.

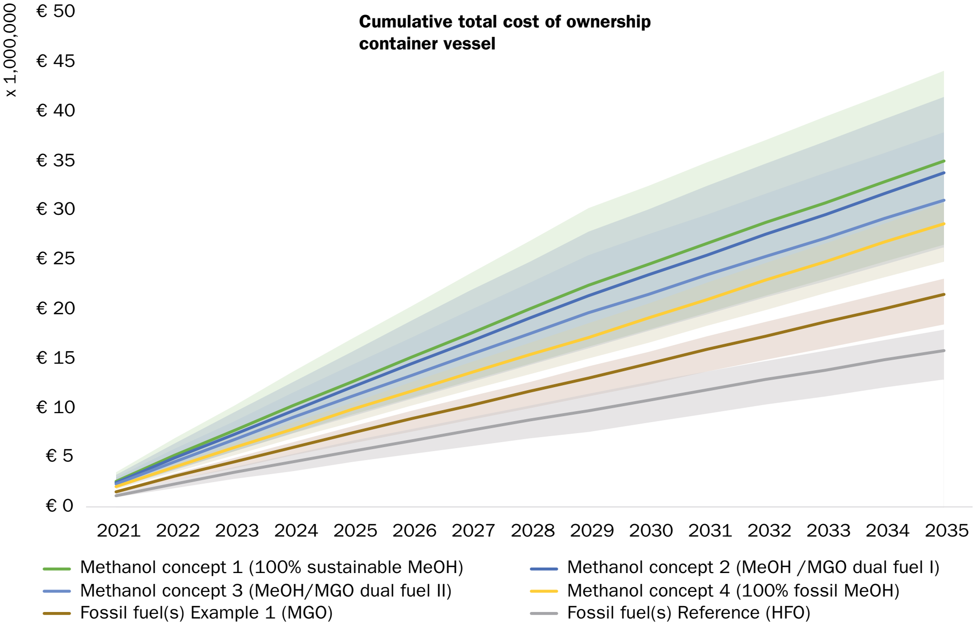


Figure 19: TCO results for a short sea container vessel.

The results for the inland patrol vessel show a relative smaller difference in the TCO for the use of different options compared to that of the short sea vessel. Due to the difference in sailing profile, the share of operational costs is much smaller for an inland patrol vessel than for the short sea vessel. Therefore, the risk a switching to sustainable methanol is smaller for this vessel type, making it a good option for a pilot.

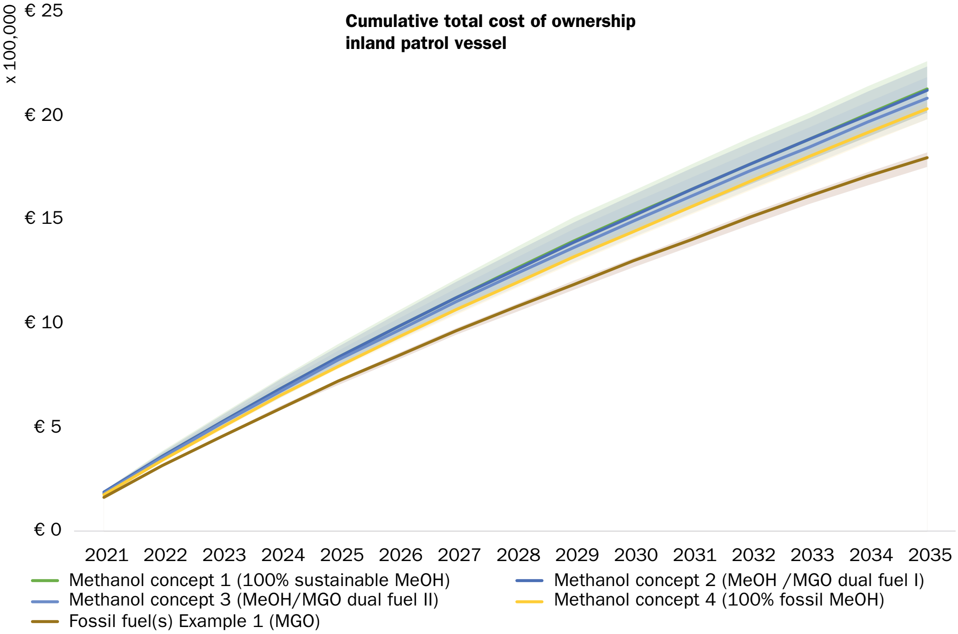


Figure 20: TCO results for an inland patrol vessel.

From the analysis of the availability and prices of methanol for different feedstocks, policy was considered as an important driver for future cost development. Policies are developed at different levels.

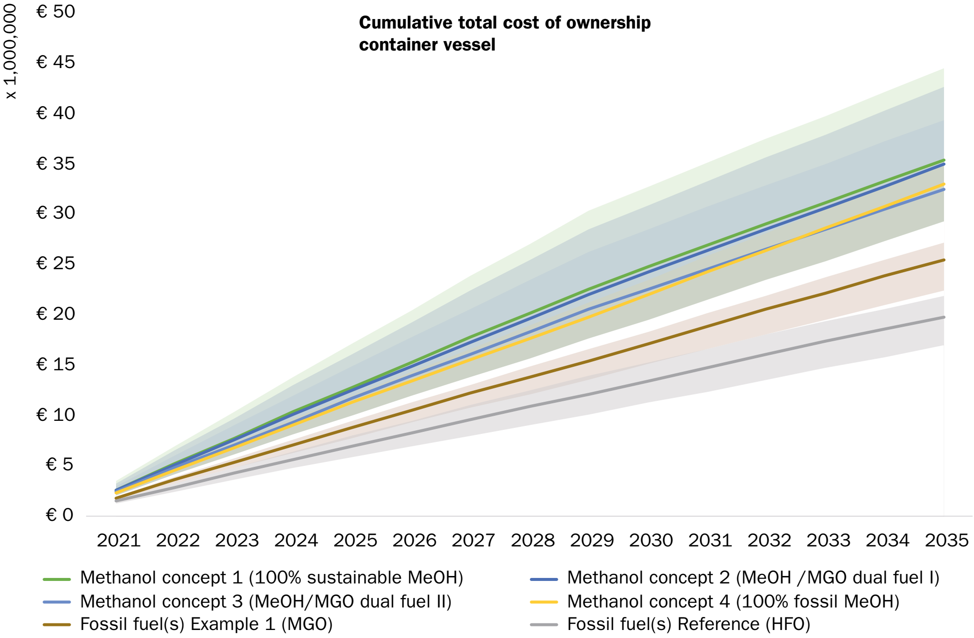
A first set of policies is the *Dutch national* CO_2*-taxation*. As set in the Climate agreement of the Dutch government in 2021 a 30 euro per ton CO_2-equivalent GHG tax will be imposed, which is expected to rise to 150 euro per ton CO_2-equivalent GHG in 2030. Inland and maritime shipping, as well as aviation, are exempted from this tax. However, similar strategies may be implemented in the future.

In September 2020 The European parliament voted in favor of the commission's proposal to include the maritime sector in *the EU emissions trading system*. With this amendment, ships of 5,000 gross tonnage and above will be added to the ETS. This market-based policy instrument is the first and biggest carbon market, it operates in all EU member states, Iceland, Liechtenstein and Norway. The cap and trade system limit the amount of emissions of more than 11,000 heavy energy-using installations and airlines. Emission allowances can be bought and traded within a certain emission cap. The emission cap is reduced over time. The EU ECTS covers 40% of the EU GHG emissions.

In the Renewable Energy – Recast to 2030 *(RED II)*, the overall EU target for Renewable Energy Sources consumption by 2030 has been raised to 32%. The Commission's original proposal did not include a transport sub-target, which has been introduced by co-legislators in the final agreement. Member States must require fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy. The Directive 2009/28/EC specifies national renewable energy targets for 2020 for each country, taking into account its starting point and overall potential for renewables. [5] The proposal with respect to REDII implementation in the Netherlands is expected to be finalized in Q3 2021. The target for 2030 is set at 5 PJ of renewables for inland shipping, ports and domestic maritime shipping. The opt-in for sea shipping and aviation will end in 2025, making it less attractive to use sustainable biofuels in maritime shipping.

In order to consider the effects of policy on prices, specific scenarios were developed in which different levels of CO_2-prices were considered:
- CO_2-tax of € 30 per ton CO_2, equivalent to the 2021 levels of the Dutch tax.
- CO_2-tax of € 150 per ton CO_2, equivalent to the expected upper levels of the Dutch tax.

Results for these scenarios for the short sea container vessel show that the impact on the comparative levels of the different fuel options are considerate. The option for sustainable methanol becomes substantially more attractive with an active policy support.



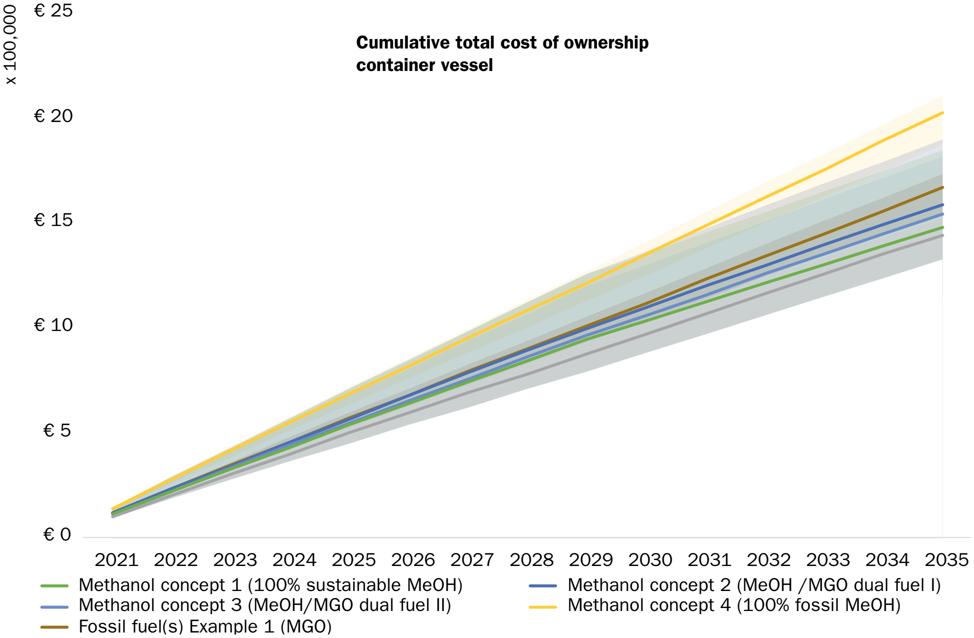


Figure 21: TCO results for a short sea container vessel with a CO_2-tax of € 30 per ton (top) and € 150 per ton (bottom).

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

In the Green Maritime Methanol project, a consortium of leading Dutch and international maritime companies and knowledge institutes have investigated a wide range of topics in order to assess the technical, operational and economic feasibility of methanol in different shipping markets and make the next step towards implementation.

The consortium concludes that applying methanol as a shipping fuel is deemed to be feasible from a technical and operational perspective:

- Within the project several options for applying methanol in a combustion engine have been tested. The option for blending a methanol-pilot fuel mixture directly in an engine does not seem operational feasible. Test results with the spark-ignited engine are very promising.
- The safety analysis demonstrates that through additional measures methanol bunker fuel can be designed into the tolerable safety risk region. Through these measures, sailing on methanol can be considered at an equivalent safety level as MGO and HFO.
- When considering bunkering, ship-to-ship transshipment seems to be the preferable option, as is currently the case for MGO and HFO. Safety measures need to be taken when implementing the bunkering process. These adjustments are however less impactful compared to measures for bunkering LNG.

Methanol is an important industrial feedstock, and therefore widely available throughout the world. There are several options for sustainable production from sources such as biomass, municipal waste and through a synthetic production from hydrogen and a sustainable carbon source. Application of these sources lead to a very large reduction of Greenhouse Gas emissions. However, the availability and price levels of these feedstock routes are still uncertain. This is also reflected in the business cases performed as part of the project.

From the six methanol ship designs that were performed as part of the project it is concluded that retrofitting existing vessels is more complicated and costly than redesign of newbuild vessels. The use cases however show significant differences in the redesign costs, based on the current layout and available space onboard and the preferred bunkering solution (either switch to methanol as single fuel option or as a dual fuel). To make future conversions better possible, modular design of vessels will be an important step.

RECOMMENDATIONS

The consortium considers methanol to be a promising option and aims to make a follow-up on the project, in close coordination with other initiatives such as the Horizon 2020 project FASTWATER. The following topics have been identified as part of this follow-up:

- There are some remaining safety and ship design issues that need to be tackled. This includes solutions for venting during the bunkering and ventilation during operations on board.
- Additional knowledge is needed on the engine performance of both spark-ignited and direct separated injection in a compression ignited engine. These tests should be performed in several engine classes.
- More real-life experience is needed with application of methanol in operational circumstances for different vessel types. Therefore, pilot projects are needed.
- There are still uncertainties concerning the availability and pricing of sustainable methanol. Additional research is needed in setting up different supply chains. Because policies and legislation are very important in the steps towards implementation, results will be discussed with policy makers.

GREEN MARITIME METHANOL

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