Public final report – Methanol as an alternative fuel for vessels

Project data

Project number:	*MIIP 001 -2017*
Executed for:	*Netherlands Maritime Land and Ministry of Economic Affairs*
Executed by:	*Maritime Knowledge Centre, TNO and TU Delft*
Project title:	*Methanol as an alternative fuel for vessels*
Project leader:	*Maritime Knowledge Centre*
Project duration:	*01-01-2017 until 31-12-2017*
Publication date:	*15-01-2018*
Status:	*Public final report*

Maritiem Kennis Centrum

TNO innovation for life

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1. Preface

The international pressure to reduce ships emissions like Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x) and Particulate Matter (PM) is rising. Application of natural gas in liquefied form (LNG) offers good perspectives for larger vessels, but offers no solution for smaller vessels, mainly because of the lack of available space on board. Methanol (CH_3OH or MeOH) can be used as an alternative fuel and although NO_x emissions are slightly higher than with LNG, the storage is easier and the entire installation can be smaller in size and simpler than with LNG.

For vessels under 50 metres in length several challenges must be overcome in order to realise methanol as a transport fuel. Technology is available, but there is a challenge to develop technical solutions that comply with regulations and are economical attractive. Maritime transport is responsible for about 2.5% of global greenhouse gas emissions. Without countermeasures this share is expected to increase between 50% and 250% by 2050, depending on future economic and energy developments.

Several studies show that energy consumption and CO_2 emissions can be reduced up to 75% by applying operational measures and implementing existing technologies.

Ship owners need reliable and accurate information about the effectiveness of the various technologies so that financial risks can be kept to a minimum.

Several good and extensive reports have been written on CO_2 reduction in shipping. These reports were used as a basis for this research. However, new opportunities seem to emerge in a steady pace.

This reports aims to establish a coherent overview of methanol as an alternative fuel in shipping including its strengths and weaknesses, opportunities and threats. These developments and solutions can provide interesting opportunities for co-operation and further (fundamental) research.

This project is executed under the auspices of Netherlands Maritime Land and supported by the Ministry of Economic Affairs.

2. Background

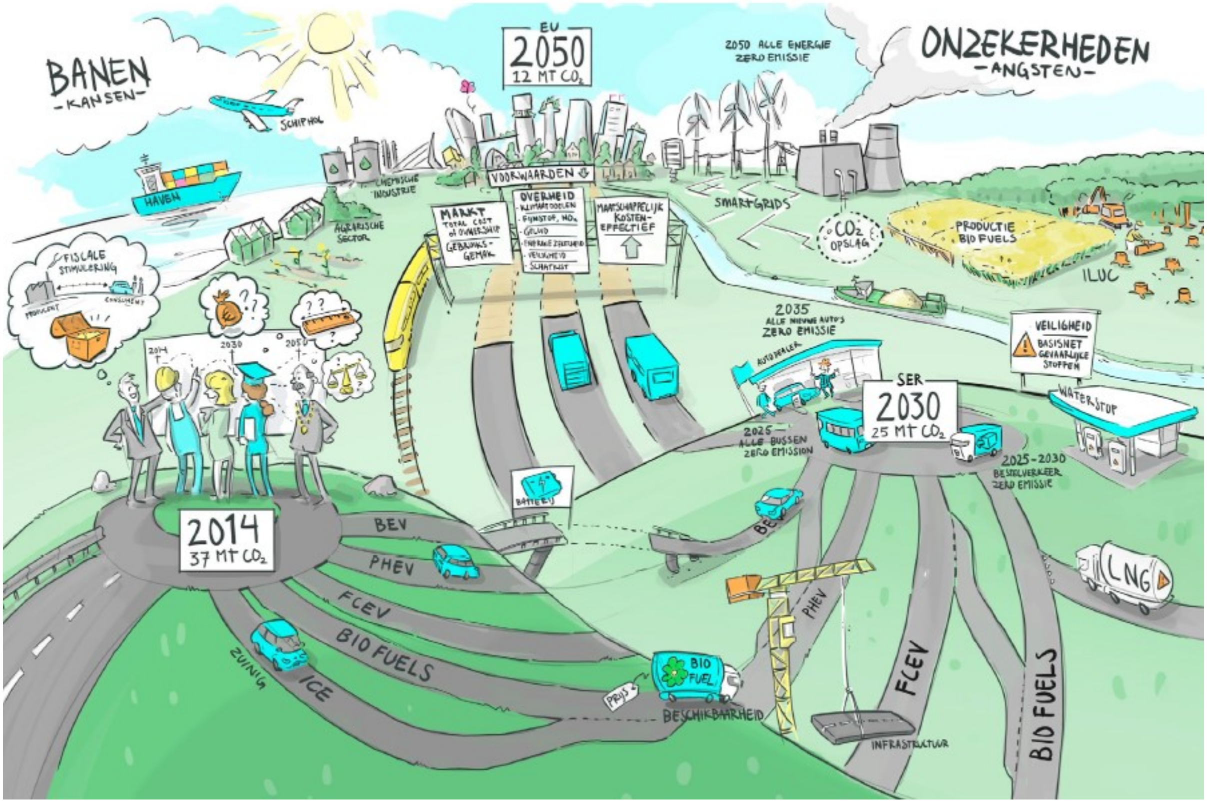
On the 30th of June 2014 the report “Een duurzame brandstofvisie met LEF” (A Dutch Sustainable Fuel Vision) was offered to the Dutch Secretary of State for Infrastructure and Environment. The vision was a continuation of the Energy Agreement for sustainable growth containing ambitious long term goals for transport in the Netherlands in order to reduce the harmful emission of greenhouse gasses.

2.1. A Dutch Sustainable Fuel Vision

The vision describes what sustainable fuels can be used and how transport means can be made more efficient in order to support the climate goals (especially CO_2 reduction), the improvement of the quality of living and to profit from green growth.

Reach the SER- goals and at the same time stimulate green growth. That is a huge challenge which requires audacity, vigour, co-operation, a consistent strategy and willingness to invest. The following three milestones are defined: 2020, 2030 and 2050.

In the year 2030 three million zero-emission vehicles are needed in The Netherlands to reach this goals. In order to reach these goals and to profit from green growth and improvements in the quality of living these developments have start as soon as possible.



The shipping sector set a goal in June 2014 to reduce CO_2 emissions in 2050 with 50% compared to 2020. Since June 2017 this ambition has increased to a 50% CO_2reduction compared to 2008. For the shipping industry the focus is on efficiency measures in combination with a transition to Liquid Natural Gas (LNG) and the use of sustainable biofuels for short sea shipping and inland shipping. For biofuels until 2030 the focus is predominantly on biodiesel and until 2050 on a transition of LNG to bio-LNG (also called Liquefied Bio Gas (LBG)).

The following actions are proposed for the maritime sector:

- *Challenge sectors like shipbuilding, production and distribution of fossil fuels and biofuels to aim for sustainability of marine transport fuels.*
- *Oblige the shipping sector to blend sustainable biofuels with fossil fuels or set targets with regard to renewable energy and put the limitation of CO_2 and methane slip on the agenda.*
- *Support a living lab for efficiency improvement for deep sea shipping and for large companies in short sea shipping and inland shipping.*
- *Create a private-public-infrastructure fund for charging battery-electric vehicles, hydrogen fuelling stations and renewable natural gas and LNG-bunker-fuelling stations.*
- *Stimulate the transition of marine diesel to LNG or sustainable applications and techniques for existing ships.*

2.2. Necessary fuel mix

It seems logical that a transition will first be aimed at LNG for shipping. However, it is insufficient to target one type of fuel to reach the sustainability goals, because it would make the sector rather vulnerable. A transition to several alternative fuels is not only required from a sustainability and climate perspective, but also from a security of energy supply perspective. Fuels other than LNG are still in an experimental stage and are regarded as nice markets for shipping.

The European Commission Clean Power Directive requires EU Member States and commercial businesses to jointly invest in tank-, loading- and bunker facilities and infrastructure for alternative fuels.

It is not only about the CO_2 emissions for the respective fuels when used in combustion engines (also called Tank To Propeller emissions), it is also about the CO_2 emissions that occur in the production process of the fuel (Well To Tank emissions).

Furthermore it is of great importance whether fossil fuels and fuels produced on the basis of fossil fuels are used or bio-fuels and renewable fuels that do not add extra CO_2 to the atmosphere.

Finally, it is very important for the maritime sector that the required storage volume of a fuel is kept to a minimum to enable a maximum efficiency for a vessel.

2.3. (Bio) Methanol

A research carried out in 2016 by MKC, TNO and TU Delft called "Framework CO_2 reduction in shipping" shows that methanol is a very interesting alternative fuel for the maritime sector.

Methanol is the simplest alcohol with the formula CH_3OH. It is a light, volatile, colourless, flammable liquid with a distinctive odour very similar to that of ethanol (drinking alcohol). However, unlike ethanol, methanol is highly toxic and unfit for consumption. Methanol is used as an antifreeze, solvent, fuel, and as a denaturant for ethanol. It is also used for producing biodiesel via transesterification reaction.

According to Methanol Institute, the global methanol production currently amounts to about 75 million metric tonnes per year. Methanol produced using natural gas as a feedstock has "Well To Tank" emissions similar to other fossil fuels such as LNG and MDO. Bio-methanol produced from second generation biomass such as waste wood has a much lower global warming potential than fossil fuels and is lower than ethanol by most production methods.

Black liquor from the pulp industry has been identified as an interesting feedstock for renewable energy. Black liquor is formed as pulpwood is mixed with chemicals (white liquor) to produce pulp as a pre stage to paper production. Black liquor can be gasified and used for methanol synthesis. The chemicals are recovered and reused. Black liquor is available in large quantities worldwide and offers a feasible way to produce methanol. Worldwide, about 400 million tonnes of pulp and paper products are produced every year. For the manufacturing of every tonne of pulp approximately seven tonnes of black liquor are produced.

Bio MCN (www.biomcn.eu) in the Netherlands operates a commercial-scale plant producing bio-methanol from glycerine. In Iceland, renewable methanol is also produced by combining hydrogen and CO_2. At present, about 200.000 tonnes of bio-methanol are produced per year.

Studies estimate that bio-methanol could reduce greenhouse gas emissions considerably compared to methanol from fossil fuels when the entire life cycle is taken into account. Therefore the feasibility of (bio)methanol as an alternative fuel for shipping will be researched.

3. Determine the international state of the art

3.1. International state of the art with regard to projects

Since the conversion of the Stena Germanica to methanol, international interest for Methanol as an alternative fuel for the maritime sector is growing. Recent projects and developments regarding the use of methanol as ship fuel include the delivery in April 2016 of three methanol dual-fuel chemical tankers to be chartered by Waterfront Shipping – these are the first new built vessels to use methanol as a fuel.

SSPA recently completed a study for the European Maritime Safety Agency on the use of methanol and ethanol as alternative fuels in shipping, with results presented at the European Sustainable Shipping Forum in January 2016.

In 2016 a report by the European Commission's Joint Research Centre on alternative fuels for marine and inland waterways concluded that methanol and LNG are currently the most promising for shipping. These and other studies show that methanol is a viable alternative fuel for improving the environmental performance of the shipping industry.

3.1.1. Stena Germanica methanol ferry

The Stena Germanica is the first major marine vessel to run on methanol after a conversion in 2015 in Poland. The Wartsila engines were converted for use of methanol with diesel as a pilot fuel. Double walled high pressure fuel pipes were installed for safety purposes as a requirement for low flashpoint fuels. A ballast tank on board was converted to a methanol fuel tank. For reliability purposes, the common rail engine can still run on marine gas oil as a backup. Operation on methanol is expected to reduce SO_x emissions by 99%, NO_x by 60%, CO_2 by 25% and particulate matter by 95%.

3.1.2. Spireth project

In 2012, during the SPIRETH project a methanol system was tested on board Stena Scanrail. In this project liquid methanol on board was converted to DiMethylEther (DME) via a catalytic reaction that enabled a 90% conversion of methanol to DME, water and methanol. This mixture served as a fuel for a modified diesel engine. The risk & safety analysis in SPIRETH has contributed to the development of ship classification society rules for methanol as a ship fuel. The work has also contributed to the International Maritime Organization's draft IGF code (International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels). SPIRETH has been of key importance in the development of methanol as a marine fuel and in showing that it is a viable alternative, particularly in the Nordic region and the Baltic Sea.

3.1.3. Summeth project

Started in 2015, one of the main goals of the SUMMETH project is to test and evaluate different methanol combustion concepts in a laboratory and to identify the best alternatives for the smaller marine engine segment. The work is focused on engines with power up to about 1.200 kW and both Spark Ignited (SI) and Compression Ignited (CI) combustion concepts are considered.

The Stena Germanica project demonstrated that large engines (6000 kW) can be successfully converted to run on methanol. The SUMMETH project aims to show that this can also be done for smaller engines and vessels.

Handling and storage of methanol is similar to that of liquid fuels such as diesel or gasoline. Thus it is considered to be relatively inexpensive. to provide infrastructure for methanol fuel storage and distribution at smaller ports. Methanol is widely used in the chemical industry in Europe and there is an established transport and distribution infrastructure in place. However, there is currently no specific methanol infrastructure for marine fuels and the SUMMETH project will investigate possibilities for this. The feasibility of using renewable methanol as marine fuel is also investigated.

Although renewable methanol currently constitutes only a very small percentage of the methanol on the market, it has great potential for reducing greenhouse gas (GHG) emissions in shipping. Renewable methanol can be produced from many feedstocks, including municipal or industrial waste, biomass, and carbon dioxide. Methanol produced from wood, also called wood alcohol, may be one of the first examples of methanol production. In Sweden, renewable methanol has been produced via gasification of black liquor from a pulp mill. Reductions in GHG emissions from renewable methanol on a "well-to-propeller" basis can be approximately 90% compared to emissions from conventional fuel use. Reductions depend on the feedstock and production method for the fuel.

3.1.4. Green pilot project

The objective of the GreenPilot project is to demonstrate that introduction of methanol as a fuel for smaller ships can improve competitive power and reduce the environmental impact. The target group is both commercial operations and recreational boating.

GreenPilot, which began in March 2016, intends to convert a pilot boat to methanol operation to show how a methanol conversion of a smaller vessel can be carried out in practice and to demonstrate the emissions reductions that can be achieved. There are currently no rules in force that applies for installation of low flashpoint fuel in small ships. The project will address this issue as well and propose relevant rules and requirements.

In the project, a variety of methanol combustion concepts will be evaluated. The concept that is considered to be the most appropriate will be further developed. Laboratory test will be performed to verify performance regarding operation and emissions and the engines will be equipped for marine installation. The project has the following main activities

Adaptation of a suitable pilot boat

Adaption work will include replacing the existing engine with a new engine that is converted to methanol operation and modifying a number of auxiliary systems such as the fuel bunker tank and piping, gas and fire detection system, fire suppression system, etc.

Proposals for applicable rules and regulations for methanol fuel installations on smaller vessels

There are currently no rules in force for the use of low flashpoint fuel on smaller ships. The project will identify and propose relevant and applicable rules that will ensure that the current safety levels are maintained or improved where appropriate.

The project results could potentially serve as the basis for development of official regulations and classification society rules.

Engine Adaptation

A number of methanol engine concepts are possible for implementation on a pilot boat. Different concepts will be analysed and the most applicable for the case boat will be selected. Results from laboratory tests carried out in related projects such as SUMMETH will be utilized for evaluation and engine adaption/calibration.

System for distribution of methanol

Methanol can be delivered by truck but a local fuel storage tank needs to be installed at the pilot boat station. Fossil free methanol will be purchased from a demonstration plant in Piteå, Sweden. Fossil free methanol is also available on the European market. Carbon Recycling International in Iceland has an annual production of 4 000 tons of methanol from recycled CO_2.

Modification of other ship systems to reduce environmental impact

Other ship systems apart from the engine will be analysed in order to identify their environmental impact. Possible methods for reducing these impacts will be investigated and implemented where possible.

3.1.5. Waterfront methanol tankers

Other recent projects and developments regarding the use of methanol as ship fuel include the delivery in April 2016 of three methanol dual fuel chemical carriers to be chartered by Waterfront Shipping – these are the first new build vessels to use methanol as a fuel. The vessels are powered by a MAN designed Hyundai–B&W ME-LGI dual-fuel, two-stroke engine, that can alternate between methanol, fuel oil, marine diesel oil or gasoil. The first vessel named Lidanger is operated by the Norwegian company Westfal-Larsen and has been given the additional class notation LFL FUELLED to demonstrate her compliance with DNV GL's rules for low flash point marine fuels.

3.1.6. Methanol fuel cell project – MS Innogy

The company Innogy in Germany has recently executed a conversion of a passenger vessel into an electrical vessel using fuel cells on methanol. This methanol is climate neutrally produced, enabling the vessel to operate completely carbon neutral.

With this pilot project Innogy intends to research and test the use of sustainable produced methanol (green methanol) as an alternative fuel for transport vehicles. Innogy will test the continual production of electrical energy using fuel cells and the robustness of this system in a maritime environment. The vessel is outfitted with a 330 litre methanol tank, a stack of 35kW fuel cells, two 50kWh batteries and a 80 kW electromotor. MS Innogy can sail for ten hours on a full methanol tank.

Concurrently, Innogy presents a climate neutral production method for methanol from CO_2 and water. The CO_2 is retrieved from the atmosphere and is mixed with water. With the use of bio-catalytic enzymes, high pressure and high temperature methanol will be formed. The required energy for the installation is retrieved from a berth near the hydropower station at the Baldeney lake in the vicinity of Essen. The synthetic methanol is stored in a special tank.

During the chemical reaction of methanol in the fuel cells both water and CO_2 is released. The amount of CO_2 emission is the same as the amount of CO_2 retrieved from the atmosphere for the production of methanol. Since the methanol synthesis is executed with green electricity, the entire cycle from well to propeller is climate neutral.

3.1.7. Methanol fuel cell project – Viking Line Mariella

Installed as part of the E4ships project, funded by the German government's National Innovation Program Hydrogen and Fuel Cell Technology, this project represents 'the most serious, most advanced and largest fuel cell development project in the world'. The aim of the project is to prove the viability and safety of fuel cells for marine operations, develop feasible technical solutions and feed into the development of regulations facilitating their use – notably the International Maritime Organization's IGF Code for low flashpoint fuels.

Under the Pa-X-ell sub-project, Meyer Werft established demonstrators both at its yard – for first technical examinations of reliability and suitability – and on board the Viking Line ferry *Mariella*, where a 90kW system comprising methanol-fuelled high temperature polymer electrolyte membrane (PEM) fuel cells have been installed.

The liquid cooled fuels cells were developed by Fischer Eco Solutions and SerEnergy. They are 5kW modules arranged in racks of six (so three racks are on board *Mariella*), and feature internal methanol reformers for hydrogen production.

3.2. International state of the art with regard to engine technology

3.2.1. Methanol as fuel for Internal Combustion (IC) engines.

The combustion relevant physicochemical parameters for methanol have been summarized and compared with popular engine fuels in Table 1. The description of these properties provides the necessary background for discussing possible engine conversion paths.

Properties	Gasoline	Diesel	Methanol	LNG
Chemical structure	$C_4H_{10} – C_{12}H_{26}$	$C_{12}H_{26} – C_{14}H_{30}$	CH_3OH	CH_4
Molecular weight	95-120	190–220	32.042	16
Density (kg/m3)	740	830	790	419
Viscosity at 298.15 K (mPa s)	0.29	3.35	0.59	0.146
Boiling point (C)	27-245	180-360	65	-161.4
Freezing point (C)	-57	-1 to -4	-98	-182.5
Auto-ignition temperature (C)	228-470	220-260	450	585
Lower heating value (MJ/kg)	44.5	42.60	19.9	51.85
Vaporization heat (kJ/kg)	310	260	1110	-
Octane number	80-98	15-25	111	127
Cetane number	0-10	45–50	3	
Stoichiometric air/fuel ratio	14.6	14.5	6.5	17.2
Flame speed (cm/s)	37-43		45–52.3	40
Flammability limits (vol)	1.47-7.6	1.85-8.2	6.7-36	5-15
Adiabatic flame temperature (C)	2030	2054	1870	2197
Flash point (C)	-45	78	11	-136

Table 1: List of most relevant combustion engine related physicochemical parameters of popular transport fuels.

3.2.2. General properties

Methanol is a methyl alcohol with chemical structure CH_3OH. The Hydrogen to Carbon (H/C) ratio is 4/1 for methanol (similar to the H/C ratio of LNG), which allows classifying it as a low carbon content fuel. Accounting on molar mass and lower heating value, this results in around 20% less CO_2 emitted while combusting methanol, compared to diesel with similar efficiencies. This result is similar to LNG (for LNG, methane slip creates additional GHG issue) and along with sustainable production potential (from captured CO_2 and electricity) predefine methanol as one of short-term transition fuels for transport.

Methanol is harmful for human beings and when ingested it can cause serious health issues (blindness is one of most common first symptoms) up to death. Note that people are particularly unprepared to digest methanol. On the other hand, it is relatively easily decomposed by other living organisms. Therefore, poses less ecological threat, when spilled into the sea compared to other fuels. Yet, large scale spills would increase sea vegetation. Also, contrary to LNG, vapour slip does not impact GHG emission.

Methanol is miscible in water, gasoline and alcohols, yet creates a stratified mixture with diesel and other oils. Only 25% of methanol mixed in water leads to a flammable liquid. As shown in Table 1 the boiling point of methanol is 64.5^{o}C and its freezing point is -97^{o}C, which results in a liquid phase of methanol at room temperature. This gives the possibility to use storage tanks with the same provisions as for gasoline. The flash point refers to the temperature at which the fuel forms an ignitable mixture with air. The value of this parameter for methanol (11^{o}C) is lower compared to diesel (78^{o}C), yet much higher compared to gasoline and LNG (-45^{o}C and -136^{o}C respectively). Despite that, MeOH is classified as a low flash point fuel which imposes increased risk during storage and imposes similar handling measures as for LNG.

Methanol is also known for its corrosive character. Some materials used in current combustion engines might not be prepared to handle methanol which imposes redesigning of engine parts or use of corrosion inhibitors (as additives to fuel) for long term durability.

3.2.3. Combustion related properties

Combustion engine fuels are defined by its cetane and octane number. Whereby, the cetane number quantifies the ability to self-ignite, and the octane number quantifies the ability to resist knock. Methanol has a higher octane number than gasoline and therefore suitable for Spark Ignition (SI) engines with a higher compression ratio without the occurrence of knock. This enables higher efficiencies in a SI engines compared to gasoline. The cetane number of methanol is low, revealing weak self-ignition properties, which is confirmed by high auto-ignition temperature. Therefore, methanol is generally not preferable for direct implementation in Compression Ignition (CI) engines, without large scale hardware changes or/and fuel reforming.

Methanol does not contain Sulphur (S), which results in the absence of SO_x emissions during combustion. The stoichiometric Air to Fuel Ratio (AFR) shows the quantity of oxygen needed to establish complete combustion. Due to significant oxygen content less air is acquired to combust methanol compared to diesel, gasoline and LNG. This explains the low stoichiometric air to fuel ratio of MeOH, less than half the amount of diesel. The lower heating value (LHV) of methanol is also less than half of the LHV of diesel, which results in the necessity of using more fuel to accomplish equivalent power output, therefore bigger fuel storage facilities are needed when using methanol instead of diesel. Furthermore, in some cases, it might be required to install different injectors to cope with the increased fuel flow demand. Due to the fact that the stoichiometric air/fuel ratio of methanol is less than half of diesel, the doubled injection volume of methanol requires roughly the same amount of air to accomplish a complete combustion. Therefore with the same engine volume and volumetric efficiency, no power loss is expected when the engine is converted to methanol.

Methanol has much lower kinematic viscosity than diesel, which might exacerbate lubrication ability in injection pumps and injectors; however this issue can be mitigated by applying sealing oil for pump lubrication, additional to standard fuel line (2). Lower kinematic viscosity will also have impact on spray patterns for direct injection applications. Additional options are redesigning the injection pumps to directly facilitate methanol or to use viscosity improvers as addition to fuel.

The heat of vaporization (kJ/kg) of methanol is roughly 4 times higher than that of diesel fuel. When liquid fuel is injected into the cylinder during compression stroke, it absorbs heat energy through evaporation. Larger heat of vaporization means that liquid fuel needs to absorb more energy in order to vaporize, resulting in a decrease of in-cylinder temperature. This causes longer ignition delays for Direct Injection Compression Ignition (DICI) concepts fuelled with methanol and, in general, lower NO_x emission which is a heavily temperature dependent process.

Alcohol fuels in general have wider range of flammability limits compared to gasoline. It allows using leaner mixtures which can theoretically provide higher thermal efficiencies. Also, laminar flame propagation velocity for methanol is higher than for conventional fuels which results in a faster combustion and potentially higher efficiency with optimizing the combustion phasing.

3.2.4. Benchmark of available methanol engine technologies.

From the above discussion it can be clearly noticed that Methanol has some common advantages and several drawbacks compared to other marine fuels, regardless of the combustion concept. The high level pros and cons of using methanol in Internal Combustion (IC) engines have been summarized in Table 2.

Criterion	***Benefits***	***Issues***
Engine, On-board technology	Well tested and documented in the automotive industry (light duty and heavy duty engines). First implementations in marine industry by Wartsila and MAN. Variety of conversion paths available depending on user requirements, including direct use with minimum hardware changes. Engine conversion much cheaper compared to natural gas (NG); no need for pressurized and or insulated tanks; direct high pressure injection much easier. Safer in storage than natural gas (NG) or gasoline – significantly higher flash point.	Current engines are not designed (material wise) for methanol use specifically. Increased engine component wear might occur due to corrosive character and low viscosity. Problems with injector system sealing reported. These issues must be handled either by chemical additives (increased fuel cost) or redesigning engine parts (retrofit cost) Catalytic conversion of exhaust gas (Diesel Oxidation Catalysts (DOC) and Selective Catalytic Reduction (SCR) especially) might be problematic on methanol due to possible presence of formic acid, large content of water and lower exhaust temperatures. Categorized as low flash point fuel (like NG) – subjected to special safety requirements.
Efficiency, Power output, Range	Higher Break Thermal efficiency and power output achievable for most engine concepts compared to conventional reference fuel.	Lower energy capacity – requires about two times bigger tanks to satisfy same range as diesel – similar range as with LNG.
Emissions, environment	Lower CO_2 footprint (up to 20% reduction – similar to LNG), Lower engine out NO_x, PM and Soot emissions compared to diesel, regardless on the conversion path. No Sulphur content – no SO_x emissions. No methane slip issue. Methanol leakage considered less (or non) ecological problem than diesel (easily decomposed by sea eco-system)	Usually higher hydrocarbons (HC) emissions compared to diesel for most conversion paths (similar to NG); except direct use of methanol in diesel engine. Exhaust can contain formaldehyde (methanal) – Cancerogenic; Not the case for other fuels; Might become part of legislated emissions if methanol engines become more popular. Toxic to people. Problematic due to the fact that it can't be distinguished from ethanol visually (clear liquid) or by smell. The potential leakage can have impact on increased sea vegetation.
Other	Mixable with other fuels (also with HFO and diesel but emulsion needs to be created); Can be fed directly for CI with CN improvers. Wider flammability limits allows to burn leaner mixtures (potential of lean-burn & low temperature combustion concepts can be better exploited)	May require emulsifiers / improvers to be feed directly to CI engines.

Table 2: Summary of main benefits and issues associated to using methanol as a fuel for combustion engines (regardless from combustion concept); with references to diesel and Natural Gas (NG).

The remarks summarized in Table 2 are generally valid for any chosen engine conversion path involving methanol. Besides, the way the engine is realized will also have its own advantages and disadvantages. Those have been summarized in Table 3, for chosen conventional and novel combustion concepts, excluding the specific effects associated to methanol.

	SI	*CI*	*HCCI*	*RCCI*
Ignition type	Spark Ignited	Compression Ignited	Compression Ignited	Compression Ignited
Fuel type	High Octane	High Cetane	Blend of every liquid or gaseous fuel	PFI of high octane and DI of high cetane fuel
Power Output Control	Airflow control, with near stoichiometric (ϕ =1) airfuel ratio	Fuel flow control, with lean (ϕ < 1) airfuel ratio	Fuel flow control, typically with lean ($\phi \leq$ 1) air fuel ratio or charge dillution	Fuel reactivity stratification, airfuel ratio stratification, typically without charge dillution
Mechanism controlling fuel burning rate	Flame propagation speed	Time for fuel vaporization and mixing	Chemical kinetics	Chemical kinetics and fuel reactivity
Emission Characteristics	Cleaner with three-way catalyst and higher CO_2	Higher PM and NO_x (without after-treatment) and lower CO_2	Higher unburned hydrocarbons (UHC) and CO and lower NO_x, PM and CO_2	Very high UHC and CO (without after-treatment) and ultra-low NO_x, PM and CO_2

Table 3: Brief characteristics of chosen conventional (Spark Ignition (SI) – stoichiometric, Combustion Ignition (CI)) and novel (Homogeneous Charge Compression Ignition (HCCI) , Reactivity Controlled Compression Ignition (RCCI)) combustion concepts.

Furthermore some concepts are more suitable for methanol fuelling than others which will influence the final performance of the retrofitted engine.

In Table 4, the most relevant methanol combustion concepts have been assessed against various criteria. Blend Ratio (BR) understood as energy based diesel replacement with methanol was included since it determines the GHG reduction potential and sustainability of the concept. BR was given in absolute values representing the typical range at which the different concepts are realized. Efficiency and emission factors have been assessed by generalized trends, taking conventional direct injection compression ignition (DICI) diesel engine as a baseline. Furthermore, the hardware change costs and redundancy (understood as ability to operate conventional diesel if methanol is not available) were also included. The operational costs of the engine (maintenance intervals, fuel cost, cost of additives and spares) were not included in the assessment because they can be influenced by many factors related to the way the engine is implemented and therefore are hard to compare.

From the concept perspective only methanol combustion systems that can provide at least the same efficiency and load range and better emissions than diesel are included in the benchmark. Two DICI concepts were selected as minimum hardware change options. Further, SI was included, yet limited to the lean burn concept since the conventional – stoichiometric combustion system results in peak efficiencies far below the diesel baseline. Also, engine-out emissions are high which disqualifies the concept in the scope of the current project despite low-cost, good controllability and easy exhaust after treatment. Similarly, HCCI and PCCI concepts were not included in the assessment, in Table 4. The reason is that their common drawback is the inability to realize full, diesel-like engine load and extremely difficult controls.

From the assessment in Table 4, a clear trade off can be seen between engine efficiency, emissions and technology complexity level. The later will influence cost of implementation which consists of hardware changes required for a retrofit and effort to develop control / calibrate the engine on new fuel. The costs should be balanced by lower fuel costs influenced by base price, price of additives and consumption (engine efficiency). Furthermore, the economical calculations have to be balanced out by the emission advantages and a target needs to be established here. Those targets will be directed by legislation (different for inland waterborne transport and open sea shipping) or direct costumer ambitions supported by various ecological support programs. Furthermore, when considering a retrofit project, parameters / benefits of methanol combustion concepts can be judged with different weights depending on vessel size and operational profile, methanol availability, or ambitions of the project members.

Combustion system / categories	Blend Ratio (BR) (%Eng.)	Brake Thermal Efficiency (BTE)	NO_x	PM / smoke/ CO	Total Hydro Carbons (THC)	Retrofit Cost	Diesel / methanol switching	Demonstrated
DICI - emulsions	10-30	=↑	=↓	=↓	=↓	=	Yes	Automotive, marine
DICI - CN improved	100	=↑	↓	↓	=↑	=	Yes	automotive
SI lean burn	100	=	↓	↓	↑	↑↑	No	automotive
Conv. Dual Fuel	50-70	=↑	↓↓	↓	↑↑	↑	yes	automotive
HPDI (methanol)	75-95	↑	↓	↓	=↑	↑↑	yes	marine
RCCI	75-95	↑↑	↓↓↓	↓↓	↑	↑↑↑	yes	In research automotive

Symbols: *= comparable; =↑ comparable or slight increase – depending on operating point; ↑ noticeable increase common for all operating points; ↑↑- significant increase; ↑↑↑ - very large increase.*

Colours: *denote relation to listed combustion concepts; green – best in the given category; yellow – second best; red – worse; Note that the red field still denotes minimum equal performance compared to conventional diesel.*

Table 4: High level benchmark of different methanol engine concepts. Trends refer to state of the art conventional DICI diesel engine.

For example, DICI with CN improvers can be a good option for smaller vessels, with relatively small, average fuel consumption, where the increased cost of fuel (CN additives) over the planned exploitation time can be balanced out by small costs of the conversion. This would not be the case for large, heavy loaded engines where the single cost of retrofit operation would be a fraction of the costs of exploitation. Similarly, projects which need to show innovative character will support more advanced concepts.

Note that after-treatment was excluded from the above considerations and engine out emission potential was considered. This is justified by the fact that current state of the art marine LNG engines are able to meet IMO Tier III without after-treatment. A methanol engine (or any other fuel technology) should meet at least the same goals to be competitive. Yet if after-treatment would be considered it would greatly affect the result of the benchmark. On the other hand, methanol combustion can have substantial effect on modern after treatment systems (SCR, DOC, 3-way catalyst). Catalyst poisoning, and accelerated aging might occur due to potential presence of formic acid or formaldehydes in the exhaust. This topic requires separate study.

3.3. International state of the art with regard to legislation

According to international maritime legislation methanol is a low flashpoint fuel. This has implications for both statutory as well as classification society requirements.

3.3.1. Statutory requirements

Fuels with a flashpoint below 60°C are not allowed for use in merchant vessels, according to SOLAS (Safety Of Life At Sea) 1974. Methanol has a flashpoint of approx. 12°C and therefore considered as an alternative fuel. To introduce a low flashpoint fuel on a merchant vessel, a risk assessment approach has to be taken according to SOLAS Ch. II-2 Reg. 17. This is to ensure that the proposed system has an equivalent level of safety, from a fire safety perspective, as a conventional fuel oil arrangement.

3.3.2. Classification society requirements

As for today, Lloyd's Register (LR) has drafted rules for the use of methanol in marine environments. DNV GL has published tentative rules on the same subject. Although LNG still attracts the biggest attention as a sulphur- free fuel, methanol has proven to be a strong alternative. One of the targets in the SPIRETH project was to develop an additional set of class rules that would involve low flashpoint fuels, other than LNG. During the course of the project, a methanol rule draft has been proposed by Lloyd's Register. In parallel to the rule development work done by LR, Det Norske Veritas – Germanischer Lloyd (DNV-GL) has done equivalent efforts. In July 2013 they published tentative rules for low flashpoint fuels, including methanol. In the same period, IMO published the drafted IGF code which now addresses methanol as a low flashpoint, sulphur- free, fuel.

LR and DNV-GL have taken slightly different paths for the class approval process. The LR Ship rules dictate that when designing an unconventional arrangement, a formal risk assessment approach shall be taken with MSC/Circ. 1023 as a starting- point. This approach is somewhat time- consuming, with the benefits of a well thought through result and great open- mindedness to unconventional solutions. DNV GL has adopted a more prescriptive model, with no requirements for risk assessment sessions. Ratified rules from both Societies are expected within the next couple of years.

3.3.3 Tentative Rules Low Flash Point Fuels DNV-GL 2013

The tentative rules for Low Flashpoint Fuels as developed by DNV-GL in 2013 contain the following paragraphs and elements:

B 100 Location of fuel tanks

101 Fuel shall not be stored within machinery spaces (SOLAS Ch.II-2 Reg.4.2.1.4).

102 Fuel shall not be stored within accommodation spaces.

103 Minimum horizontal distance between the fuel tank side and the ship's shell shall be at least 760 mm.

104 The spaces forward of the collision bulkhead (forepeak) and aft of the aftermost bulkhead (after peak) shall not be arranged as fuel tanks.

105 Two fuel service tanks for each type of fuel used on board necessary for propulsion and vital systems or equivalent arrangements shall be provided. Each tank shall have a capacity sufficient for continuous rating of the propulsion plant and normal operating load at sea of the generator plant for a period of not less than 8 hours.

3.3.4. Tentative Rules for Low Flash Point Fuels Lloyds Register 2016

The tentative rules for Low Flashpoint Fuels as developed by LR in 2016 contain the following paragraphs and elements:

5.3 Regulations – General

5.3.1 Fuel storage tanks shall be protected against mechanical damage.

5.3.2 Fuel storage tanks and or equipment located on open deck shall be located to ensure sufficient natural ventilation, so as to prevent accumulation of escaped gas.

5.3.3 The fuel tank(s) shall be protected from external damage caused by collision or grounding in the following way:

.1 The fuel tanks shall be located at a minimum distance of B/5 or 11.5 m, whichever is less, measured inboard from the ship side at right angles to the centreline at the level of the summer load line draught; where:

B is the greatest moulded breadth of the ship at or below the deepest draught (summer load line draught) (refer to SOLAS regulation II-1/2.8).

.2 The boundaries of each fuel tank shall be taken as the extreme outer longitudinal, transverse and vertical limits of the tank structure including its tank valves.

.3 For independent tanks the protective distance shall be measured to the tank shell (the primary barrier of the tank containment system). For membrane tanks the distance shall be measured to the bulkheads surrounding the tank insulation.

.4 In no case shall the boundary of the fuel tank be located closer to the shell plating or aft terminal of the ship than as follows:

.1 For passenger ships: B/10 but in no case less than 0.8 m. However, this distance need not be greater than B/15 or 2m whichever is less where the shell plating is located inboard of B/5 or 11.5 m, whichever is less, as required by 5.3.3.1.

.2 For cargo ships:

.1 for Vc below or equal 1,000 m3, 0.8 m;

.2 for 1,000 m3 < Vc < 5,000 m3, 0.75 + Vc x 0.2/4,000 m;

.3 for 5,000 m3 ≤ Vc < 30,000 m3, 0.8 + Vc/25,000 m; and

.4 for Vc ≥ 30,000 m3, 2 m,

where:

Vc corresponds to 100% of the gross design volume of the individual fuel tank at 20°C, including domes and appendages.

.5 The lowermost boundary of the fuel tank(s) shall be located above the minimum distance of B/15 or 2.0 m, whichever is less, measured from the moulded line of the bottom shell plating at the centreline.

.6 For multihull ships the value of B may be specially considered.

.7 The fuel tank(s) shall be abaft a transverse plane at 0.08L measured from the forward perpendicular in accordance with SOLAS regulation II-1/8.1 for passenger ships, and abaft the collision bulkhead for cargo ships.

3.4. Feasibility of methanol logistics

The International Council on Clean Transportation (ICCT) has written a white paper on the long term potential for increased shipping efficiency through the adaption of industry leading practices. The ICCT estimates the annual global fuel consumption in 2015 at about 200 Million tonnes of HFO, 60 Million tonnes of MDO and 50 Million tonnes of MGO. This confirms a marine fossil fuel consumption of 310 million tonnes per year. In Figure 5 a prediction of the main marine fuels is given including the effects of the Energy Efficiency Design Index (EEDI) and other currently available and implemented energy efficiency measures.

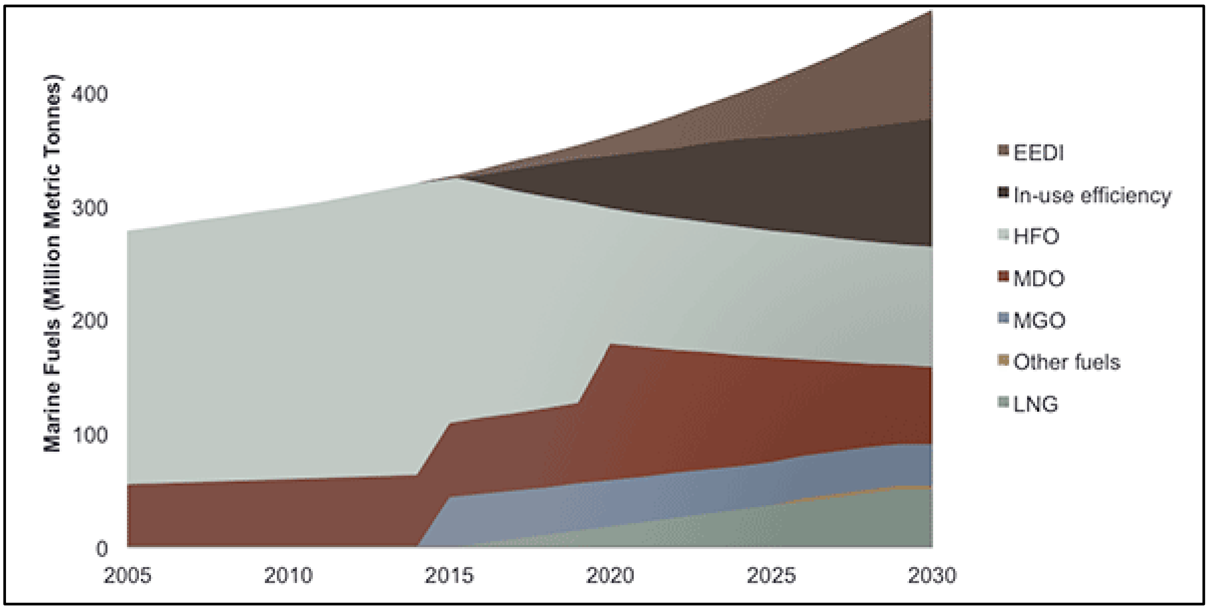


Figure 5: Global consumption of marine fuels.

The required amount of marine fossil fuels for the shipping industry is enormous. When the required volume of alternative fuels for shipping is taken into account, only a few alternatives seem to be feasible as a serious option for the shipping industry in the near future.

The best options for the shipping industry in the near future include the use of Liquefied Bio Gas (LBG), (Bio)Methanol, Bio-Ethanol and Ammonia. Biodiesel is already tested as a blend in the shipping industry.

Over the last 10 years, methanol has become a notable substitute for oil and coal. Its consumption has increased from approximately 35 Million tonnes per year in 2004 to approximately 64 Million tonnes per year in 2014. Of the 64 Million tonnes of consumption in that year, approximately 60% was in chemical applications.

The chemical applications of methanol are not substituting oil- or coal-based products. These applications tend to grow with the increased use of polymers in the general economy. Approximately 40% of the methanol consumption is in oil-substitute applications. In addition, approximately 5 Million tonnes, of captive methanol production from coal in China typically is not considered part of the methanol market, but it also substitutes for oil. According to Methanol Institute, the global methanol production currently amounts to about 75 Million tonnes per year.

Figure 6 shows the availability of methanol worldwide. South East Asia and Australia, East China and Korea, Japan and Taiwan have the largest methanol storage capacity, followed by USA Gulf Coast, Latin America Atlantic coast and North West Europe. North West Europe has an estimated methanol storage capacity of almost 700.000 tons.

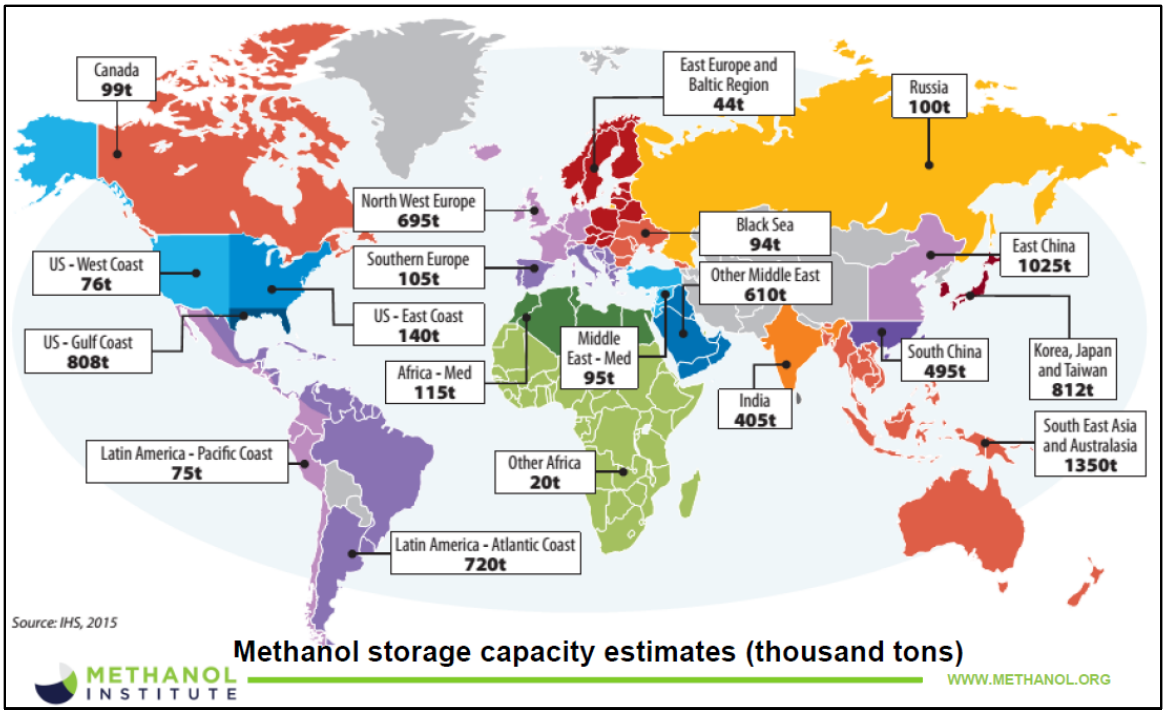


Figure 6: Methanol storage capacity worldwide

Methanol production primarily takes place in China followed by Saudi Arabia, Trinidad & Tobago, Iran and Russia. China is by far the major producer and investor in methanol production plants worldwide with a production capacity of about 50 Million tonnes per year.

In North West Europe the major production facilities are located in Germany, The Netherlands and Norway. These facilities account for about 3 Million tonnes of methanol per year. Figure 7 shows the production capacities worldwide.

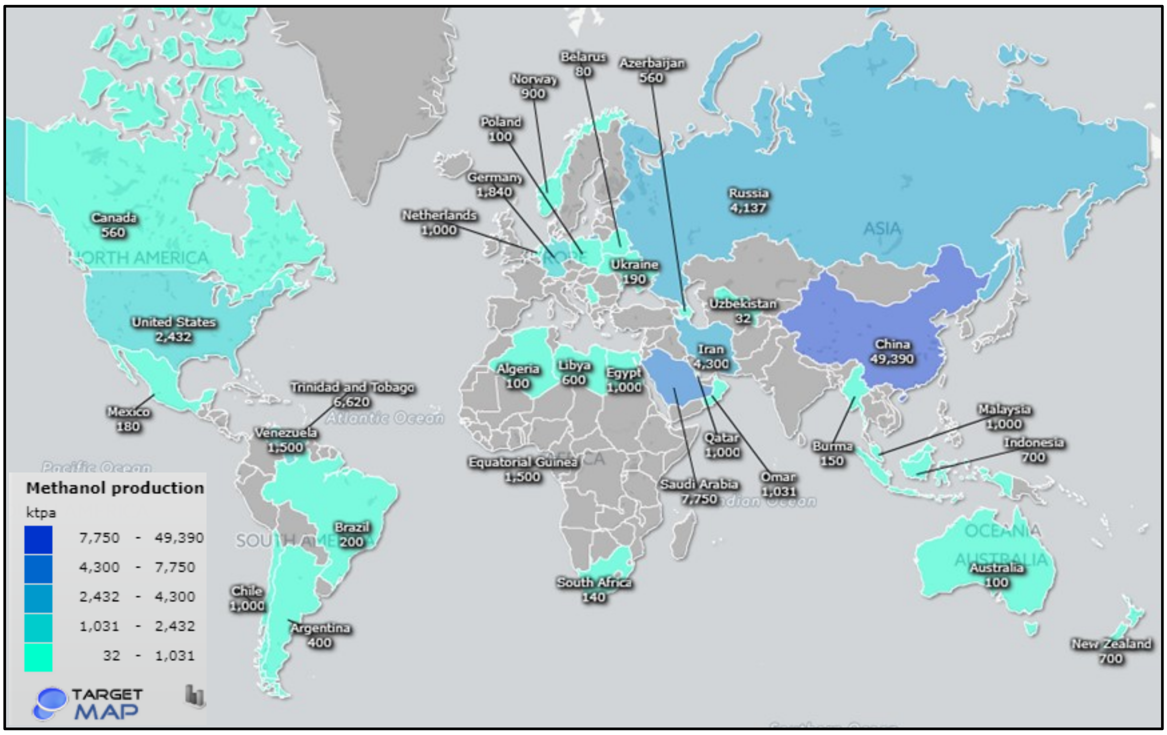


Figure 7: Methanol production capacities worldwide

3.5. Methanol pricing

The price of methanol is like any major commodity determined by the balance between supply and demand. The price of methanol on the spot market (FOB) in Rotterdam is given in figure 8 and varies between 100 Euro per tonne and more than 500 Euro per tonne over the last 10 years.

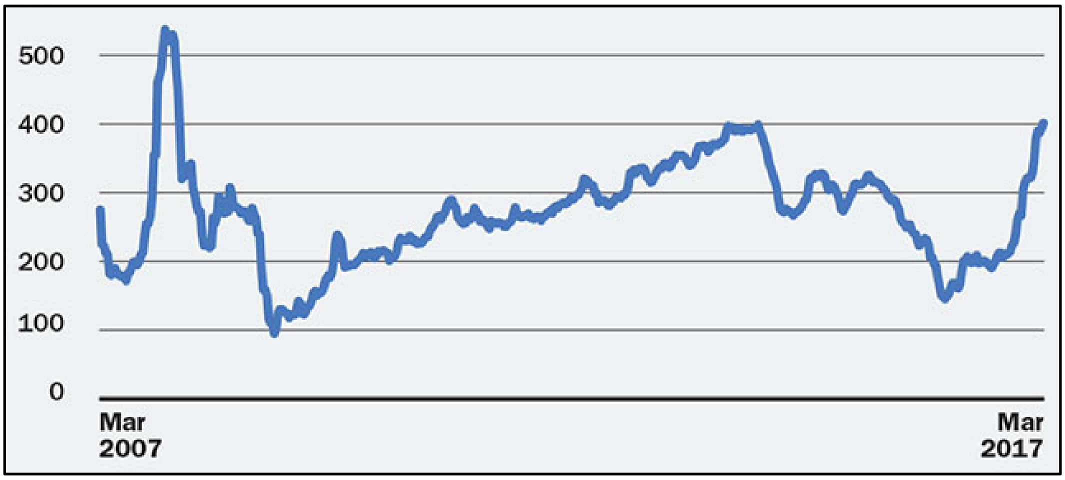


Figure 8: Methanol price in Euro per tonne

Although the price of methanol hit a 400 Euro per tonne in March 2017, the current trading price in November 2017 for methanol is down to 260 Euro per tonne.

The high prices of methanol in March this year were attributed to the temporary shutdown of several methanol plants worldwide for maintenance purposes. It shows the sensitivity of methanol to supply and demand under growing market demands.

Figure 9 displays the price range for bio methanol or green methanol as opposed to normal or grey methanol. The price range (FOB) Rotterdam for green methanol is estimated at a price level of about 550 euro per tonnes (price ranges between 500 and 600 Euro per tonne).

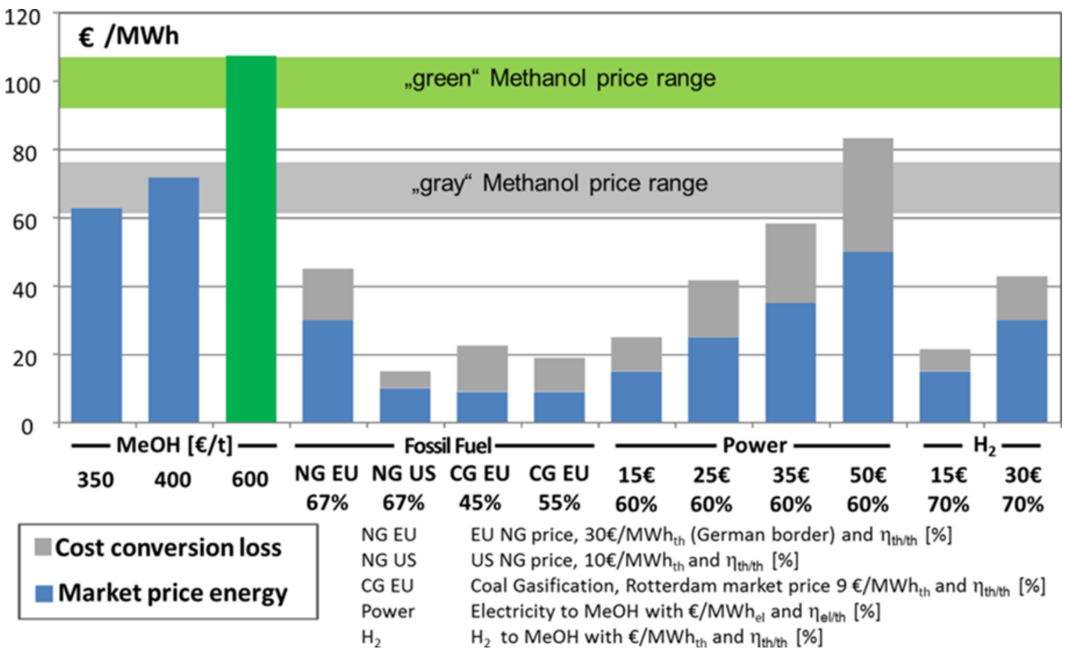


Figure 9: Methanol price range for grey and green methanol

Considering a Lower Heating Value (LHV) for methanol of 21,2 MJ/kg and a LHV for MGO of 42,4 MJ/kg, 2 tonnes of methanol will theoretically provide the same amount of combustion engine energy as 1 tonne of Marine Gas Oil.

The current price for Low Sulphur Marine Gas Oil according to Ship & Bunker is approximately 460 Euro per tonne (FOB) Rotterdam.

The equivalent amount of methanol is two tonnes for one tonne of MGO i.e. 520 Euro for methanol versus 460 Euro per tonne for MGO.

<u>The business case for grey methanol as opposed to MGO based on fuel prices is currently not feasible.</u>

The business case for green methanol seems even more difficult with an equivalent cost price for methanol of 1.100 Euro per tonne versus 460 Euro per tonne for MGO.

However in the Netherlands a subsidy is awarded to producers of green methanol. These so-called bio-tickets or renewable fuel units will offer the producer a subsidy is approximately 7-9 Euro per Gigajoule of produced renewable energy.

For Green Methanol the subsidy is even doubled to 14 -18 Euro per Gigajoule.

With a Lower Heating Value (LHV) for methanol of 21,2 MJ/kg or 21,2 GJ/tonne the amount of subsidy for the producer is on average 21,2 * 16 = 340 Euro / tonne.

For every tonne of MGO with a present value of 460 Euro per tonnes, two tonnes of Green methanol are required with a cost price of 420 Euro (1.100 – 2 x 340 = 420 Euro)

<u>The business case for green methanol as opposed to MGO based on fuel prices alone is currently marginally feasible.</u>

The double counting of the renewable fuel units under the current plans of the Dutch government might stop in 2023. The fuel price for green methanol is likely to rise and if no other measures are taken the business case for green methanol might be not feasible anymore.

Furthermore investment costs for engine and engine room modification will have to be taken into account for determining the overall feasibility of methanol as a transport fuel.

When a payback period of the investment of 5 years is taken into account for a work vessel using 15 tons of fuel per week for 45 weeks per year, the available investment cost for modifications on a vessel for break even after 5 years is 135.000 Euro.

In that case the risks for the investment are fully on the ship-owner and it seems unlikely that he will invest in this clean technology when confronted with so many insecurities (fuel prices for methanol and MGO) and risks (renewable fuel units and engine maintenance costs).

On the positive side is the performance of a combustion engine which has been reported cleaner and more efficient when running on methanol. This should be a subject of further study.

If a fuel efficiency improvement of 5% can be achieved for the same work vessel under the same conditions as sketched above, than the available investment costs for modifications on that vessel for break after 5 years is about 200.000 Euro.

4. Analysis, conclusions and recommendations

Main consequences of the implementation of Methanol as a fuel in a ship propulsion configuration are summarized in *Table 2: Characteristics for integration of Methanol fuel combustion engines in ships, reference to gasoline or diesel fuel combustion engine benchmark*. What does that mean for further elaboration of the potential of Methanol as a fuel in ship systems towards higher Technology Readiness Levels (TRL's)?

First of all, the main objective to consider Methanol as a fuel for shipping should be defined. If zero emission of the ship is the main design objective, including a carbon neutral emission performance, all dual fuel options do not hold, as they make use of fossil fuel. The remaining options for single fuel application of Methanol are Spark Ignited and Direct Injected Methanol. It was concluded, that direct utilization of methanol in Direct Injected diesel systems is generally not favourable due to its significantly different physicochemical properties. Mainly the low cetane number does not allow for a controllable auto ignition of direct injected methanol.

Furthermore, for a carbon neutral combustion of Methanol as a single fuel, the fuel should be bio-methanol or synthetic methanol which is produced by renewable energy resources, like solar or wind energy. The implementation of spark ignited injection technology has the most potential for this specific application. As a further advantage, the application of spark ignited methanol injection technology can be performed on existing engines without structural modifications to the engine design and structure.

From that perspective, the following research questions remain:

a. Methanol combustion might reduce NO_x -emissions, but the reduction is not expected to be sufficient for compliancy with Tier 3 and Euro 5 regulations. Which additional measures have to be taken to comply with NO_x -regulations?
b. A higher efficiency of the engine may not be the case, and the lower heating value is much lower compared to diesel fuel or gasoline. So the higher specific fuel consumption will result in a higher total fuel consumption (in terms of total mass flow and required fuel storage). With a reference to the operational profile of the ship, what will be the effect on the fuel storage facilities of the ship and the logistic refuelling opportunities?
c. Although existing engines may be modified to spark ignited methanol engines, which engine and systems parts will have to be re-engineered with better corrosion preventive materials?
d. The transient behaviour and acceleration/deceleration performance of a single fuel methanol engine are expected to have a lesser quality than the control stability of a diesel engine. Which control dynamics, control system and/or energy storage or electrical configuration should be applied to ensure the operational stability of a methanol driven ship propulsion system?
e. Given the operational profile of the ship, what will be the investment cost and the exploitation cost of the resulting configuration and operational exploitation of the ship?
f. Given the targets as defined in the Paris Agreement with regard to CO_2 emissions, what measures should be taken by international, European and national governmental bodies to facilitate the transition of the maritime industries towards zero-emission in shipping.