Traffic & Transport
Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

TNO report

TNO 2019 R11732

Green Maritime Methanol
WP2 Initiation and Benchmark analysis

Date	4 June 2020
Author(s)	Jorrit Harmsen, Nina Nesterova, Cemil Bekdemir, Karin van Kranenburg
Copy no	2019-STL-REP-100327175
Number of pages	52 (incl. appendices)
Number of appendices	1
Sponsor	TKI Maritime & the Netherlands Ministry of Economic Affairs
Project name	Green Maritime Methanol
Project number	060.38323

Contents

1 Introduction ... 4
1.1 Introduction ... 4
1.2 Aim and approach of the study ... 4
1.3 Structure of the report ... 6

2 Regulatory context ... 7
2.1 Regulations on greenhouse gas emissions ... 7
2.2 Regulations on pollutant emissions ... 8
2.3 Fuel sustainability regulations ... 9

3 Methanol as a fuel for shipping ... 10
3.1 Methanol feedstock and production ... 10
3.2 Methanol pricing ... 13
3.3 Bunkering of methanol ... 13
3.4 Methanol engine technologies ... 15
3.5 Methanol impact on ship design ... 18
3.6 Comparison of methanol as shipping fuel with other fuels ... 20

4 Methanol demand within shipping industry ... 30
4.1 Current world demand for methanol ... 30
4.2 Break down and fuel consumption of the global shipping market ... 31
4.3 Suitability of methanol as a fuel for different shipping sectors ... 33
4.4 Estimation of potential methanol demand for ships calling at Dutch ports ... 40

5 Conclusions: key challenges and opportunities for methanol as a maritime fuel ... 45

6 References ... 47

7 Signature ... 49

Appendices
A Shipping statistical information

Glossary

Abbreviation	Definition
AFID	Alternative Fuels Infrastructure Directive
AIS	Automatic Identification System
DF	Dual Fuel
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EGR	Exhaust Gas Recirculation
EU MRV	European Union Regulation for Monitoring, Reporting and Verification of CO_2 emissions from large ships using EU ports
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HPDI	High Pressure Direct Injection
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IGF code	International Code of Safety for Ship Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organization
IMO DCS	IMO Data Collection System
kW	Kilowatt
LFL	Low Flashpoint Liquid
LNG	Liquefied/Liquid Natural Ggas
LSFO	Low Sulphur Fuel Oil
MBTE	Methyl-tert-butylether
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MW	Mega watt
NECA	NO_x Emission Control Areas
NO_X	Nitrogen Oxides
PM	Particulate Matter
RCCI	Reactivity Controlled Compression Ignition
RED II	Renewable Energy Directive II
SCR	Selective Catalytic Reduction
SECA	Sulpher Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
SI	Spark Ignition
SO_X	Sulphur Oxides
US EPA	United States Environmental Protection Agency
TRL	Technology Readiness level
VVT	Variable Valve Timing

1 Introduction

1.1 Introduction

The maritime sector is facing a major challenge. Whilst a globally growing global economy leads to greater demand for the transport of goods, the goals from the Paris climate agreement (UNCC 2016) and the subsequent agreement in International Maritime Organization (IMO 2018) require a 50% reduction of CO_2-emissions from maritime transport by 2050. 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 the 2020 Global Sulphur Cap and NO_X Emission Control Areas (NECA) regulations through equipment and systems that can be introduced with minimal disruption to the existing ship layout.

The use of methanol is considered as one of the most promising options for implementation in the short to medium term, based on its potential availability, emission reduction potential and energy density (Lloyd’s Register and UMAS (2019b). As an energy carrier fossil-based methanol can already reduce TTW CO_2-emissions by up to 10% compared to marine gas oil (MGO)[1], and furthermore reduce TTW emissions influencing air quality emissions (SO_X, NO_X and PM). This project will also consider ways to further improve the CO_2 performance of methanol investigating different feedstock options, such as biofuels and synthetic fuels, and thus becoming even greener.

Adoption of methanol as a viable fuel for the maritime shipping industry requires the development of knowledge and expertise in the following key areas:

- Economic and technical viability compared to alternatives such as MGO and Liquefied Natural Gas (LNG). This analysis includes, but is not limited to, the design of the supply chain and the impact to ship operations; and
- Technical development of the powertrain and associated emissions and efficiencies.

1.2 Aim and approach of the study

In this project, the benefits and feasibility of the application of methanol for the maritime sector will be explored, with a focus on the Short Sea domain.
The project considers the technical development of the powertrain alongside logistics and operational aspects.

[1] WTW CO_2-emissions of methanol are however similar or slightly higher than MGO. Please refer to section 3.6.4.

The ambition of the project is to deliver a system design of a prototype at a technology readiness level (TRL) 6 to promote and further advance methanol as an alternative fuel for the maritime shipping sector over the following years.

This project will lead to a follow-up with implementation in an actual pilot study onboard a modified vessel that will identify where further analysis is necessary and if any knowledge gaps are required to further develop methanol as a viable fuel source for seagoing vessels.

The current report summarizes the results of the work conducted within WP2 with the following.

It has four main objectives:

- Perform the state- of- the- art analysis on ship combustion technologies and any vessel-adaptations that are necessary for application of methanol onboard Short Sea vessels;
- Develop a clear understanding of the availability and challenges of growing a reliable maritime methanol supply chain;
- Establish a clear distinction between methanol and other alternative fuels in terms of physical and emission performance; and
- Communicate the viability of methanol as an alternative fuel for the Dutch Short Sea sector and where relevant identify areas for further research.

In order to achieve these objectives, a literature review has been performed on the potential usage of methanol as a shipping fuel; approximately 80 documents were analyzed:

- Publications relating to the implementation of methanol in maritime shipping, including results from concluded and ongoing projects;
- Other publications on methanol, including supply chain development;
- Publications on the implementation of other next generation fuels in maritime shipping;
- Long term scenario studies concerning the decarbonisation of maritime shipping; and
- Policy and legislation documents by national and international government bodies (Dutch government, EU, IMO).

Additionally, the literature review was further supplemented with by interviews conducted with project stakeholder interviews.

In order to identify the potential of methanol for different types of vessels, the detailed input on the technical and operational characteristics of different vessel types was collected. Firstly, the world's shipping fleet (based on an IMO study) was broken down according to an analysis of the segmentation of the world fleet and the main technical and operational characteristics. On the basis of this analysis, a list of KPIs was developed to highlight the requirements needed for a vessel to switch to the use of methanol as a fuel. Next, the ship operators and ship builders within the consortium gathered required detailed data for a selected ship within their respective sector. This included data on the technical specifications of the vessel, AIS data, data from the ship management systems, noon reports and fleet management systems.

Each shipping sector was analysed to determine the impact of switching to methanol. Finally, based on the aforementioned, individual analysis overarching conclusions on the applicability of methanol for the different shipping sectors were made.

To establish an initial vision whether methanol would be a good option for the Dutch maritime shipping sector, the results from the analysis were cross referenced with vessel movement data gathered from the individual segments entering the Dutch ports of Rotterdam and Amsterdam. For this analysis detailed port call information was collected by the local port authorities.

1.3 Structure of the report

The report is organised as follows: Chapter 2 describes in detail the policy context of this study, summarizing the most important regulations that frame the development of methanol as a fuel for the maritime shipping sector. Chapter 3 looks in detail into the supply chain aspects of the methanol, presenting the main findings of the literature study concerning both the technical characteristics of methanol as a shipping fuel as well as the associated impact on supply chain development of methanol. Furthermore, the chapter compares methanol to other next generation fuel types. Chapter 4 presents the findings of the analysis of the ship operational profiles, giving an insight into a first idea picture for the potential methanol demand for different shipping segments. This chapter provides an overview of the segmentation of the world's shipping fleet according to sector, identifying the importance of each sector in the Dutch context and presenting detailed results for selected shipping sectors of interest.
Finally, chapter 5 summarises the main results and presents the key challenges to be addressed in the future work packages of this project.

2 Regulatory context

2.1 Regulations on greenhouse gas emissions

The main goal of the initial IMO greenhouse gas reduction strategy is to reduce Greenhouse gas emissions (GHG) from shipping in 2050 by at least 50% compared to the 2008 emissions level (IMO 2018).

As part of the strategy, the following measures have been defined: to further strengthen the energy efficiency design index (EEDI) for different ship vessel types and to improve the operational efficiency in two stages:

- By 2030: 40% CO_2 reduction per transport work, expressed in gram CO_2 per ton per nautical mile (ton.nm) compared to 2008; and
- By 2050: 70% reduction per transport work, expressed in gram CO_2 per ton per nautical mile (ton.nm) compared to 2008. Reduction of 50% of the absolute GHG emissions compared to 2008.

Possible technical, operational and market-driven measures for reduction on short, long and medium term still need to be defined and are currently under discussion.

The sections below summarise the most important policies which underpin the regulatory framework for the sustainability aspects of the maritime shipping sector.

Particular focus is given to:

- Policies that have an impact on the energy efficiency of ships and thus CO_2 emissions of vessels;
- Regulations on other types of emissions beyond CO_2; and
- Fuel regulations.

Energy efficiency policies

The *Energy Efficiency Design Index (EEDI)* is a mandatory IMO regulation for new vessels with keels laid down as of from the 1st of January 2013. These ship types make up for about 85% of the CO_2-emissions of the world fleet (IMO 2020). The EEDI for new ships aims to promote the use of more energy efficient (less polluting) equipment and engines, requiring a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different vessels in accordance with their ship type, size and sector within which they operate and size segments.

The *Ship Energy Efficiency Management Plan (SEEMP)* is an operational fleet management measure that establishes a mechanism to improve the energy efficiency of a ship in terms of cost-savings as well as environmental protection. The SEEMP became legally binding as of the 1st of January 2013 according to IMO regulation MEPC.203(62), for all active, operational vessels (IMO 2020).

Closely related to the SEEMP is the monitoring tool: *Energy Efficiency Operational Indicator (EEOI)* as a monitoring tool. The EEOI shall allow operators to measure the fuel efficiency of a ship in operation and to estimate the impacts of any changes in operation, e.g. improved voyage planning, or more frequent propeller cleaning, or the introduction of technical measures such as waste heat recovery systems or a new propeller.

The *Regulation for the monitoring, reporting and verification of carbon dioxide emissions from maritime transport (EU MRV)* requires vessels over 5,000 GT that are loading/ or unloading cargo and/or passengers at European ports to monitor and report their related CO_2 emissions.

The first monitoring and monitoring reporting cycle has begun January 1st, 2018, with two data sets collected:

- Data on fuel consumption for all maritime voyages from, to and within the European Union is converted to CO_2-emissions (ton) using emission factors from the 2014 guidelines for calculating the EEDI (resolution MEPC.245(66)).
- Data on total transport work on these voyages (either cargo in tons or number of passengers).

The IMO has also set up a *Data Collection System (IMO DCS)* as part of the SEEMP. Aggregated data is collected on fuel consumption and is therefore less detailed than the MRV. The first reporting period began January 1st, 2019.

2.2 Regulations on pollutant emissions

Besides regulations focussing on CO_2-emissions, there are policies focussing on air pollutant emissions to which vessels sailing on methanol need to comply as well. Concerning the emission of Nitrogen Oxides (NOx), limits have been set for new build ships when operating in a *NECA*. The current regulatory level in a NECA is *Tier III* and applies to ships constructed after a specific date. Outside of the NECA, IMO Tier II is of application. The allowed NOx levels emissions in Tier III are about 80% less than that of Tier I (ships vessels built after January 2000). NECA has been set up in coastal waters around USA and Canada with effect as from January 1st ,2016 for new build vessels. As of January 1st, 2021 a NECA will apply to the North Sea and the Baltic Sea.

Fuel regulations: As of January 1st, 2020, the allowed SO_x limit outside of emission control areas will be reduced significantly. The worldwide fuel sulphur limit will reduce from 3.5% m/m (mass by mass) to 0.5% m/m.

In order to comply with NO_X and SO_X regulations, vessel owners can undertake one of the following abatement options:

- Application of exhaust gas-after-treatment systems (scrubbers for SO_X and SCR catalysts for NO_X);
- Switching to fuel with a lower sulphur content, for instance from Heavy Fuel Oil (HFO) to Marine Gas Oil or Marine Diesel Oil (MGO/ MDO) or to very low sulphur fuel oil (VLSFO with ≤0.5%Sulpher) or Ultra-low sulphur fuel oil (ULSFO with ≤0.1%S)[2].
- Switch to an alternative energy carrier, such as methanol or LNG. These engines automatically comply with the SO_x regulations due to the absence of

---

[2] It should be noted that for road transport, the term ULSD – Ultra Low Sulphur Diesel, is used for a much lower sulphur level, namely < 50 ppm (compared to 1000 ppm, 0.1% for maritime).

sulphur in the fuel. Depending on the engine technology, these engines can comply to the Tier III NOx level, with or without aftertreatment.

2.3 Fuel sustainability regulations

European fuel regulations also shape the further development of the shipping sector towards alternative fuels with the most important regulations mentioned as follows.

The EU *Renewable Energy Directive II (RED II)* sets targets for the use of renewable energy until the year 2030 (DG MOVE 2019b). RED II has been adopted in 2018 and replaces the Renewable Energy Directive from 2009. RED II is setting an overall EU target for Renewable Energy Sources consumption of 32% by 2030.

RED II furthermore defines a series of sustainability and GHG emission criteria that bioliquids used in transport must comply with, in order to be included in the overall target of 14% renewables.

Maritime as well as aviation is exempted from RED II; however, the sector can "opt in" to contribute to the target. The contribution of "non-food renewable fuels" supplied to these sectors will count 1.2 times their energy content (DG MOVE 2019b). If waste feedstock (listed in Annex IX, A) are used, the 1.2 energy content will be counted twice leading to a 2.4 multiplier. This makes the application of biofuels in the maritime sector attractive for reaching the overall target.

The *Fuel Quality Directive (FQD)* sets targets to the GHG reductions of sustainable fuels and the annual reporting of GHG intensity of the supplied fuels.

The *Alternative Fuels Infrastructure Directive (AFID)* adopted by European parliament in 2014, requires the development of national policy frameworks to address the development of alternative fuels in conjunction with their infrastructure development and accompanying the development of technical standards (DG MOVE 2019a). Furthermore, the directive required a minimum coverage for infrastructure of certain alternative fuels. As part of AFID, ports that have been identified as maritime core ports in the Trans-European Transport Network (TEN-T) (40 major ports in Europe) are required to be able to provide bunkering of LNG by the end of 2025. AFID does not refer to gradual uptake of any other alternative fuels within the maritime sector or indeed support any potential contenders to LNG when such actions should be required. Development of infrastructure for fuels (such as methanol), therefore needs to be addressed in new regulations.

3 Methanol as a fuel for shipping

Whether methanol is a promising future fuel for shipping depends on several factors: its suitability for the maritime sector from a chemical and a technological points of view, global availability of the feedstock, development of the supply chain including infrastructure requirements and competition from other alternative fuels.

Chapter 3 identifies the basics version of the methanol supply chain for maritime shipping, analysing key developments on the level with respect to the suitable feedstocks, and its production and bunkering. It also highlights different types of existing and future ship technologies, assessing what types of ship engines are compatible with methanol and what kind of changes are necessary for the usage of methanol as a shipping fuel. Figure 1 schematically describes the high level supply chain for methanol as a maritime fuel as discussed in this chapter.

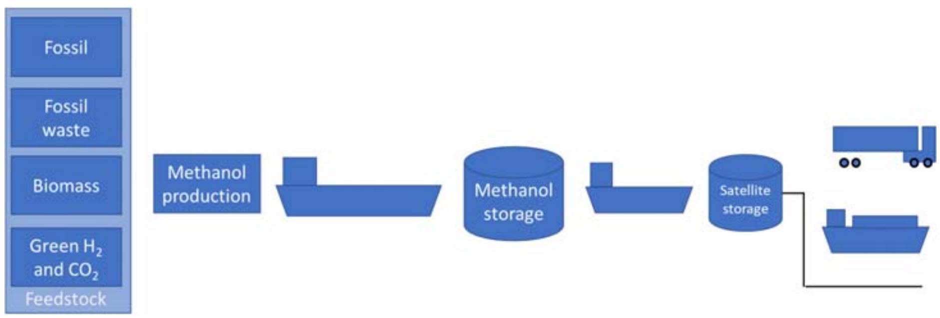

Figure 1: Supply chain of methanol as a maritime fuel.

In the next sections methanol is compared to MDO/MGO, HFO, LNG, hydrogen and ammonia, in terms of the fuel characteristics, the market readiness of the fuels, on the financial impact and environmental impact.

3.1 Methanol feedstock and production

Methanol is a hydrocarbon which exists as a liquid at room temperature and has a place in the top five most widely available chemicals (in terms of volume) in the world. It is currently mainly used as a feedstock for other products such as formaldehyde, dimethyl ether (DME), MBTE, biodiesel and acetic acid (DECHEMA 2017). Methanol has the structural formula CH_3OH.
It thus comprising atoms of carbon (C), hydrogen (H) and oxygen (O) and can be produced from feedstocks containing these elements.

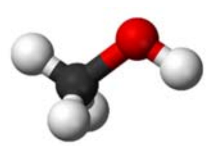

Figure 2: Methanol structure: CH_3OH (Picture source: Creative Commons).

While methanol is currently mainly produced from the fossil fuel feedstock, there is expected to be a shift to more sustainable production processes, based on biomass feedstock or electrolysis, all of which will be discussed shortly. Both the supply chain and production process of the following four types of methanol are all very different.

3.1.1 *Fossil based methanol*

Traditionally, methanol is produced from natural gas or from gasified coal. Hydrogen is obtained from natural gas via steam reforming.

Subsequently, methanol can be produced by CO or CO_2 hydrogenation:

- CO Hydrogenation: $CO + 2\ H_2 \rightarrow CH_3OH$
- CO_2 Hydrogenation: $CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$

Production emissions from fossil based methanol are at a level of 0.76 ton CO_2 per ton methanol (DECHEMA 2017). Production of fossil based methanol mainly takes place near fossil feedstock sources, for example in Russia, the Middle East and Western Africa. In Europe most fossil methanol production facilities have been closed (F3, 2017).

3.1.2 *Methanol from biomass and recycled materials*

Methanol from biomass

A more sustainable alternative for the use of natural gas is to produce methanol from biogas which can be obtained from biomass sources such as manure, sludge, algae or digestate. Different conversion routes from biomass to methanol are used depending on the source.

Fermentation and gasification allow for heterogeneous types of the biomass, including biogenic waste streams, to be converted into biogas/biomethane and then into bio-methanol. If produced from biogenic wastes (listed in the RED II), the produced bio-methanol qualifies as an advanced biofuel.

BioMCN in Delfzijl, the Netherlands, is the largest producer of bio-methanol in Europe, utilising crude glycerine as feedstock. It produces bio-methanol from biogas that has been upgraded to biomethane and is transported through the gas transport grid.

Figure 3: BioMCN plant in Delfzijl (Picture source: Wikipedia).

Bio-methanol currently only accounts for a very small portion of the total methanol production (around 1 Mton or 7%, (WTC 2019). Large scale production of biogas requires a significant quantity of biomass and since it is not available on a large scale in the Netherlands, biomass imports would be necessary.
Import of bio-methanol from countries with higher biomass production would be a viable alternative for biomass import. Another viable option is the use of available biomass waste-streams such as biogenic fraction MSW, biogenic industrial waste and manure.

The cost of methanol produced from biomass is significantly higher than that of methanol from natural gas due to the additional processing requirements. According to F3 (2017), bio-methanol will need to command a premium of 40-50%, above the current market rate of methanol from natural gas, to make it financially viable to producers.

Methanol from recycled plastics

In Rotterdam a waste-to-chemicals plant is being developed, that produces methanol from waste such as plastics. This project is a cooperation between Nouryon, Air Liquide, Enerkem, Port of Rotterdam and Shell (WTC 2019).

3.1.3 E-methanol - Electrolysis based methanol

A third production method for methanol is by electrolysis, also referred to as "Power-2-Methanol". Hydrogen produced from water through electrolysis and the subsequent process of hydrogenating CO_2 or CO generates the methanol. When electricity from renewable sources such as wind or solar is used, the hydrogen production process is CO_2 neutral.

Realisation of Power-2-Methanol requires close cooperation between the chemical industry and the energy sector. To produce green hydrogen (as feedstock for methanol), using electricity from renewable sources is necessary. In the Netherlands, wind farms are the main source of 'green electricity'. 'Green hydrogen' will be produced at moments when enough electricity is produced and electricity prices are low; at moments of shortage production will be dispatched to near zero. Electrolysis is a relative flexible process. Therefore hydrogen production facilities can offer flexibility services to the electricity grid. It must however be noted that a substantial amount of operational hours is required to realise an acceptable return on investment for this process..

Demand for green electricity is expected to rise significantly in the following decades, due to sustainability targets and electrification of many processes such as heating, mobility and fuel production. In case that annual green electricity production is insufficient in meeting this growing demand, imports will be necessary.

For Power-2-Methanol there are three viable options for import:

- the import of electricity from countries with larger a surplus of green capacity potential for electricity generation from renewable sources (like large solar farms in sunny areas);
- the import of green hydrogen produced in these countries; or
- the import of green methanol produced in these countries.

However, for options 1 and 2 to be attractive, regulation on the use of guarantees of origin has to be in place. Current regulation under the RED II does not provide for the use of imported renewable electricity or hydrogen to qualify as a Renewable Methanol. Use of Methanol based on green hydrogen for Shipping will only take place if regulation allows for the methanol to qualify as a Renewable Fuel of Non Biological Origin.

However, use of Power-2-methanol in shipping under the RED II (and its criteria) is, together with application in the industry, one of the most viable options for production and upscaling of Electrolysis technology. Power-2-methanol in transport can be a driver for development of large scale Electrolysis, necessary to bring down the costs of this technology. Power-2-methanol has the advantage over direct H_2 use of easier handling and available infrastructure to bring volumes into the transport market.

Production costs of synthetic methanol are currently between €120 to € 680 per mWh (Brynolf et al 2018). Production costs are dependent on the plant investment level of the plant. Although it is expected that these prices will fall as the technology matures, the most impactful cost driver for the production of synthetic methanol will be renewable electricity cost. The costs are expected to lower significantly in the future. Brynolf et al (2018) foresee a substantial decrease of the production to € 100 to € 260 per mWh in 2030.

3.2 Methanol pricing

The price of methanol is rather volatile, and closely linked to that of crude oil prices. In the period from 2007-2018 it fluctuated between €200/ton and €850/ton. An extensive analysis of the forecasted future methanol price development will be included in WP4 of this project.

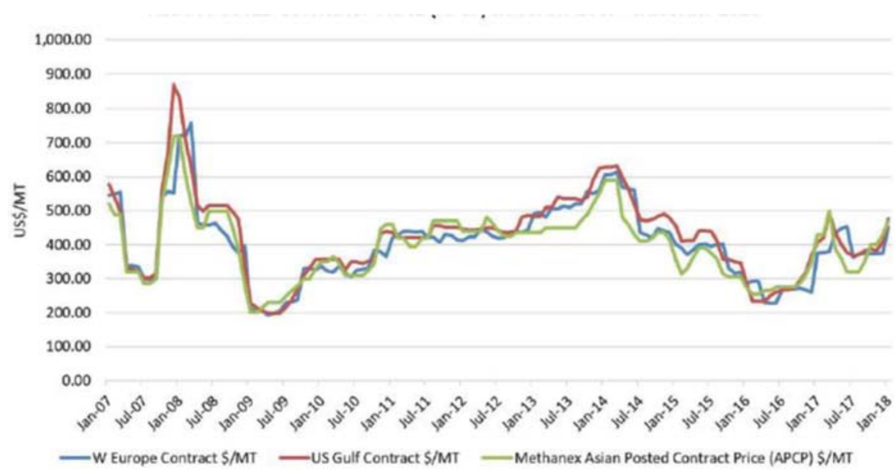

Figure 4: Methanol price development between January 2007 and January 2018 ($ per ton) Source: WTC (2019)

3.3 Bunkering of methanol

In order to apply methanol as a fuel for shipping, the fuel needs to be widely available as a bunkering fuel in ports across the globe, which requires:

- Reliable and robust supply chain between the refineries and ports;
- Sufficient storage facilities at the ports to meet demand plus appropriate reserves; and
- Flexible bunkering facilities to accommodate a variety of vessel types.

Naturally, the development of methanol infrastructure in ports (and by port stakeholders) depends on the size of the market of methanol as a maritime fuel in the port (which will determine investment appetite) and the investment costs needed to make methanol as a fuel available. This latter factor is influenced by the current availability of methanol in the port (either local production or storage facility for local industrial usage) and the investments in bunkering equipment. Methanol is currently available globally in all main ports. Adjustments in infrastructure should be made for allowing the bunkering of methanol as a fuel.

For the bunkering of alternative fuels there are three main options available:

- Truck-to-ship: the transfer of fuel from avia road tanker offers flexibility since the port facilities required to support this are limited; however, carrying a maximum of 40 ton per road tanker limits this option predominantly to smaller vessels. (Ellis 2017).

- Shore-to-ship: the transfer of fuel from a fixed, on-site, storage location via a pipeline towards a bunkering station within the port to a vessel. Storage facilities on shore can be of different sizes, ranging from tank containers to large storage tanks. The main advantage of this option is that bunkering can be directly facilitated from the storage facility, thus allowing large quantities to be bunkered. Furthermore, the operational costs of this option are relatively low, since limited intermediate steps are required.

  This option, however, is less flexible and requires vessels to relocate to a dedicated bunkering station where other activities such as the loading and unloading of cargo and/or passengers cannot be performed concurrently. Since bunkering also can’t take place during loading and unloading of the vessel, the transit time of the vessel could be increased.

- Ship-to-ship: the transfer of fuel via bunkering vessel to a vessel which is moored at a port alongside the receiving vessel offers more flexibility to that of a road tanker, because a bunker vessel alongside a cargo vessel does not interfere with the loading/ unloading process whereas a truck might intervene in the process. However, whilst there is the option to significantly increase the quantity of the fuel delivered (up to 200-300 tons), the drawback is the significant CAPEX and ongoing OPEX required to support a fleet of bunkering vessels. Early on, it is expected that existing fuel bunkering vessels will be modified and retrofitted to accommodate methanol. Another option is to use inland vessels that are used for the long distance hinterland transport of methanol for ship-to-ship bunkering of maritime vessels.

Safety during methanol bunkering requires much more attention than HFO or MGO bunkering because of its volatility, low flash point and toxicity. However, there is ample experience with handling methanol in the chemical industry, which can be used to realise bunkering systems which are sufficiently safe.

It is important to note that the bunkering zone must be separated from any other zones of activity in order to attain an acceptable safety level. Only competent crew should have access to the bunker station. Ship to ship bunkering is clearly an advantage in this respect.

Learning from the experiences with LNG in Dutch ports, truck-to-ship will be the most likely bunkering option for the first vessels sailing with methanol. Shore-to-ship options could also be developed for certain vessel types, such as ferries or port vessels. Ship-to-ship will become an option at a later stage, in which the bunkering vessel might facilitate multiple ports in a certain area.

3.4 Methanol engine technologies

In this section, an overview of selected engine technologies is given that bear high potential for use of methanol and, therefore, will be studied experimentally in WP3 of this project. This selection was made on the basis of a previous project on methanol [TNO, MKC, TU Delft (2018)]. The relevant parts of that study are summarized here. Focus is on the type of engine and combustion regime, hence it is assumption that methanol from either of the three aforementioned sources has the same purity level, such that the combustion characteristics of them should be the same within each engine technology presented in this section.

Major marine powertrain manufacturers already offer engines capable of running on methanol, such as Wartsila and MAN (Wartsila 2016, MAN 2014). Their solution consists of a direct-injected methanol-diesel concept, which has the advantage of staying close to the reliable and high efficiency diesel operation. Tier III can be met with SCR aftertreatment or by using a methanol-water mixture. Engine concepts which would deliver Tier III compliance without SCR or water addition may be feasible, but need to be investigated. This may lead to lower engine costs which would especially be important for smaller engines. . For the business case of the conversion of existing short sea ships it is, besides the conversion costs, also important to determine the impact of different engine modification options on the performance of the drivetrain.

Three main retrofit technologies for methanol engines were identified (TNO, MKC, TU Delft 2018) that are feasible solutions for shipping on the short term, depending on the emission level and cost target:

1. Methanol used in a lean-burn spark ignition engine (100% single-fuel);
2. Methanol emulsification in diesel used in a compression ignition engine (pre-blended “mono-fuel”), using a blend ratio range of 10% to 30%; or
3. Dual-fuel methanol-diesel used in a compression ignition engine (individually injected in the engine), using a blend ratio range of 50% to 95%.

The fuel injection and combustion events for these methanol combustion technologies are depicted schematically in Figure 5. This figure highlights the fuel injection and combustion processes using the coloured blocks as a function of time in the combustion cycle. The x-axis is the time represented by the engine crank angle relative to the piston Top Dead Center (TDC).

The introduction of methanol to the engine can be similar for the spark ignition and the dual-fuel engine, by means of liquid injection in the intake manifold/port or alternatively directly into the cylinder, where the methanol droplets will simultaneously evaporate and mix with the intake air. Combustion will start by the actuation of the spark plug for the spark ignition engine whereas for the dual-fuel engine a pilot injection of diesel fuel during compression is responsible for the start of combustion. The methanol and diesel injection timings determine the type of dual-fuel combustion that will result. Without going into details, one can say that early methanol injection and late diesel injection is typical for conventional dual-fuel and micro-pilot operation, both early methanol and diesel injection is typical for a more premixed type dual-fuel operation (often called RCCI), and both late methanol and diesel injection is typical for non-premixed diesel type combustion. Methanol-Diesel emulsion combustion will in principle follow the same steps as conventional Diesel combustion. The emulsified fuel is injected directly into the cylinder when the piston is close to TDC, where the high pressure and high temperature in-cylinder conditions will make the fuel ignite in a short period of time, and as long as the fuel injection continues a combusting fuel jet releases heat.

Each of these combustion regimes runs at lean conditions; fuel lean and air rich. The leaner the conditions the higher the thermal efficiency can potentially reach, however, this is limited by combustion stability, air (turbo-)charging capabilities, and pollutant emissions (soot, unburnt hydrocarbons, CO, etc.) due to incomplete combustion. Despite the lean conditions, all of the abovementioned methanol combustion concepts will most probably emit engine-out NO_X-levels that are higher than IMO Tier III limits, with the possible exception of the premixed type dual-fuel operation that typically shows very low NO_X production. Therefore, de-NO_x technologies need to be considered which can be in-engine or aftertreatment options.

In-engine NO_X reduction technologies aim to reduce the production of NO_X by reducing combustion temperatures and/or the oxygen concentration. For IMO Tier III one option can be the application of the well-known Exhaust Gas Recirculation (EGR) technique. The extent to which EGR can be applied for the reduction of NOx formation follows a similar trade-off as for running lean conditions as mentioned above. Boundaries and optimizations regarding lean-mixtures and EGR conditions need to be investigated for each combustion technology separately. Furthermore, a methanol-water mixture can help to reduce NO_X-production in the engine.

An aftertreatment de-NO_X technology that is well known for its effectiveness is the Selective Catalytic Reduction (SCR) technique. SCR needs a reactive agent (urea or a hydrocarbon) to function. SCR works well with lean combustion concepts, however the exhaust temperatures need to be sufficiently high to activate the catalyst. Therefore, one cannot always simply combine in-engine de-NO_X measures with an SCR.

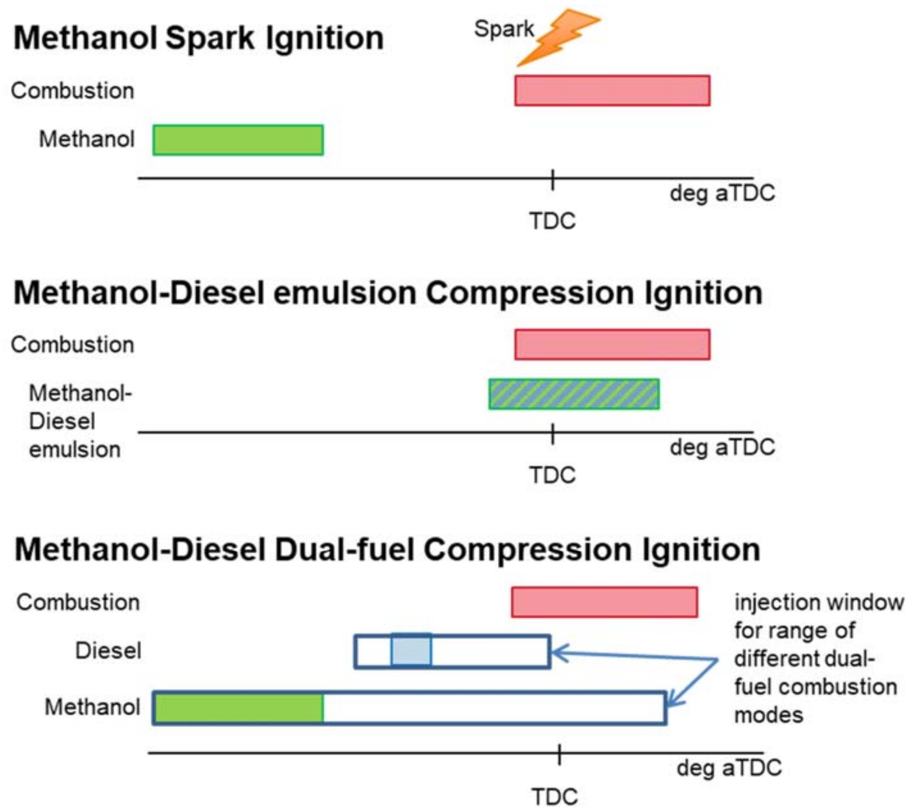

Figure 5: Three combustion technologies for use of methanol in engines. The x-axis is the time represented by the engine crank angle relative to the piston Top Dead Center (TDC). The coloured blocks mark the fuel injections and the combustion process in time.

The main characteristics of methanol application in a maritime engine for these three retrofit solutions are listed in Table 1 for comparison. Most of the underlying data and expertise, however, stem from different and smaller automotive engines. Therefore, the technical feasibility of all three engine technologies regarding current and future emission constraints and GHG reduction targets will be investigated by means of experimental research on maritime engines in WP3.

Table 1: Characteristics of methanol application in a maritime engine. Reference: state of the art diesel engine. Emissions are engine-out.

	1. Methanol used in a lean-burn spark ignition engine (100% single-fuel)	**2. Methanol emulsification in diesel used in a compression ignition engine (pre-blended "mono-fuel")**	**3. Dual-fuel methanol-diesel used in a compression ignition engine (individually injected in the engine)**
1. Is retrofit of existing engine easy?	Yes, mainly injection equipment	Yes, some seals, components, and the lubricity of the emulsion need attention	No, modification of engine configuration required
2. Is the solution carbon neutral from Well-to-Propeller?	Potentially yes. Only if bio-methanol or synthetic methanol produced from renewable resources is used	Potentially yes. Only if bio-methanol or synthetic methanol produced from renewable resources is used	Potentially yes. Only if bio-methanol and bio-diesel or synthetic methanol and diesel produced from renewable resources is used
3. Engine efficiency	Neutral	Neutral	Neutral to higher (depending on dual-fuel combustion mode)
4. NO_X	Lower (but not within Tier 3 and Euro 5 limits?)	Lower (dependent of diesel/methanol blend ratio)	Lower
5. SO_X	Zero	Lower (dependent of diesel/methanol blend ratio)	Lower (dependent of diesel/methanol blend ratio)
6. Soot	Lower	Lower	Lower
7. CO	Higher	Unknown	Higher
8. Unburnt HC	Higher	Lower	Higher
9. Controllability/ Stability	Lower (more cycle-to-cycle fluctuations but not necessarily a problem)	Unknown	Neutral/Higher
10. Cycle to cycle variations	Higher	Unknown	Neutral
11. Maintenance	Shorter maintenance intervals (spark plug)	Unknown	Unknown
12. Material requirements	Higher due to methanol	Higher due to methanol	Higher due to methanol

3.5 Methanol impact on ship design

Chemical and physical characteristics of methanol require certain ship design modifications in order to maintain reliable and safe ship operation. Adaptations are necessary due to, mainly: the liquid state of methanol and its specific safety requirements.

Key safety considerations related to methanol are:

- A low flashpoint at 11 degrees Celsius and overall wider flammability limits results in the requirement for tank inertisation by the IGF code when using methanol, as well as additional fire detection and protection methods;

- Combustion of methanol produces a barely visible flame and that forms no smoke, therefore regular smoke detectors are not effective in the early warming of fire and instead infrared flame detectors are to be used;

- Corrosion related to methanol has an impact on the selection of components for the materials (e.g. stainless steel is resistant to corrosion from methanol) and sealing materials (methanol is only compatible with some plastics and rubbers) to be used within the ships;

- The toxicity of methanol requires for eye, skin and respiratory protective equipment whilst working with it;

- Methanol vapour density is different to traditional fuels such as diesel and therefore due consideration is required for the placement of vapour detectors; and

- Methanol has little to no lubricating properties so appropriate lubrication oil selection for the engine is important.

SUMMETH deliverables (2016) and IMO (2016) summarise possible impacts on ship design, looking at necessary modifications per type of ship and size of the vessels.

Key impacts related to bunkering of methanol are:

- Additional control barriers should be added (due to low needed ignition energy and low flashpoint); and

- Additional monitoring and control systems are needed (e.g. overfill alarms, automatic shutdown, monitoring of ventilation and gas detection).

Key impacts related to storage of methanol on board are:

- Additional space may be required for storage of methanol on board, due to the considerations regarding placement and protection of tanks;

- Fitting of equipment and control systems (e.g. pressure/vacuum relief valves, shut off valves, pressure sensors connected to alarms) is necessary due to the requirements regarding gas freeing, inertisation and the venting of the tanks as well as the monitoring, ventilation and safe emergency shutdown of systems;

- Additional monitoring and control systems are needed (e.g. overfill alarms and shutdown), monitoring of ventilation liquid and gas detection; and

- Fire detection systems with infrared cameras in spaces adjacent to fuel storage and appropriate firefighting systems.

Key impacts related to handling and processing of methanol between the storage tanks and main engine(s) are:

- Necessary piping arrangement with double walled piping including: needed gas freeing and inertisation capabilities, ventilation of annular space between the pipe walls, and vapour and liquid leakage detection;
- Remotely operated shut off valves to the tanks and valves operated during normal operation and low flashpoint liquid (LFL) fuel supply valves to each consumer with their corresponding control system; and
- Placement of gas detectors and ventilation at lower elevations is essential due to the difference in vapour density.

Key impacts related to combustion of methanol in the main engine are:

- Additional methanol booster injectors, a liquid gas injection block fitted on the cylinder, which contains a control valve for methanol fuel injection, a methanol sealing booster activation valve, a forces suction activation valve, a purge valve and methanol fuel inlet/outlet valves; and
- Lubrication requirements: methanol requires a cleaner lubrication environment, but induces significantly greater engine wear compared to fuel oil since it has no lubricating properties in comparison. Therefore, fuel pumps and engines require additional lubrication to the likes of diesel.

These recommendations remain general and need case specific adaptations depending on the vessel size and type, and whether the design is a new build or retrofit. WP5 of this project will provide further analysis on the impact of methanol on the ship design for different vessel types.

Methanol does offer some advantages as a fuel, that also impact the ship design. For example, its lower heat radiation makes firefighting easier; its solubility in the water significantly reduces environmental effects from potential spillage damage in the event of a leak and therefore a single hull is sufficient for storage of methanol (SuMMETH D4.1).

3.6 Comparison of methanol as shipping fuel with other fuels

Different alternative energy carriers are currently available or potentially available for maritime shipping in the future. The following fuels have been taken into consideration: MDO/ MGO and HFO (in some cases grouped as diesel), LNG, Hydrogen and Ammonia. This is not a complete list of all options (for instance DME and LPG are also considered). The fuels that were selected were often mentioned as options in scenario studies. Within the next few paragraphs, key differences in the fuel characteristics are presented and aforementioned fuel types are compared in terms of their market readiness, impact on costs and environmental impact.

3.6.1 Fuel properties

Table 2 summarizes the technical characteristics of different fuel types.

Table 2: Technical characteristics of different fuel types

Properties	Diesel	Methanol	Ethanol	Hydrogen	Ammonia	LNG
Chemical structure	$C_{12}H_{26}$–$C_{14}H_{30}$	CH_3OH	C_2H_5OH	H_2	NH_3	C_nHN
Molecular weight	190–220	32.042	46.07	2.02	17	16
Density (kg/m3) liquid	830	790	790	73,22 (20K)	680 (20k)	419
Density (kg/m3) gas	-	-	-	0.084	0.73	0.83
Boiling point (°C)	180-360	65	78	-253 (20K)	-33	-161.4
Lower heating value (MJ/kg)	42.6	19.9	26.9	120.2	18.6	48 - 50
Flammability limits (vol)	1.85-8.2	6.7-36	4.3 - 19	4.1 - 74	15-28	5-15
Flash point (C)	78	11	12	-	-	-136

Source: TNO, MKC, TU Delft (2018).

Some conclusions from this table are:

- The energy density (lower heating value) of methanol is about half of the value of regular diesel; 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;
- The flash point of a fuel is the temperature at which the fuel forms an ignitable mixture with air. The value of this parameter for methanol is lower compared to diesel/ MDO, and the flammability limits are wider. Methanol is classified as a low flash point fuel which imposes increased risk during storage and imposes similar handling measures as for LNG (IGF code); and
- Metals corrode due to contact with methanol (just like ammonia). It is currently uncertain to what extent the effect of this will be on the durability of the engine. Some materials used in current combustion engines might not be prepared to handle methanol which imposes redesigning of some components or engine parts or the use of corrosion inhibitors (as additives to in the fuel) for long term durability.

The energy density of a fuel is an important factor for its applicability. The higher the energy density is, 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 and safety zones). 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 compared fuels, especially when taking into account packaging.

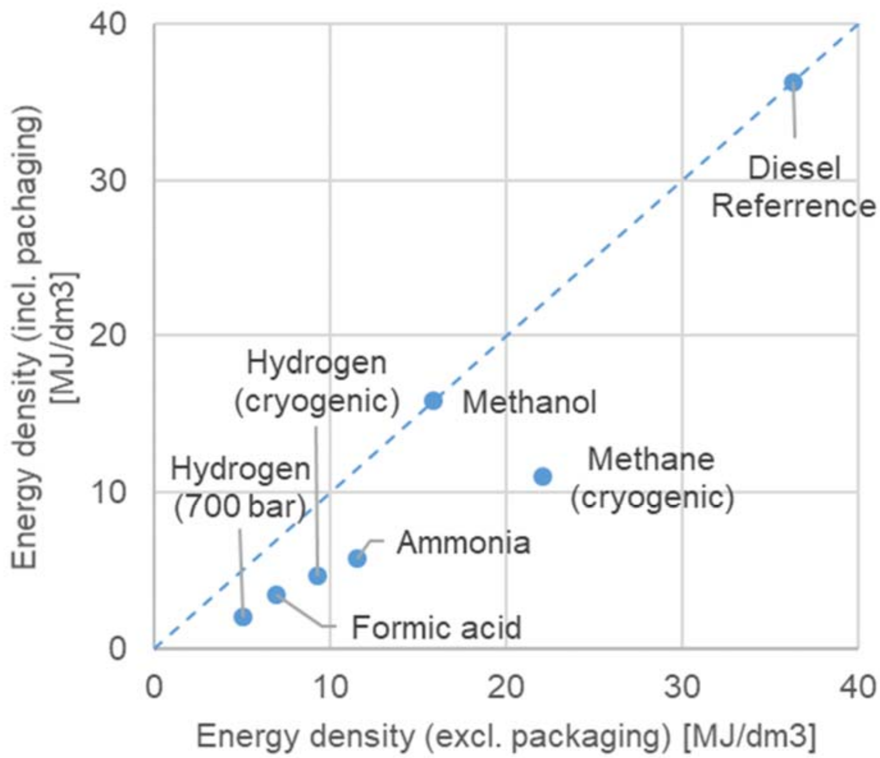

Figure 6: Energy density of different fuel types (TNO (2019)

3.6.2 *Technology readiness level*

MGO, HFO and, to a lesser extent, LNG are already widely available in the market (TRL 9). Methanol has been tested as a fuel in marine engines in laboratories in a few projects and has been successfully installed in a few vessels. A first full scale installation was on board the Stena Germanica Ro-Pax ferry in 2016 (see SUMMETH 2018). Engine performance was shown to be comparable with conventional fuels for these tests and emissions were found to be lower.
In addition, the construction of seven chemical (methanol) tankers with dual fuel methanol engines was commissioned by Waterfront Shipping to be delivered in 2016. In 2019, two additional vessels were commissioned (Waterfront 2019). Both companies did not report significant problems for these vessels. Since several vessels are already existing, the technology readiness level is considered to be TRL 6 to 8. For ammonia and hydrogen, maritime pilots are in development. For ammonia, MAN Energy Solutions has developed a design for a two-stroke engine using ammonia and LPG (MAN ES 2018). Wartsila recently performed combustion trials using ammonia (Wartisla 2020). Several projects are currently ongoing for using hydrogen as a fuel for smaller ships, either using a combustion engine (i.e. CMB Hydroville) or fuel cell (i.e. Zemship, Norwegian hydrogen ferry).

The uptake of renewable fuels in shipping depends on the technological development in the production of the fuels.

The following table presents an overview of the forecasted development of the TRL of different routes based on workshops with stakeholders and literature review (MKC et. al. 2020).

Table 3: Current and future TRL levels for various alternative fuels.

End product	**Feed stock / Production route**	**Fuel production TRL**	
		2019	**2030**
Conventional			
FAME	Oil crops	10	10
HVO	Oil crops	10	10
Hydrogen (grey)	Natural gas steam reforming	10	10
Advanced			
HVO	used oil	10	10
Methanol	Black liquor Gasification	6/8	8/9
Methanol	waste based	8/9	9/10
Methane / bio-LNG	Lignocelluloses Gasification	6/8	8/9
Methanol	Lignocelluloses Gasification	6/8	8/9
DME	Lignocelluloses Gasification	6/8	8/9
FT-Diesel	Lignocelluloses Gasification	6/8	8/9
Renewable diesel	Wood extractives pulping/ catalytic upgrading	8/9	8/10
Renewable diesel	Algae/oil extr / catalystic upgrading	4	5
Methane / bio-LNG	sludge/maize/manure/ residues Fermentation	10	10
Power to X			
Hydrogen	Electrolysis renewable electricity	9	10
Pt methane	H2 + C + methane synthesis	5/6	6/8
Pt methanol	H2+C + methanol synthesis	5/6	6/8
Pt diesel	H2 + C + Fischer Tropsch	5/6	6/8
Pt ammonia	H2 + N	5/6	6/8

Source: MKC et al 2020

3.6.3 *Development of fuel pricing*

Fuel price for shipping (Free on Board (FOB)) consists of production costs, distribution costs and a margin for the seller. There are no levies since bunkering of international marine fuels (e.g. HFO, MGO) is free of duty and VAT (MKC et. al. 2020). Because the margins of the producer are unknown and the distribution costs greatly depend on the distance between the fuel production location and the location of the vessels, it is difficult to determine the prices for alternative fuels. Another factor that needs to be taken into account for the short term pricing of renewable fuels in shipping is the use of tickets for the production of alternative fuels as described in the European Renewable Energy Directive (RED II).
The price of these tickets and even a possible double counting of these tickets can substantially lower the price of renewable fuels on board ships. Since this is a temporary system until 2030 and due to change in 2023 it is difficult for ship-owners to base their long term investments on these rather unpredictable incentives.

Based on several workshops with stakeholders and a literature review, MKC et al (2020) created a long list of the prices of different alternative and renewable fuels (respectively red and green bars in Figure 7). The found price level for renewable methanol is comparable to that of other biofuels.

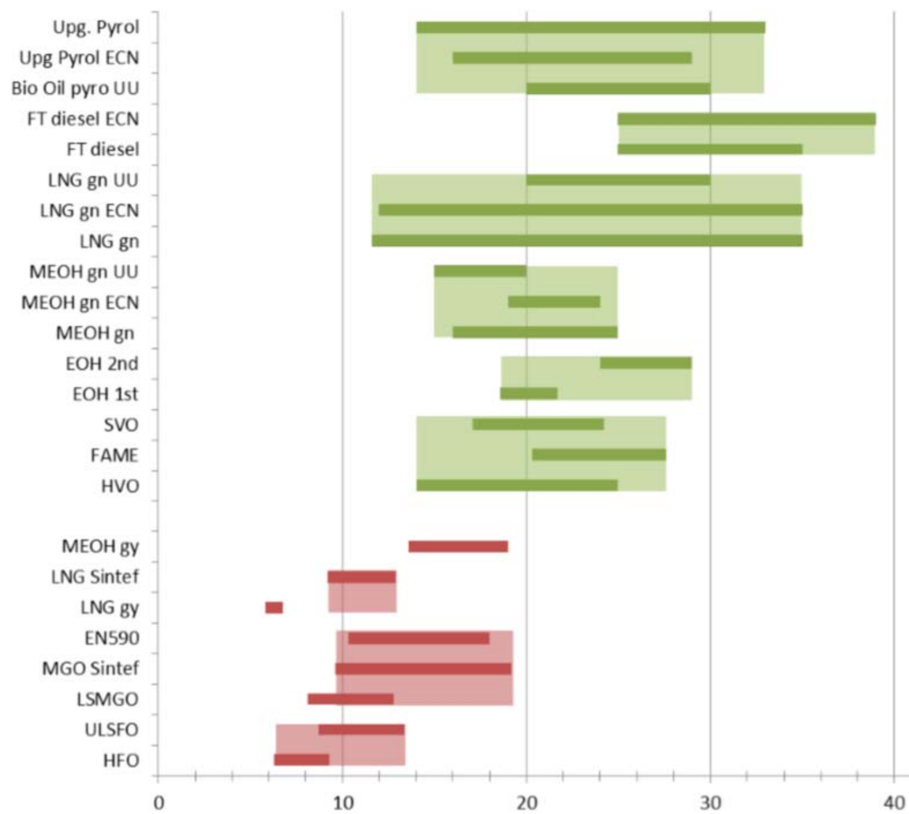

Figure 7: Comparison of fossil and renewable fuel prices (Euro per GJ).
Source: MKC et al 2020

The long term development of the pricing for different alternative fuels is related to the development of the maturity of the technology. Lloyd's Register and UMAS (2019a, 2019b) developed a set of studies comparing the price of different energy carriers using different feedstocks.

Cost components that need to be considered include:

- Production and transportation costs of the fuel (price of the fuel);
- Engine room investments; and
- Lost revenue due to loss of cargo space (for cargo vessels).

The figure on the next page presents an overview of the production and transportation costs for different energy carriers (LNG was not taken into account in this study) and can be considered as a proxy for the fuel price development.

When considering production costs in 2030 (purple lines), production costs of bio-based and synthetic methanol are estimated to be considerably higher than the price of low sulphur heavy fuel oil (LSHFO) and MDO.

However, the price of biofuel and synthetically produced methanol are estimated to decrease significantly due to increased production and technological maturity. The price development however is uncertain and requires a large increase in the production capacity, either in biomass cultivation (up to 2.5 billion hectares on arable land by in 2050) or in the production capacity of renewable energy (100 EJ by 2050).

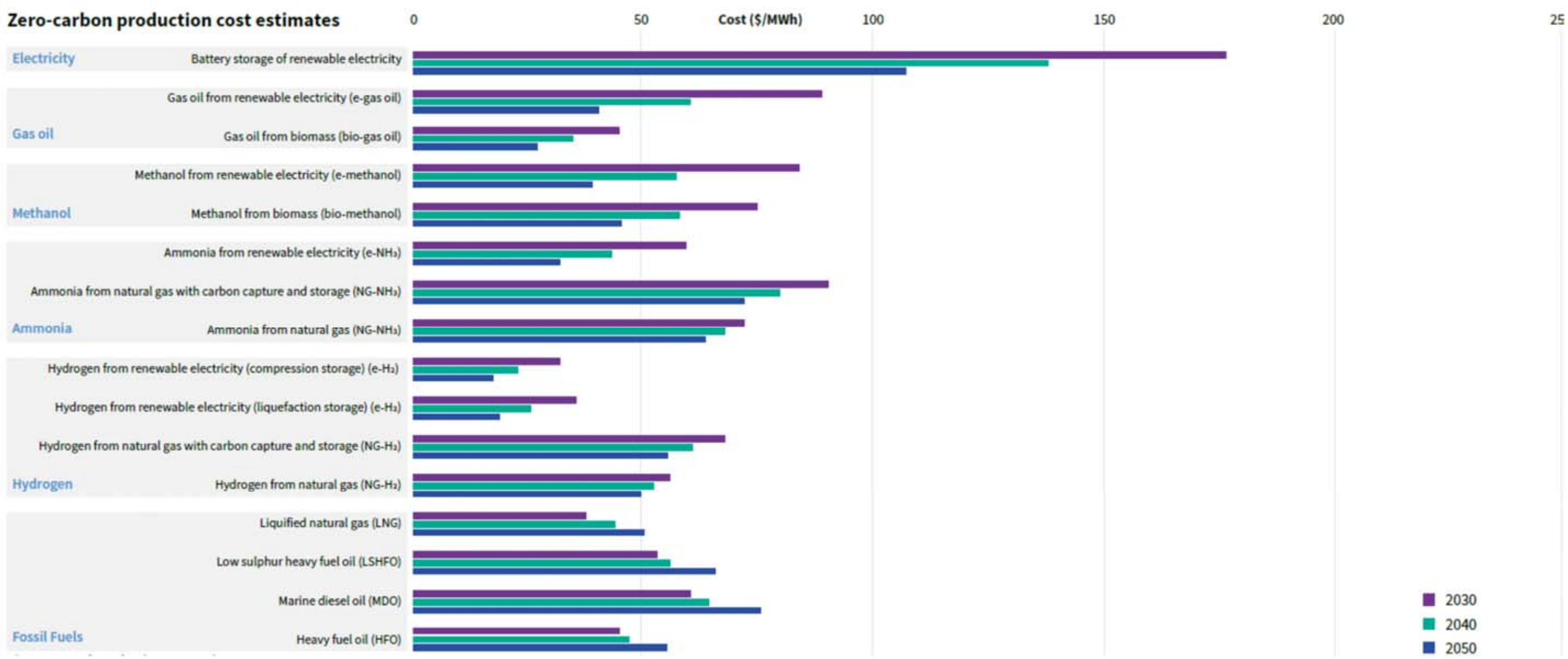

Figure 8: Cost estimation for different production pathways for zero-emission fuels (Lloyd's Register and UMAS (2019a))

3.6.4 *Effect on GHG emissions*

For the assessment of the environmental performance of methanol compared to other energy carriers, the GHG emissions for the well-to-wake (WTW, for shipping also referred to as well-to-propeller or WTP) have been considered. This includes all emissions, from of the entire fuel chain, from the mining of the energy source to the use in the mode of transport. All GHG emissions have been translated into CO_2 equivalents using their global warming potential (GWP). Other greenhouse gases, besides CO_2, such as methane, are considered.

An important consideration for calculating the WTP emissions of different options is the feedstock and the production methodology that has been used to create the fuel.

Main feedstocks are taken into account:

- Fossil (oil, gas, and coal);
- Recycled carbon fuels (plastic waste);
- Biobased (e.g. oil crops, wood pallets, organic waste) and waste-to-energy; and
- Synthetic (Power to fuel: created from electric energy and a carbon source).

Table 4 presents the WTW emissions for different energy carriers for different feedstock options. All emissions have been expressed in g CO_{2eq}-per MJ energy, to make them comparable. The numbers are based on JRC (2014). For LNG a correction is made to the WTW emissions due to the usually relative high methane emissions of ship engines. 0.71 g/MJ methane emission leads to an additional CO_2 equivalent of about 20 g/MJ (100 year GWP).

In general for each option, biofuels and synthetic fuels (P2fuel, using green electricity) lead to considerably lower GHG emissions than fossil fuels. The table shows a range in the outcomes for each section, due to differences in the well to tank emissions of different feedstocks (e.g. oil crops, wood pallets) or different production methodologies.

Diesel, MGO and HFO are considered as reference fuels. They all roughly have the same GHG emission. No detailed information was available for a synthetic diesel (E-diesel) or synthetic gas (e-LNG).

Compared to the reference fuel, methanol has significant lower Tank-to-Wake (TTW) emissions (7% lower than MGO). The fossil production process (TTW), however, has higher CO_2-emissions, and shows a considerable range. As a result, fossil diesel and fossil methanol have very similar WTW GHG emissions. Bio-based methanol and synthetic methanol lead to much lower GHG emissions.

LNG has similar TTW emissions the (diesel) reference fuels. The advantage of the low carbon content is lost due to the high methane emission. As a consequence the WTW emission is similar to the top of the range of methanol and slightly higher than fossil diesel (all fissile based). As biofuel, bio-LNG has somewhat higher WTW emissions than bio-methanol and has similar emissions as biodiesel.

H_2 and Ammonia are considered good options, especially in the case of synthetic production. H_2 and ammonia contains no carbon and consequently no CO_2 source is needed for the production, which simplifies the production. H_2 and ammonia can both be used in a fuel cell or in a combustion engine, although both options are hardly developed, especially for ships. In any case, there are no TTW CO_2 emissions for H_2 and ammonia.

Table 4: Well-to-wake CO_2 emissions for different energy carriers (CO_2eq g/MJ).

	Diesel	**MGO (0.1)**	**HFO (0.5)**	**Methanol**	**LNG**	**Ammonia**	**Electricity**	**H_2**
Fossil								
WTT	15.4	14.2	11.1	24.9 to 32.2	19.4	NA	142.4	115.2
TTW	73.2	74.1	77.4	69.1	75	0	0.0	0
WTW	88.6	88.3	88.5	84.2 to 94.3	94.4	NA	142.4	115.2
Biofuel								
WTT	-62.8 to -13.7			-66.9 to -62.5	-52.3		7.7	15 to 20
TTW	70.8			69.1	75		0.0	0.0
WTW	8.1 to 57.1			2.2 to 6.6	22.7		7.7	15 to 20
Synthetic P2Fuel								
WTT	not available			-67.5	not available	1.8	1.0	4 to 13
TTW	not available			69.1	75	0	0.0	0.0
WTW	not available			1.6	not available	1.8	1.0	4 to 13

Source: JRC (2014), TNO (2017). Biodiesel based on HVO, numbers for FAME are quite similar.
LNG TTW includes CO_{2eq} of engine methane emission.

3.6.5 *Effect on air pollutants*

For ship owners, compliance with SO_X and NO_X regulations is an important consideration for switching to alternative fuels. In the table below, the engine (TTW) emissions are given for a number of engine-fuel options, primarily meant for Emission Control Areas (ECA). This is seen as the main application area for clean fuels as methanol and LNG. So the diesel emissions are based on a 0.1% sulphur fuel. The emissions are primarily based on Brynolf (2014), Verbeek (2015), Ter Brake (2019). The most common technologies are chosen for methanol and LNG, namely dual-fuel with a diesel pilot injection (2% pilot fuel). The resulting SO_X emissions of these engines are primarily related to the sulphur content in the diesel pilot. NO_X emissions are usually calibrated just below the emission limit, since a further reduction would lead to addition costs in fuel or urea (for SCR aftertreatment) consumption.

Ammonia, electricity and H_2 are not included in the comparison, since they would all have zero or very low emission (when Ammonia and H_2 are used with fuel cells). Ammonia and H_2 can also be used in combustion engines. In that case they will need to comply with Tier III and will likely have similar emissions as with methanol and LNG.

Table 5: Emissions of medium speed engine using different fuels: Diesel (S<0.1%), methanol, LNG as dual-fuel engines. Based on E3 test cycle. Range for NOx indicates variation due to engine size.

Engine/fuel	**Diesel Tier II**	**Diesel Tier III**	**Methanol dual fuel Tier II**	**Methanol dual fuel Tier III**	**LNG dual fuel Tier III**
Technology emission control	Engine out	SCR or EGR	Engine out	SCR or methanol-water	Engine out (IDI) or SCR (DI)
NO_x limit value[3] g/kWh	8.6 – 12.4	2.2 – 3.0	8.6 – 12.4	2.2 – 3.0	2.2 – 3.0
NO_x g/kWh	8.0 – 11.5	2.0 – 2.7	~ 5	2 - 3	2 - 3
PM g/kWh	0.23	0.23	0.03	0.03	0.02
SOx g/kWh	0.36	0.36	0.007	0.007	0.009
Methane g/kWh	0.0036	0.0036	n.a.	n.a.	5.7

MS engine speed range : 250 – 1200 RPM

Sources: Brynolf (2014), Verbeek (2015), ter Brake (2019)

[3] The NOx limit is a function of max engine speed if max speed is between 130 – 2000 rpm: Tier II: NOx limit = $44.n^{(-0.23)}$. Tier III NOx limit = $9.n^{(-0.2)}$.

4 Methanol demand within shipping industry

This chapter looks at the potential demand for methanol from the maritime shipping industry. For this, we start from understanding the overall potential demand for methanol from other industry sectors. Next, we identify for which segments of ships methanol demand can be applicable and represent the good alternative fuel option, thus, looking into potential demand for methanol from shipping industry. In order to do this we are looking at methanol applicability for the different operational profiles of the ships. Using input from involved partners, detailed data was collected for these profiles on technical specifications and operational use. The impact of use of methanol on these ships in terms of fuel usage and storage on board has been calculated.

Finally, once those sub-markets are identified, we are looking either switch to methanol as a fuel for shipping as a beneficial option for the Dutch market.
For this we are translating the situation to the ports of Rotterdam and Amsterdam, and get first ideas about potential application of methanol for shipping industry within the Dutch market.

4.1 Current world demand for methanol

Due to the increase in the use of methanol, among others as a fuel for the transport industry, for example in mobility, or as a feedstock for other fuels such as DME, and for alternative production of ethylene, the overall demand for methanol is expected to rise to ca. 100 million metric tons by 2020, as can be seen in Figure 9, and to up to 160 million metric tons by 2030.

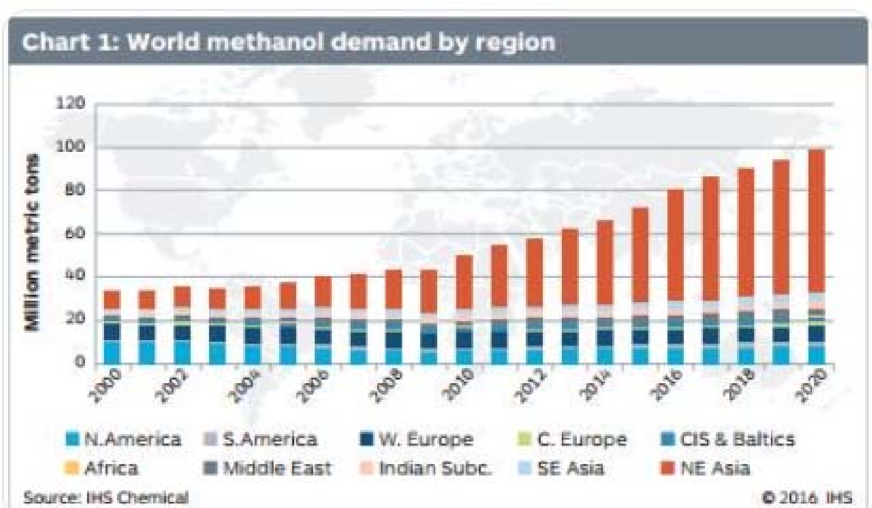

Figure 9: World methanol demand (IHS chemical).

The following figure presents an overview of the different market segments for methanol for the year 2017. Roughly 60% of the market consists of applications in constructions, the chemical industry and other industry applications in the form of formaldehyde, MMA, Acetic Acid (Metanex 2017).

Hexa Research expects a gradual increase of these markets as result of ongoing growth in the construction industries and urbanisation (Hexa Research 2018).

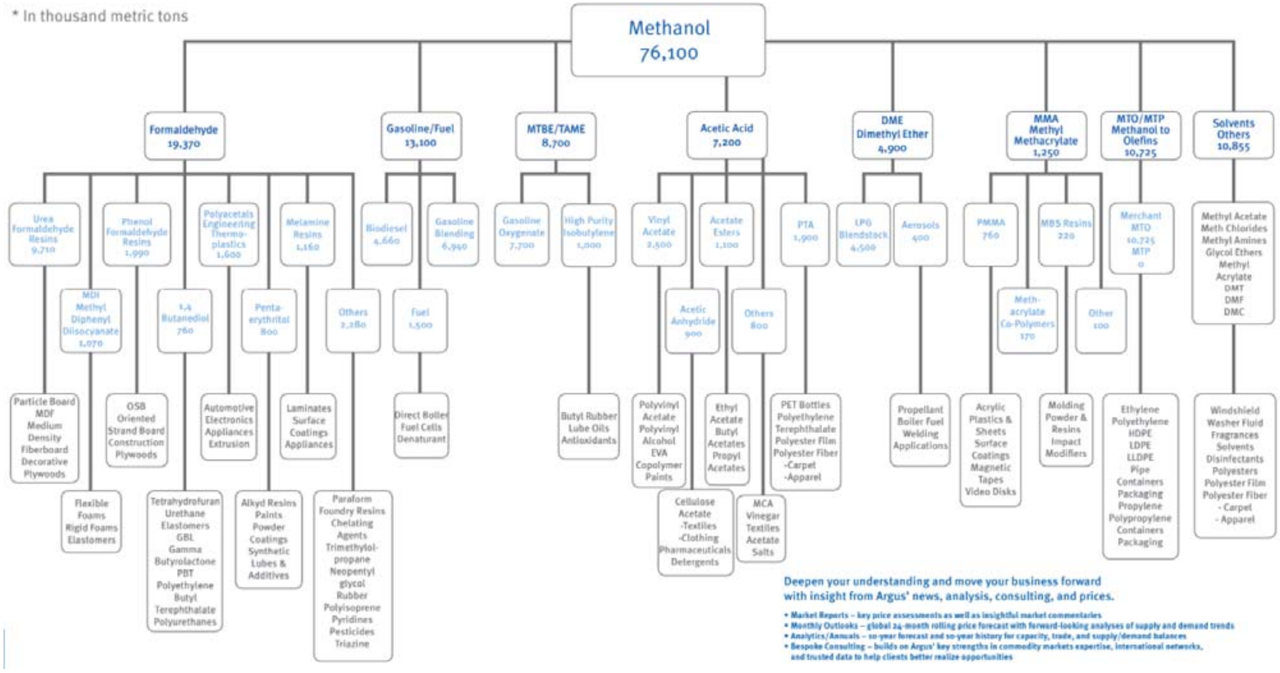

Figure 10: Overview of market segments of methanol in 2017 (Hexa Research 2018).

Another important segment for application of methanol is as a source for alternative fuel. This includes application as a blend for ethanol, as a feedstock for biodiesel (FAME) production, feedstock for DME production or as a direct boiler fuel. The market segment is expected to grow significantly with the increased demand for biofuels, through regulations mentioned in chapter 2 (RED II) and increased attention for sustainability. The current market for methanol as a direct fuel, as would be the case in maritime application, is limited (1.5 Mton).

4.2 Break down and fuel consumption of the global shipping market

In order to estimate the shipping demand for methanol, as a first step, we look at the breakdown of the global shipping market and the expected growth of different segments. As a second step, an impact calculation of the application of methanol on operations as a shipping fuel for individual ships of different segments is presented. It includes the effect on fuel usage, effect on bunkering volume and bunkering options.

4.2.1 Breakdown of the global shipping market in segments and their characteristics

In the following table, an overview is presented of the development of the worldwide maritime fleet between 2015 and 2030 according to a recent DG CLIMA study (TNO et. al, 2015).
The table describes the development of the average vessel size, the number of vessels and the work performed by these vessels expressed in billion ton nm.

Table 6: Number of vessels, average vessel sizes and freight moved (in billion ton.nm, 2015 compared to 2030).

	Vessel type		Number of vessels		Freight work	
	2015	**2030 Forecast**	**2015**	**2030 Forecast**	**2015**	**2030 Forecast**
Dry Bulk	69,300	98,000	11,200	15,300	22,000	42,400
General Cargo	6,200	7,000	17,000	29,500	2,600	5,100
Container	44,300	77,000	5,600	6,200	9,900	19,100
Reefer	6,000	7,000	1,050	2,300	200	500
RoRo & Vehicle	8,900	11,000	2,600	4,200	600	1,200
Oil Tanker -above 80'dwt mainly crude	185,800	189,000	2,400	4,500	11,000	21,200
Oil Tankers -below 80'dwt mainly product	10,700	12,000	5,400	9,400	2,100	4,100
Chemicals	19,000	29,000	5,400	6,800	2,500	4,800
LNG & LPG	29,000	46,000	1,800	2,100	1,700	3,200
RoPax	1,800	2,300	2,308	5,400	100	300
Average Cargo Vessels	**31,500**	**42,500**	**54,800**	**85,700**	**52,700**	**101,900**
Ferry-Pax only	170	200	3,300	5,600	10	20
Cruise	4,000	4,800	550	900	20	40
Yacht	170	200	1,750	1,750	0	0
Offshore	1,700	1,800	6,500	6,500	140	150
Service	540	600	18,100	18,100	90	100
Fishing	180	180	22,100	22,100	50	50
Other	1,100	1,100	3,000	3,000	20	20
Average Other Vessels	**570**	**600**	**55,300**	**60,500**	**330**	**380**
All Vessels	**15,600**	**19,500**	**110,100**	**146,200**	**53,000**	**102,300**

Source: TNO et all 2015

The table shows that around half of the current worldwide fleet consists of cargo vessels. A large share of these vessels consists of general cargo vessels (21% of total 2015 fleet), dry bulk carriers (12%), oil tankers (12%) and container vessels 6%). In the non-cargo vessels fishing boats (20%), service vessels (16%) and offshore vessels (6%) have a large share. The average size of cargo vessels is substantially larger than that of other vessels. 29% of the ships - namely container ships, bulk carriers and oil tankers - are accountable for 85% of the total deadweight of the fleet.

The projections for 2030 show that the cargo fleet is expected to increase significantly. The maritime freight (in terms of ton nautical mile) is almost doubled in size compared to the 2015 level. Part of this increase is captured by an increase in vessel size, especially in the container segment.

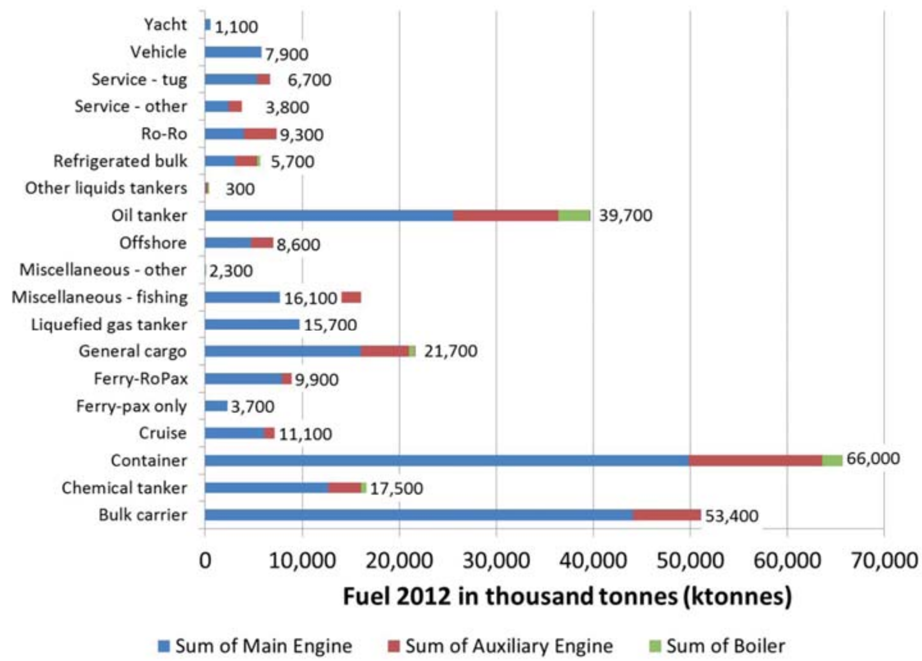

Figure 11: Fuel consumption of the worldwide maritime ship fleet (IMO (2015).

Figure 11 presents the total fuel consumption of different maritime sectors. The greatest share in fuel consumption is in the segments of dry bulk, oil tankers and container sectors. Comparing the fuel consumption to the overall deadweight tonnage from Table 6 shows that relative to the deadweight tonnage (dwt),) the fuel consumption of container vessels is higher than other cargo vessels of the same dwt class. In Annex A some key figures are presented on the fuel usage for different maritime sectors ship segments relative to vessel for different ship sizes.

4.3 Suitability of methanol as a fuel for different shipping sectors

In this section, the suitability of methanol is considered for a few different vessel types, based on input from involved shipping companies. First, some KPIs that will influence the overall compatibility of methanol as a shipping fuel are assessed. Afterwards, the results for individual shipping sectors are presented.

4.3.1 KPIs for assessing the compatibility of methanol

Several studies identify characteristics of the suitability of a shipping segment sector to switch towards an alternative fuel such as methanol. Based on these studies (CE Delft, et all 2016, Dierickx et al 2018, EMSA 2015), the following technical and operational KPIs have been identified:

- Technical aspects of the vessel:
  - ship size (dwt);
  - engine characteristics;
  - bunker tank size; and
  - layout of the vessel.
- Operational characteristics:
  - function of the vessel (freight, passenger, other);
  - average sailing speed;
  - operational hours per year;
  - sailing routes (fixed route or widespread reach); and
  - average time between bunkering.

The above-mentioned aspects will influence the financial (CAPEX & OPEX), operational (supply side availability, flexibility to switch bunkering fuel) and other (i.e. safety) consequences of switching to alternative fuels.

4.3.2 *Methanol as a viable fuel for the different shipping segment sectors*

Green Maritime Methanol partners identified several shipping sectors where methanol could be viable alternative.

These segments sectors are:

- Short Sea dry bulk;
- Short Sea liquid bulk;
- Short Sea container vessel;
- Ferries;
- Platform support vessel;
- Yachts;
- Dredging; and
- Support vessels (Patrol/ pilot/ tug vessel).

Deep sea / intercontinental vessels have not been included in this section, due to the expected large tank size. However, current investment of CMA CGM in LNG powered container vessels with a capacity of 23,000 TEU shows that also for these vessels, switching to alternative fuels with a lower energy density is possible (CMA CGM 2020).

Several consortium members, either in their role as ship owners, shipping companies or ship builders companies, made detailed technical and operational data available of an example vessel for research purposes. Within the consortium, not all vessel types were available. Therefore, no information is presented for liquid bulk, container vessels and ferries.

4.3.3 *Operational assessment for the use of methanol in selected segments*

For the selected ship sectors, the ship owners in the project have collected technical and operational information on a representative ship in a ship segment. The technical and operational profile was used to estimate how sailing on methanol would affect the operational capabilities of a vessel. As identified in section 3.2, methanol has less than half the energy density of MGO, which means that the ship can bunker less energy in the existing bunker tank volume. This may not be a problem, if the ship has bunker overcapacity, if the bunker frequency can be increased or if other solutions are available. In the calculations that follow, the chemical properties from Table 6 are used.

Table 7: Chemical properties used in this section.

Mass			**Energy**		
MGO density	850	kg/m3	MGO energy content	42.6	MJ/kg
Methanol density	792	kg/m3	Methanol energy content	19.9	MJ/kg
Ratio	1.07		Ratio	2.14	m/m
MGO to Methanol	2.30	v/v			
MGO to Methanol	1.89	m/m			

The results of the analyses are presented in tables similar to Table 7.

The letters are interpreted as:

A. Current bunker tank volume capacity of the vessel using the reference fuel. MGO is used as a reference fuel.

B. Volume of reference fuel (MGO) typically bunkered in current operational profile.

C. Volume of MGO in bunker tank when bunkering starts which is referred to as the margin. For example, if a vessel typically bunkers 75m^3 MGO with a total tank capacity of 100m^3, the margin in the fuel tank would be 25m^3.

D. Volume of MGO in bunker tank when bunkering starts expressed as a percentage. Following the example above, the margin would be 25%.

E. Total range that can be sailed when the total volume of MGO (see A) is consumed. Fuel consumption per nm is calculated using the technical specifications and the operational profile of the vessel.

F. Total range that the ship can still travel on the margin in the fuel tank when bunkering.

Letters G to L present the same values but using methanol as a fuel. In the analysis the same tank capacity size is used for MGO and methanol (letter A and G). Based on the output, conclusions are made on the expected range of the vessel under current conditions and with application of methanol in the current layout.

Table 8: Format used to present MGO to Methanol bunker numbers. Nm stands for nautical miles.

MGO				**Methanol**		
Capacity	**A**	m3		Capacity	**G**	m3
Bunkering quantity	**B**	m3		Bunkering quantity	**H**	m3
Margin	**C**	m3		Margin	**I**	m3
% in tank	**D**			% in tank	**J**	
Total range MGO	**E**	nm		Total range methanol	**K**	nm
Range when bunkering	**F**	nm		Range when bunkering	**L**	nm

Short Sea Freight vessel

For the short sea segment, the results of a Roll on Roll off vessel were used. The vessel sails a one week round line service (about 3000 nm).

The ship requires typically consumes ~290 m^3 of fuel to complete a roundtrip, and is bunkered once per two round trips (or every two weeks). On MGO this is still possible, since there is enough bunker capacity (572m^3) to complete the second roundtrip. The vessel bunkers normally at the same location.

When sailing on methanol, the consumed volume of fuel doubles, and less than 280m3 of methanol will be left after a single round trip. Therefore, bunkering should take place after every trip, or the storage capacity of the vessel needs to be increased.

Since the vessel bunkers at the same location, it is sufficient to have methanol available at only this one location. The bunkering quantity (~670 m^3) is quite large, therefore bunkering with tank-trucks (~ 40 m^3) as described in 3.1.2 does not seem plausible.

Table 9: Bunker volumes for a short sea RoRo vessel per roundtrip.

MGO				**Methanol**		
Capacity	865	m3		Capacity	865	m3
Bunkering quantity	293	m3		Bunkering quantity	673	m3
Margin	572	m3		Margin	192	m3
% in tank	66%			% in tank	22%	
Total range MGO	10504	nm		Total range methanol	4572	nm
Range when bunkering	6946	nm		Range when bunkering	1015	nm

Dredging vessel

For dredging, a trailing suction hopper dredger was analysed in two operational modes: one in which it dumps dredged material through the bottom doors, and one where sand is pumped ashore.

The vessel has the following characteristics:

- Weight of 22,000 mt deadweight dwt.
- 12,000 m^3 hopper capacity.
- Propulsion and pumping power is both supplied by two 5,080kW engines which power shaft generators and the propellers directly. Electricity from the shaft generators powers the pumps.

In the current situation, the ship bunkers just over 1,600m^3 of MGO. At an approximate fuel use of 40 to 50 m^3 per day, the ship operates 37 days between bunkering. This leaves a margin of 25%. The vessel operates worldwide, and does not have a standard bunkering port.

When operating on methanol, since the dredger has a significant bunker capacity and can operate for at least 37 days on MGO, the reduced energy content of methanol requires changes in the operations or in the technical layout of the vessel. Bunkering methanol would be possible in many regular projects. In these cases bunkering should take place every 2 weeks. Increasing the bunker volume to fit the normal operational profile should be further investigated in the project. It is likely that this would affect the hopper capacity.

Given the operational profile of the vessel, bunkering methanol will be an issue at an early stage of development. Methanol would be needed to be available in many ports around the world. Given the bunkering quantity, truck-to-ship bunkering would not be an option.

Table 10: Example bunkering profile for the trailing hopper dredging.

MGO			**Methanol**		
Capacity	1653	m3	Capacity	1653	m3
Bunkering quantity	800	m3	Bunkering quantity	1838	m3
Margin	853	m3	Margin	-185	m3
% in tank	52%		% in tank	-11%	
Total operating time MGO	37	days	Total range methanol	16	days
Time margin when bunkering	19	days	Range when bunkering	-4	days

Platform Supply Vessel/Cable laying vessel

As reference for the offshore work vessels, a 7,000 DWT cable laying vessel was selected.

The ship has a bunkering capacity which is fairly similar to the dredging vessel (1,500 m^3). The typical MGO usage is ~25 m^3 per day, which is significantly lower than other vessels in this assessment. Typically, the vessel bunkers more regularly (every 2 weeks). Platform supply vessels and cable laying vessel often operate in specific area for a long period of time, and thus often have a regular bunkering port.

With the current tank size, switching to methanol is feasible in the current operational profile. Shortages could arise in longer projects (4 weeks and more). For bunkering, again, truck-to-ship would not be an option.

Table 11: Example fuel use of cable laying vessel.

MGO			**Methanol**		
Capacity	1511	m3	Capacity	1511	m3
Bunkering quantity	300	m3	Bunkering quantity	689	m3
Margin	1211	m3	Margin	822	m3
% in tank	80%		% in tank	54%	
Total operating time MGO	60	days	Total range methanol	26	days
Time margin when bunkering	48	days	Range when bunkering	14	days

Pilot/ Port Vessel

For the analysis a typical patrol and port vessel was selected. This port vessel typically doesn’t leave the harbour. The main technical specifications for the vessel are:

- Length x breadth x height x draught: 19,64 x 7,94 x 3,39 x 2,49 meter
- Engines: 2x Caterpillar C18 896kW total.

The vessel has a bunker capacity of 14m^3, on which it sails for two weeks between bunkering. Sailing area is strictly within the harbour and city, mainly for inspection. When the ship is bunkered, around 40% of the bunker volume is still available, which is a significant margin. This margin may be used to assist in case of emergency.

When switching to methanol under the current bunker volume and operational profile, 14m3 should be bunkered every two weeks, leaving no margin in the tank. The vessel therefore will require a higher bunkering frequency to sustain a significant range. The ship owner (port authority) has indicated that weekly bunkering is acceptable for the current vessel operation. Bunkering could quite easily be performed from a stationary location or by using a tank truck.

Table 12: Bunker profile for MGO (current) and methanol for the port petrol vessel. Sailing on methanol will require more frequent bunkering to sustain an operational range.

MGO				**Methanol**		
Capacity	14	m3		Capacity	14	m3
Bunkering quantity	6	m3		Bunkering quantity	14	m3
Margin	8	m3		Margin	0	m3
% in tank	57%			% in tank	2%	
Total range MGO	1604	nm		Total range methanol	698	nm
Range when bunkering	916	nm		Range when bunkering	11	nm

Yacht

A 67m motor yacht was selected to represent the (high end) leisure sector. This ship has a variable sailing profile and can cover a large range.

Luxury yachts typically bunker between 60 and 80m^3 of MGO. This ship is required to have at least trans-Atlantic capabilities, which means >3500nm. On MGO, the ship has an estimated range of 6,000nm. The current bunker policy is to refuel at ~50%. From the fuel consumption in the operational profile, a range of ~3000nm can be covered with the remaining fuel.

When sailing on methanol, the range that can be covered with full bunker tanks reduces to 2,600nm. This would be insufficient for trans-Atlantic sailing, and the bunker volume therefore needs to be increased. Additionally, the current bunker policy of refuelling at 50% MGO cannot be sustained after a trans-Atlantic passage. To sustain trans-Atlantic range and have a margin of 20% fuel left on arrival, an additional 102 m^3 of bunker capacity would need to be installed.

All bunkering options would be feasible for this vessel type. Given the geographical area in which the ship is operating, a global wide availability of methanol would be required for it to switch.

Table 13: Bunker quantities for a 67m yacht.

MGO			**Methanol**		
Capacity	167	m3	Capacity	167	m3
Bunkering quantity	82	m3	Bunkering quantity	189	m3
Margin	85	m3	Margin	-22	m3
% in tank	51%		% in tank	-13%	
Total range MGO	6000	nm	Total range methanol	2612	nm
Range when bunkering	3041	nm	Range when bunkering	-347	nm
			Additional bunker volume needed to sustain range	217	m3
			Additional bunker volume for tans-atlantic (20% margin)	102	m3

Overall comparison

The fuel consumption and bunker capacity are important parameters to determine the feasibility of sailing on methanol. Since the energy density of methanol is approximately half that of diesel, the operational range halves when switching to methanol.

Whether this is an issue, depends on the extent to which the ship uses the fuel capacity. From the gathered fuel data, it can be seen that the match between fuel use and bunker capacity is different for different ship types. For almost all ships, sailing on methanol would require to bunker more frequent bunkering, or an increased bunker capacity.

Table 14: Comparison between fuel types.

Ship	Currently Feasible	Consequence
Short Sea Freight	Yes	More frequent bunkering
Platform supply	Yes	No change needed
Dredging	No	Significant changes in the operational profile and technical layout
Port Patrol	Yes	No action needed
Yacht	No	Bunker tank size must increase

The operational profile and technical capacity of the Short Sea line service, port vessel and pipe laying vessel are fit for a switch to methanol. Methanol fits the operational range of the vessels and the effect on the autonomy of the vessels is limited and no large changes to the layout of the ship would be required. The operational profile of dredging vessels requires a large period in between bunkering and requires a worldwide availability of the fuel. For yachts, the occasional transatlantic voyage cannot be made with the application of methanol. A shift to methanol therefore would only be possible with a change of the operational profile or a significant change in the technical layout of such vessels.

4.4 Estimation of potential methanol demand for ships calling at Dutch ports

Based on the results of the previous section, an analysis has been performed on the potential uptake of methanol for the major Dutch ports. The analysis used port call information from the data systems of the Port of Rotterdam and Port of Amsterdam.

Anonymised information was provided on:

- The total number of visits;
- The division of the visits for different ship types and subtypes (IMO Categories);
- Size class of the vessels (in dwt);
- Frequency of visits of unique vessels; and
- Last port of call before arriving in Amsterdam or Rotterdam.

By combining this dataset with the information from the operational profiles and input from the fleet studies, a calculation of the energy demand per day sailing was made for each ship type taking into account the size class where possible (cargo vessels only). This analysis takes into account the average sailing speed of the vessels. Based on a port distance database, the total sailing days for each category was calculated and thus the total energy demand for the last journey for both the reference fuel and application of methanol.

In the analysis several aspects have been highlighted. The first aspect is the number of calls per year a ship makes in a port in order to identify whether a vessel is in a service with a standard route and would be able to bunker in the port.
A second aspect is the number of sailing days and the associated fuel consumption. Ships having a high rate of fuel consumption per trip are less likely to be included amongst the early adopters of methanol.

Regularity of visits

As discussed in the previous section, an important element for uptake of an alternative fuel is the regularity of visits in a certain port. Figure 12 shows a division of the port calls by the number of visits of individual vessels. As an example, 46% of the port calls in the port of Rotterdam were vessels that visited the port up to 5 times annually whilst 19% were vessels visiting at least 52 times in a year.

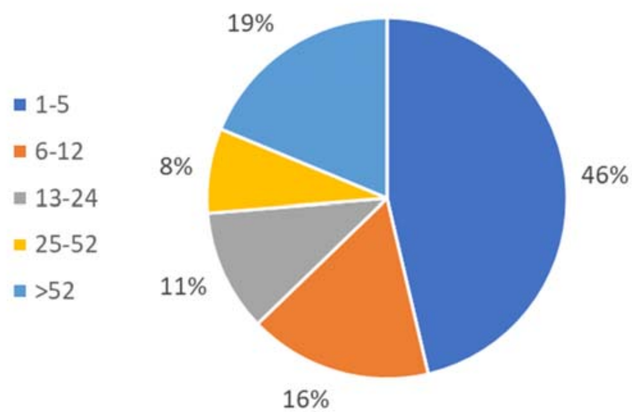

Figure 12: Number of annual calls per vessel at the port (% of total port calls for 2018).

Figure 13 shows the frequency of the visits per vessel type.

The outcome is largely consistent with what would be expected:

- Ferries are at a very regular schedule and most often call the port at least once a week (but often daily);
- Container vessels are operating often on a fixed route and therefore are frequently visiting the same ports. The smaller vessels (short sea) visit approximately once every two weeks;
- Bulk ships and to a lesser extent tankers, are operating more on the spot market (contracts for individual voyages or short term time charters) and are visiting less regular;
- General cargo shows mixed results with part of this market operating on the ‘on the spot’ market and others are longer term charters; and
- Offshore vessels were expected to have a large part in calling the ports quite regularly (reflecting work performed in the North Sea), however, this is not reflected by the data.

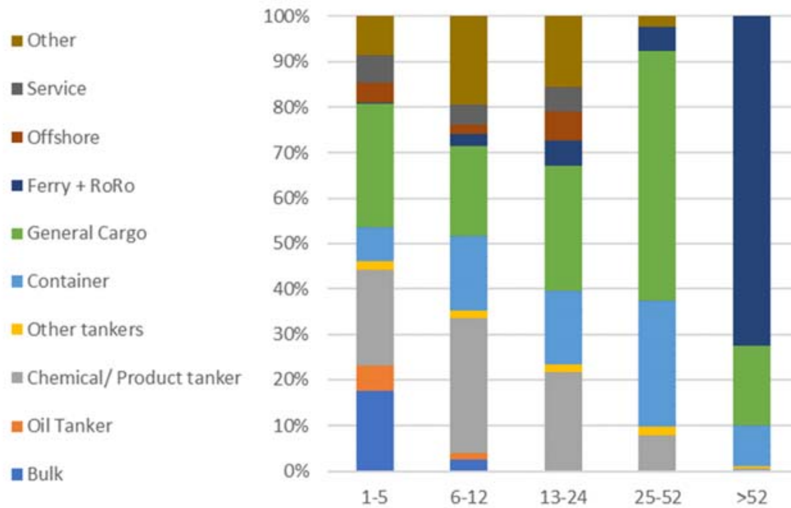

Figure 13: Number of annual calls per vessel at the port per vessel type.

Days sailing

Based on information on the previous port of call and the average sailing speed of the vessel, an overview of the average days at sea before entering the ports was derived. The results that are presented only include the nominal sailing time at sea (excluding time for berthing, waiting, etc.) and therefore are not representative of the actual single trip time. The results, as such, should be treated broadly. The results of the figure below show that over 50% of the vessels entering the port had sailed for just one day and about 80% within sailed up to a week between ports. The data also shows that there is a clear relationship with the vessel size - smaller vessels sail for shorter periods on average.

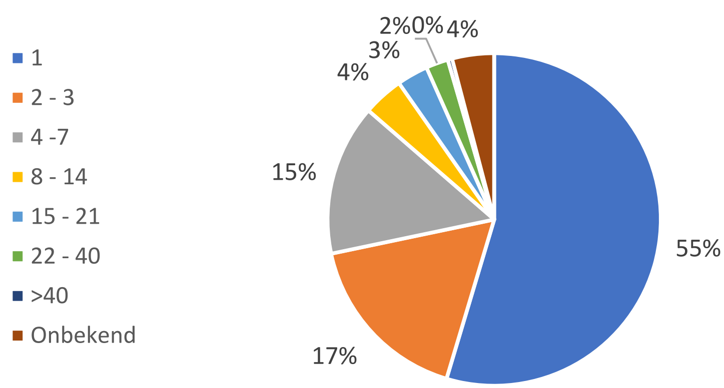

Figure 14: Number of days sailing from previous port of call.

Comparing the results with the previous section, there is a clear relationship between the days sailing and the number of arrivals. The same classes that arrive on a regular basis often also sail relatively short distances.

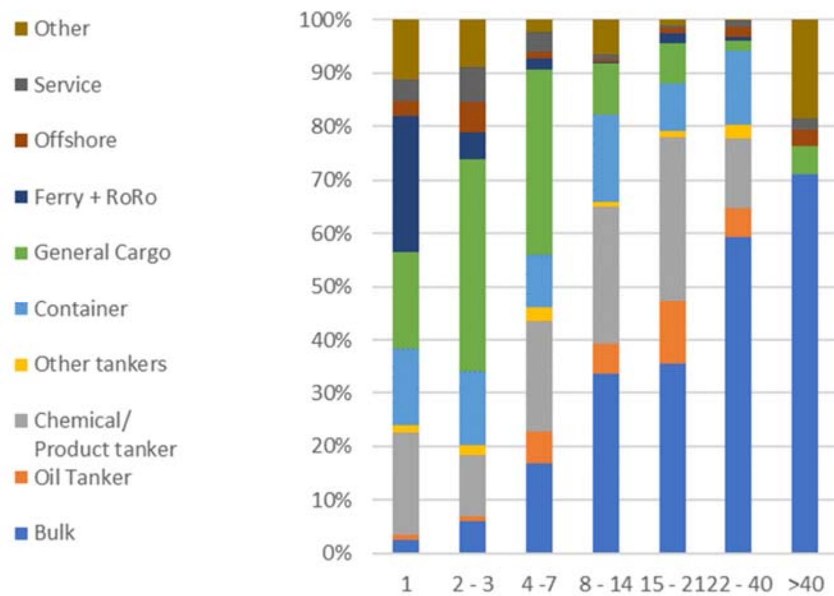

Figure 15: Number of days sailing from previous port of call per vessel type.

Fuel usage

Based on the port call data an overview was made on the fuel usage in ton MGO of the last voyage, before entering port. The following table shows that the majority of the vessels consume under 60 ton (or 70 m^3) MGO on their last trip and 87% of the voyages consume less than 150 ton (or 174 m^3) which is approximately the same as the Short Sea freight vessel referenced in section 4.2. These vessels are likely to be suitable for methanol. In terms of total bunker volume, these vessels account to for approximately 25% of the total bunker market.

Vessels that have a high fuel consumption are intercontinental cargo vessels or vessels with a really high fuel consumption, such as cruise vessels. It is uncertain whether the lay-out of the vessel could be suitable for the increased tank size needed in order to switch to methanol.

A quite large section of the port calls is performed by vessels with a very low fuel usage per trip (under 20 ton). Examples include the ferries that also have steady voyage routes. These vessels could also be suitable for less dense zero-emission fuel options, such as hydrogen or battery electric.

Table 15: Overview of percentage of port calls per fuel class (based on last voyage) and total bunker volume.

Fuel use single trip in ton MGO	% Port calls	% Bunker volume
0 - 20	**43%**	**4%**
21 - 40	**22%**	**6%**
41 - 60	**10%**	**5%**
61 - 100	**7%**	**5%**
101 - 150	**7%**	**8%**
150+	**13%**	**73%**

Conclusion

A large share of the vessels calling at Dutch ports visits the ports on a regular basis (87% at least once a week). Ferries, container vessels and general cargo vessels are regular visitors. The fuel usage of these vessels would allow usage of methanol. For the smaller vessels travelling relatively short distances (such as ferries), application of other zero-emission fuels, could potentially also be suitable.

5 Conclusions: key challenges and opportunities for methanol as a maritime fuel

This analysis on the availability of methanol as a fuel for maritime for shipping and its applicability for the Short Sea maritime operations has delivered the following key conclusions on the different levels of supply chain levels:

- Methanol production: There is global potential for viable production volumes of methanol. Multiple production routes are possible, including production based on fossil fuels, waste stream, bio mass and from electrolysis techniques using hydrogen together with carbon (captured from the air);
- Bunkering: Truck-to-ship bunkering is the most viable option for early adopters of methanol, whilst shore-to-ship bunkering can be further developed for certain vessel types such as ferries and port vessels. Ship-to-ship bunkering is not expected to emerge until the market is further matured, but this has the option to dramatically increase availability and distribution in multiple ports supplied by the same bunkering vessel;
- Modifications of ship designs and engines; Chemical and physical characteristics of methanol require certain ship design modifications in order to maintain reliable and safe ship operation. Due to the liquid state of methanol and its specific safety requirements, some vessel adaptations are necessary for bunkering process, on board storage, in handling and processing, and its end-use in combustion engines;
- Safety: Lower heat radiation from combustion decreases firefighting risks and water solubility significantly limits the detrimental impact of a potential environmental spill. However, methanol is volatile, has a low flash point and is toxic to humans. It therefore requires due attention regarding safety. Provided that methanol fuel bunkering and handling can be kept separate from any other activities on board, it is possible to design fuel systems which provide acceptable safety; and
- Tested successfully: There are already several successful pilots of vessels operating with methanol, therefore the technology readiness level is considered to be TRL 6.

Whilst the energy density of methanol is only around half that of MGO or HFO, it is still relatively competitive in comparison to other alternative fuels, particularly hydrogen. Furthermore, it potentially can be handled by most existing diesel systems with only small adaptions required. One of the biggest disadvantages, however, is that methanol is a low flash point fuel, that imposes similar safety handling measures as for LNG. The price development of methanol and other alternative fuel options is uncertain and depends largely on the technical development of different fuel production pathways which in turn affect the environmental performance of the fuel.

In order to identify the methanol demand within the shipping industry, the overall demand for methanol by different sectors was assessed, as well as shipping-specific demand from different shipping segments.

Shipping demand (and feasibility of shipping on methanol) for methanol was established by looking at the fuel consumptions and bunker capacity for different shipping segments. It is anticipated that for almost all vessel types, sailing on methanol will require to bunker more frequently, or have increased bunker capacity onboard. For the short sea line service, port vessel and pipe laying vessel it was found that the existing tasks can be executed with the existing bunker capacity combined with more frequent bunkering. The yacht requires additional bunker tanks in order to keep trans-Atlantic capability. However, it was assessed that the fuel usage of the vessels calling Dutch ports (ferries, container vessels and general cargo vessels) would allow the usage of methanol. For the smaller vessels travelling over shorter distances (such as ferries between European ports), the application of other zero-emission fuels like pure H_2, could potentially also be viable.

This report has also identified concrete discrete challenges and knowledge-gaps that should be further addressed within the Green Maritime Methanol Project:

- Engine technology: Three main technologies have been identified for methanol engines as feasible solutions for shipping on the short term, depending on the emission level and cost target:
  - Dual-fuel methanol-diesel used in a compression ignition engine (individually injected per cylinder in the engine).
  - Methanol used in a lean-burn spark ignition engine (100% single-fuel);
  - Methanol emulsification in diesel used in a compression ignition engine (pre-blended “mono-fuel”); and

  The dual-fuel principle is currently applied in some vessels. Tier III compliance has been demonstrated (and also low SOx and PM emissions). The technical feasibility of the other two engine technologies needs to be further investigated by means of experimental research on maritime engines.
- Supply chain: The future development of the different supply chain options is largely uncertain. Most notably the long term development of bio-methanol and synthetic methanol will be assessed as part of WP4, investigating the long term viability and price development; and will be further analysed.
- Potential: Methanol seems to be a feasible viable alternative fuel option for several maritime market segments sectors based on the current operational profiles and the current fuel storage facilities on board vessels; However, there are uncertainties regarding bunkering of methanol in terms of pricing and bunkering options in different ports. There is therefore a need for a financial and operational business case which will also be included within WP4.
- Ship Design: The impact of methanol application on vessel layout has been analysed for a few different vessel types (pilot ships, ferries) in previous projects and the Green Maritime Methanol project will take this further and investigate the impact on five vessel types, providing input on the feasibility of retrofitting existing vessels and newbuild options.

6 References

Andersson K., Salazar C.M (2015) Methanol as a marine fuel report.

Brynolf S., E. Fridel, K. Andersson (2014), Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol

Brynolf S., M. Taljegard, M. Grahn, J. Hansson (2018), Electrofuels for the transport sector: A review of production costs

ter Brake (2019). M.C. ter Brake, K.F. Kauffman, J. Hulskotte: Sea Shipping Emissions 2017: Netherlands Continental Shelf, 12 Mile Zone and Port Areas. MARIN Report No. 31270-1-MSCN-rev.1

CMA CGM (2020), The CMA CGM JACQUES SAADE, the world's first 23,000 TEU powered by LNG

DG CLIMA (2019), Fuel Quality https://ec.europa.eu/clima/policies/transport/fuel_en

Dierickx J., Beyen J., Block R.; Hamrouni M.; Huyskens P., Meichelböck C., Verhelst S., (2018) Strategies for introducing methanol as an alternative fuel for shipping

DNV (2018), EU MRV and IMO DCS

Ellis J., Tanneberger K (2015) ; TECHNICAL REPORT FOR EMSA Study on the use of ethyl and methyl alcohol as alternative fuels in shipping

F3 (2017), Methanol as a renewable fuel – a knowledge synthesis

Hexa Research (2017), Methanol Market Size and Forecast By End-use (Formaldehyde, Acetic Acid, MTBE, DME, Fuel Blending, MTO, Biodiesel) and Trend Analysis, 2014 – 2024

IMO (2015), Third IMO GHG Study 2014

IMO (2016), Methanol as marine fuel: environmental benefits, technology readiness, and economic feasibility

Industrielinqs (2004), Marktkansen voor de commodity methanol

Ingham, A. (2017), Reducing the Carbon Intensity of Methanol for Use as a Transport Fuel.

IMO (2018), Initial IMO Strategy on reduction of GHG emissions from ships, https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf

IMO (2020) Energy Efficiency measures. http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx

KVNR (2019), Relevante ontwikkelingen IMO en perspectief omtrent GMM

Lloyd’s Register and UMAS (2019a), Fuel production: cost estimates and assumptions.

Lloyd’s Register and UMAS (2019b), Zero-Emission Vessels: Transition Pathways

MAN (2014), Using Methanol Fuel in the MAN B&W ME-LGI Series. https://www.mandieselturbo.com/docs/default-source/shopwaredocuments/using-methanol-fuel-in-the-man-b-w-me-lgi-series.pdf

MAN ES (2018), Ship Operation Using LPG and Ammonia As Fuel on MAN B&W Dual Fuel ME-LGIP Engines.

MARPOL (1997), Prevention of Air Pollution from Ships, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx

MKC, TNO and TU Delft (2020), Final Report: Assessment of alternative fuels for seagoing vessels using Heavy Fuel Oil

SUMMETH (2018), SUMMETH – Sustainable Marine Methanol Hazard Identification Study for the M/S Jupiter Methanol Conversion Design

TNO (2015), LNG Framework and Market Analysis for the Rhine corridor - Status Quo Analysis

TNO (2017), Towards an alternative fuels strategy for the Port of Rotterdam – A review of options until 2050

TNO, MKC, TU Delft (2018), Final Report – Methanol as an alternative fuel for vessels, 07-03-2018

TNO, MARINTEK, ISL, TML (2015), GHG emission reduction potential of EU-related maritime transport and on its impacts

UN Climate Change (2016), Paris Agreement, http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Verbeek (2015), R. Verbeek, M. Verbeek: LNG for trucks and ships: fact analysis: Review of pollutant and GHG emissions. TNO report 2014 R11668. Date February 2015.

Wartsila (2016), Methanol As A Marine And Power Plant Fuel. https://www.globalsyngas.org/uploads/downloads/2016-9-1-Wartsila.pdf

Wartsila (2020), Wärtsilä advances future fuel capabilities with first ammonia tests

Waterfront Shipping (2019), IINO Lines & Waterfront Shipping Welcome Low-Emission Methanol-Fueled Tanker

WTC (2019), Waste to Chemicals Project, Rotterdam Green Maritime Methanol

7 Signature

The Hague, 4 June 2020

Paul Tilanus
Projectleader

TNO

Jorrit Harmsen
Author

A Shipping statistical information

Table 16: Average fuel consumption per day for different ship categories (Source: IMO 2015).

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. deadweight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption (000 tonnes)			Total carbon emissions (000 tonnes)
			IHSF	AIS							main	auxiliary	Boiler	
Bulk carrier	0–9999	dwt	1216	670	0.55	3341	1640	11.6	167	9.4	0.9	0.5	0.1	5550
	10000–34999	dwt	2317	2131	0.92	27669	6563	14.8	168	11.4	3.0	0.5	0.1	24243
	35000–59999	dwt	3065	2897	0.95	52222	9022	15.3	173	11.8	4.0	0.7	0.1	44116
	60000–99999	dwt	2259	2145	0.95	81876	10917	15.3	191	11.9	5.4	1.1	0.3	45240
	100000–199999	dwt	1246	1169	0.94	176506	17330	15.3	202	11.7	8.5	1.1	0.2	36340
	200000–+	dwt	294	274	0.93	271391	22170	15.7	202	12.2	11.0	1.1	0.2	10815
Chemical tanker	0–4999	dwt	1502	893	0.59	2158	1387	11.9	159	9.8	0.8	0.5	0.6	5479
	5000–9999	dwt	922	863	0.94	7497	3292	13.4	169	10.6	1.6	0.6	0.4	7199
	10000–19999	dwt	1039	1004	0.97	15278	5260	14.1	181	11.7	3.0	0.6	0.4	12318
	20000–+	dwt	1472	1419	0.96	42605	9297	15.0	183	12.3	5.0	1.4	0.4	30027
Container	0–999	TEU	1126	986	0.88	8634	5978	16.5	190	12.4	2.8	0.9	0.2	12966
	1000–1999	TEU	1306	1275	0.98	20436	12578	19.5	200	13.9	5.2	2.2	0.4	31015
	2000–2999	TEU	715	689	0.96	36735	22253	22.2	208	15.0	8.0	3.1	0.5	25084
	3000–4999	TEU	968	923	0.95	54160	36549	24.1	236	16.1	13.9	3.9	0.6	53737
	5000–7999	TEU	575	552	0.96	75036	54838	25.1	246	16.3	19.5	4.1	0.6	42960
	8000–11999	TEU	331	325	0.98	108650	67676	25.5	256	16.3	24.4	4.5	0.7	30052
	12000–14500	TEU	103	98	0.95	176783	83609	28.9	241	16.1	23.7	4.9	0.8	8775
	14500–+	TEU	8	7	0.88	158038	80697	25.0	251	14.8	25.3	6.1	1.1	806
General cargo	0–4999	dwt	11620	5163	0.44	1925	1119	11.6	161	8.7	0.5	0.1	0.0	23606
	5000–9999	dwt	2894	2491	0.86	7339	3320	13.6	166	10.1	1.4	0.4	0.1	16949
	10000–+	dwt	1972	1779	0.90	22472	7418	15.8	174	12.0	3.4	1.2	0.1	27601
Liquefied gas tanker	0–49999	cbm	1104	923	0.84	6676	3815	14.2	180	11.9	2.4	0.6	0.4	11271
	50000–199999	cbm	463	444	0.96	68463	22600	18.5	254	14.9	17.9	4.1	0.6	29283
	200000–+	cbm	45	43	0.96	121285	37358	19.3	277	16.9	33.5	4.0	1.0	5406
Oil tanker	0–4999	dwt	3500	1498	0.43	1985	1274	11.5	144	8.7	0.6	0.6	0.2	14991
	5000–9999	dwt	664	577	0.87	6777	2846	12.6	147	9.1	1.1	1.0	0.3	4630
	10000–19999	dwt	190	171	0.90	15129	4631	13.4	149	9.6	1.6	1.7	0.4	2121
	20000–59999	dwt	659	624	0.95	43763	8625	14.8	164	11.7	3.7	2.0	0.6	12627
	60000–79999	dwt	391	381	0.97	72901	12102	15.1	183	12.2	5.8	1.9	0.6	9950
	80000–119999	dwt	917	890	0.97	109259	13813	15.3	186	11.6	5.9	2.6	0.8	25769
	120000–199999	dwt	473	447	0.95	162348	18796	16.0	206	11.7	8.0	3.1	1.0	17230
	200000–+	dwt	601	577	0.96	313396	27685	16.0	233	12.5	15.3	3.6	1.1	36296
Other liquids tankers	0–+	dwt	149	39	0.26	670	558	9.8	116	8.3	0.3	1.3	0.5	5550

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Oil tanker	0–4,999	dwt	3,500	1,498	0.43	1,985	1,274	11.5	144	8.7	0.6	0.6	0.2	14,991
	5,000–9,999	dwt	664	577	0.87	6,777	2,846	12.6	147	9.1	1.1	1.0	0.3	4,630
	10,000–19,999	dwt	190	171	0.90	15,129	4,631	13.4	149	9.6	1.6	1.7	0.4	2,121
	20,000–59,999	dwt	659	624	0.95	43,763	8,625	14.8	164	11.7	3.7	2.0	0.6	12,627
	60,000–79,999	dwt	391	381	0.97	72,901	12,102	15.1	183	12.2	5.8	1.9	0.6	9,950
	80,000–119,999	dwt	917	890	0.97	109,259	13,813	15.3	186	11.6	5.9	2.6	0.8	25,769
	120,000–199,999	dwt	473	447	0.95	162,348	18,796	16.0	206	11.7	8.0	3.1	1.0	17,230
	200,000–+	dwt	601	577	0.96	313,396	27,685	16.0	233	12.5	15.3	3.6	1.1	36,296
Other liquids tankers	0–+	dwt	149	39	0.26	670	558	9.8	116	8.3	0.3	1.3	0.5	5,550
Ferry – pax only	0–1,999	gt	3,081	1,145	0.37	135	1,885	22.7	182	13.9	0.8	0.4	0.0	10,968
	2,000–+	gt	71	52	0.73	1,681	6,594	16.6	215	12.8	3.9	1.0	0.0	1,074
Cruise	0–1,999	gt	198	75	0.38	137	914	12.4	102	8.8	0.3	1.0	0.5	1,105
	2,000–9,999	gt	69	53	0.77	1,192	4,552	16.0	161	9.9	1.3	1.1	0.4	580
	10,000–59,999	gt	115	108	0.94	4,408	19,657	19.9	217	13.8	9.1	9.2	1.4	6,929
	60,000–99,999	gt	87	85	0.98	8,425	53,293	22.2	267	15.7	30.8	26.2	0.6	15,415
	100,000–+	gt	51	51	1.00	11,711	76,117	22.7	261	16.4	47.2	25.5	0.5	10,906
Ferry – ro-pax	0–1,999	gt	1,669	732	0.44	401	1,508	13.0	184	8.4	0.6	0.2	0.0	4,308
	2,000–+	gt	1,198	1,046	0.87	3,221	15,491	21.6	198	13.9	6.0	1.4	0.0	26,753
Refrigerated bulk	0–1,999	dwt	1,090	763	0.70	5,695	5,029	16.8	173	13.4	3.0	2.3	0.4	17,945
Ro-ro	0–4,999	dwt	1,330	513	0.39	1,031	1,482	10.7	146	8.8	1.1	2.5	0.3	15,948
	5,000–+	dwt	415	396	0.95	11,576	12,602	18.6	209	14.2	6.8	3.6	0.4	13,446
Vehicle	0–3,999	vehicle	279	261	0.94	9,052	9,084	18.3	222	14.2	5.4	1.6	0.3	6,200
	4,000–+	vehicle	558	515	0.92	19,721	14,216	20.1	269	15.5	9.0	1.4	0.2	18,302
Yacht	0–+	gt	1,750	1,110	0.63	171	2,846	16.5	66	10.7	0.4	0.5	0.0	3,482
Service – tug	0–+	gt	14,641	5,043	0.34	119	2,313	11.8	100	6.7	0.4	0.1	0.0	21,301

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Miscellaneous – fishing	0–+	gt	22,130	4,510	0.20	181	956	11.5	164	7.4	0.4	0.4	0.0	50,959
Offshore	0–+	gt	6,480	5,082	0.78	1,716	4,711	13.8	106	8.0	0.7	0.6	0.0	27,397
Service – other	0–+	gt	3,423	2,816	0.82	2,319	3,177	12.8	116	7.9	0.7	0.4	0.0	11,988
Miscellaneous – other	0–+	gt	3,008	64	0.02	59	2,003	12.7	117	7.3	0.4	0.4	0.0	7,425