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Executive Summary

The FASTWATER (FAST Track to Clean and Carbon-Neutral WATERborne Transport through Gradual Introduction of Methanol Fuel) project aims to start a fast transitionary path to move waterborne transport away from fossil fuels, and reduce its pollutant emissions to zero impact, through the use of methanol fuel. FASTWATER will develop and demonstrate a path for marine methanol technology, both for retrofit and next generation systems. Specifically, the project will demonstrate feasibility on three vessels running on methanol fuel: a harbour tug, a pilot boat, and a coast guard vessel. A conversion concept for a river cruise ship using methanol-driven propulsion will also be developed and a universal, scalable retrofit kit for converting diesel fuelled ships to methanol use for a wide power range (200 kW-4 MW) will be validated.

The work within the FASTWATER project also extends to investigating the potential implications of different methanol fuel qualities on engine and vessel operation. This deliverable report includes background on methanol fuel specifications and development and an overview of methanol quality considerations for engine development concepts included in the FASTWATER project. In addition, the feasibility and implications of establishing a fuel grade of methanol from the perspectives of stakeholders involved in methanol supply, distribution and use was investigated.

Purpose

The purpose of this document is to describe the status and experience with different methanol fuel qualities in marine combustion engines and provide an overview of testing carried out on engines within the FASTWATER project. Methanol quality variations and possibilities for a methanol fuel grade from the production and supply side are also described.

Approach and scope

For the investigation of methanol fuel quality considerations for marine engines, information was collected from the literature, published standards and guidelines, and discussions with engine manufacturers. Results of testing by FASTWATER partners was obtained from the published papers and reports produced within the project and direct contact with partners.

For the investigation regarding feasibility, challenges, and opportunities with the establishment of a fuel grade methanol, interviews with stakeholders were carried out. Interviews were conducted using a semi-structured approach. Interview findings were supplemented with a literature review and search of published articles to provide supplementary information.

Results and Conclusions

The engine producers in the FASTWATER project were open to accommodating a fuel grade methanol if it was available and preferred by ship operators due to lower cost, although they did not see particular benefits for their concepts. Separate laboratory testing by engine researchers in the project with a high-speed, dual-fuel, port injection engine showed benefits such as decreased NOx emissions when water was blended.

There is an expected large growth in renewable methanol production driven by significant newbuild orders for containerships with dual-fuel two-stroke methanol engines. The manufacturer's guiding specifications for these engines allows for operation on methanol with 95% w/w purity. E-methanol producers and technology providers indicated both capital costs and operating costs could be saved as the fuel grade purity could be produced with a single distillation column rather than two columns. For current providers of chemical grade renewable methanol there would be minimal savings from production, and potentially higher costs due to the need for separate storage and distribution of the second product grade. The perspective from bunker fuel storage and distribution was that a fuel grade could be accommodated if there was demand. Ship operators were also open to a fuel grade provided it was not more corrosive to fuel tanks, resulting in more maintenance or more expensive materials. Additionally there should be cost savings associated with a fuel grade to reflect a slightly lower energy content.

Acknowledgements

We are grateful to FASTWATER project advisory board members who made time to respond to our questions about renewable methanol production and marine methanol fuel potential. These include Thomas Stenhede, Kenneth Häggblom, Alex Miles, Kjeld Aabo and Juergen Battke. Other experts outside the board including Gijs Bakker, Christoffer Lillhage, and Oliver Davidsson also kindly responded to questions. FASTWATER project partners including Ayça Yalcin, Stefan Grubic, Greg Dolan, Tim Chan, Albert Wiström, Albert Hagander, Patrik Molander, Ewout De Wilde and Sebastian Verhelst all contributed information and participated in discussions regarding methanol marine fuel quality.

CONTENTS

List of symbols and abbreviations

ASTM	American Society of Testing and Materials
IMO	International Maritime Organization
IMPCA	International Methanol Producers and Consumers Association
ISCC	International Sustainability and Carbon Certification
ISO	International Organization for Standardization
LNG	Liquefied Natural Gas

1 INTRODUCTION

The FASTWATER project aims to demonstrate the feasibility of using renewable methanol as a marine fuel on three different vessel types and to create a detailed design and feasibility study for a fourth. In addition to developing the technology and on-board installations to burn methanol as a fuel for propulsion, the logistics and procedures for providing methanol fuel to the vessels are being investigated and demonstrated. The FASTWATER project is thus investigating the complete renewable methanol supply chain from producers to transporters to port-based infrastructure and finally to the bunkering of ships.

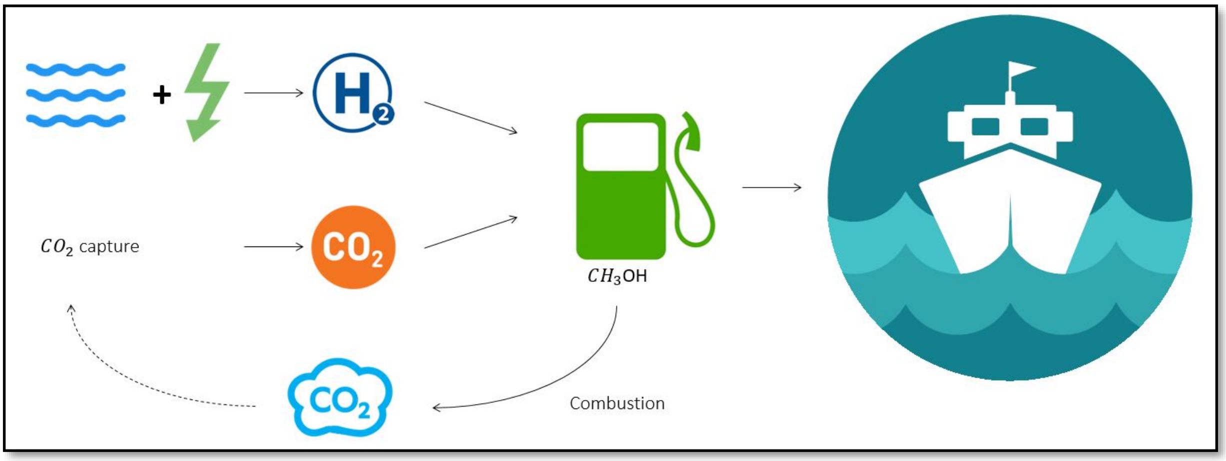

Figure 1-1. The FASTWATER project considers the renewable methanol supply chain from production of renewable methanol to supply as a vessel fuel. Source: FASTWATER consortium.

1.1 Background

An important part of fuel supply is having an agreed quality and specifications for the fuel to guide producers, suppliers, distributors, and end users. As methanol is a new fuel in the marine context, there is currently no fuel specification and to date the high purity chemical grade methanol has been used. Opportunities may exist for a fuel grade with lower purity, potentially reducing costs and energy use associated with production. There may also be challenges and impacts associated with introduction of a new grade. These were investigated as part of FASTWATER project work.

1.2 Purpose

The main objective of the work was to investigate the feasibility of establishing a marine methanol fuel grade. The FASTWATER project approached this investigation from the perspective of both the engine operation and from fuel production/supply, in two sub-tasks with objectives as follows:

- to assess the potential of marine engines to use a lower purity methanol as fuel,
- to identify supply side possibilities and potential variations in methanol purity achievable for different types of renewable methanol production, as well as possibilities for savings in costs and "well-to-tank" impacts

1.3 Scope and approach

For assessment of the potential of marine engines to use a lower purity of fuel, work in FASTWATER included laboratory testing of methanol with different water contents and qualitative assessment from FASTWATER partners who are gaining experience and operating hours with smaller marine engines. Results of testing have been published in papers by project partners (Dierickx et al., 2022, and Pu et al., 2022) and are summarized in Chapter 3. Engine concepts being tested and developed in FASTWATER include a high-speed diesel engine using direct injection methanol with ignition improver, and a medium-speed dual-fuel engine with mechanical port fuel injection. Different ignition improver concentrations were tested for the high-speed engine. Perspectives of larger marine engines were also collected through literature review and contact with engine manufacturers outside the project.

For the analysis of the potential variation in the supply side from different renewable methanol production processes, and impacts/opportunities/challenges on the supply, distribution and use chain, a combination of literature review and stakeholder interviews was used. Interviews were conducted using a semi-structured approach (Galletta, 2013) – a set of questions was prepared and sent out in advance, but follow-up questions and discussion was included in the on-line interviews.

2 Background

2.1 Fuel quality specifications

2.1.1 Marine fuel specification purpose and development

Specifications for conventional oil-based marine fuels were developed for the purpose of providing guidance for stakeholders such as marine equipment developers and suppliers and those supplying and buying marine fuels (Vermeire, 2021). The first international ISO standard for marine fuel, ISO 8217, was published in 1987 (Vermeire, 2021). The standards set limits for specific parameters to help ensure that the fuel can be safely used on board a vessel (Einemo, 2023) and not create operational problems for on-board equipment. Before a chemical compound is added to the specification there must be a clear link to operational problems, an agreed limit value, and a standardised test methodology (Einemo, 2021). Environmental regulations, such as sulphur emission requirements are also considered when setting limits for parameters for specific fuel grades.

For fuel produced from petroleum products, marine engine manufacturers specify fuel grades and acceptable fuel charactistics that may be used in their engines. Frequency of engine overhauls, emissions, and performance will be influenced by fuel characteristics. Engine manufacturers state that if non-standard fuels are used, they will not accept liability or responsibility for engine performance or potential damage. Operating with an off-spec fuel may void guarantees because the fuel may lead to excessive wear or even premature breakdowns (fuel pumps, injectors, cylinders, cylinder liners, piston rings, etc.). The acceptable fuel grades for conventional oil fuels are based on International Standards Orgnaisation (ISO) standard 8217:2017. This standard, "Petroleum products — Fuels (class F) — Specifications of marine fuels", specifies the requirements for fuels for use in marine diesel engines and boilers (ISO, 2017). This is the sixth edition of the standard – the standard is reviewed approximately every five years and as of 2023, work was proceeding on accepting revisions (ISO, 2023a). The current version of ISO 8217 specifies seven categories of distillate fuels and six categories of residual fuels. The term "fuel" is stated to include both hydrocarbons from petroleum crude oil, oil sands, and shales, and hydrocarbons from synthetic or renewable sources. The large number of categories of fuels from petroleum products is a result of international variations in crude oil supplies, refining methods, and other local conditions, and not all categories will be available in all regions (TransportPolicy.net, 2018). The standard specifies characteristics and limits for each grade, along with test methods that should be followed for each specified fuel characteristic.

2.1.2 Alternative marine fuel specifications

As new alternative marine fuels emerge, marine fuel standards may be developed if there are no existing appropriate standards that may be applied. Liquefied natural gas (LNG) was the first alternative fuel to be adopted for international shipping. The first LNG car/passenger ferry was introduced in Norway in 2001 (Laribi and Guy, 2020), and the first dual-fuel two-stroke engine was installed on a container vessel in 2014 (Xu et al., 2015). An international fuel specification, "Specification of liquefied natural gas as a fuel for marine applications" ISO 23306:2020, was published in 2020. Development of a new standard typically takes several years and experience with using the fuel is needed before appropriate specifications can be agreed. An international standard may facilitate supply and purchase of marine fuels but is not necessary for initial uptake and use of the fuel. Marine engine manufacturers may set their own fuel specifications in the interim or specify the use of an existing standard that is in place for other applications.

2.1.3 Development of methanol marine fuel specifications

The International Maritime Organization (IMO) invited the ISO to develop a methanol marine fuel standard in 2018 through a decision taken at the 99th session of the Maritime Safety Committee (MSC) (IMO MSC, 2018). The ISO project to develop a standard for specification of methanol as a fuel for marine applications was approved in 2021, and in mid-2023 the standard was in the preparatory phase (ISO, 2023b). The standard, being developed under ISO/AWI 6583, could include different categories of methanol, such as for fuel cells, which require high purity, and for internal combustion engines.

Once the standard is in place, it will be reviewed and subject to revision. Thus experience gained from the industry through operation of methanol-fuelled engines and fuel cells can be used to update the standard as necessary. Typically ISO standards are revised every five years.

MAN Energy Solutions developed a methanol fuel specification in 2016 for the MAN B&W ME-LGIM engines. They have been operating two-stroke engines on methanol since 2016, and have accumulated more than 400 000 running hours on methanol alone (Hansen, 2023). The specification is described in Section 2.2.

Within the FASTWATER project, experience and operating hours are being gained with smaller marine engines using different concepts such as a high-speed diesel engine using direct injection methanol with ignition improver, and a medium-speed dual-fuel engine with mechanical port fuel injection. Experiences gained with operating on methanol and quality considerations for the FASTWATER project engines are further described in Section 4.

2.2 Existing methanol specifications, standards, and grades

The methanol specifications published by the International Methanol Producers and Consumers Association (IMPCA) are widely used internationally and serve as a quality reference for about 90% of market interactions involving methanol (IMPCA, n.d.). Development of the IMPCA reference specifications began in 1992, to cover the need for an international standard for producers, traders, and end users. Previous to this the standard produced by the American Society of Testing and Materials (ASTM), ASTM 1152, had been the most commonly used reference. It had been developed for the national American market where the main transport modes for the product were road, rail and freshwater transport (IMPCA, n.d.). The IMPCA reference specifications were developed with an international perspective and to consider potential seawater contamination that could happen during sea transport (IMPCA, n.d.). The specifications developed by IMPCA were not meant to create a second grade of methanol and took into consideration ASTM 1152. Both currently require a minimum of 99.85% methanol by weight. Another specification commonly referred to for methanol is US Federal Specification O-M-232L Grade AA (Jensen et al., 2012). Methanol purity of a minimum of 99.85% by weight is also required by this specification, which is quite similar to the IMPCA reference specifications. IMPCA, ASTM 1152, and US Grade AA methanol specifications are all appropriate for methanol for chemical use. The specifications provide limit values as well as references for test methods to be used for samples.

For methanol to be used in fuel applications, the specifications developed for chemical use may not specify properties that could be important for efficient use. The chemical grade specifications may include parameters that are not of concern, or conversely may exclude those that are of concern, for use in the fuel applications.

Within the automotive sector, methanol both as a blend with gasoline or as a pure fuel has been investigated and used for many years. Methanol is still actively being tested and used, with the main development of commercial application in the road transport sector currently occurring in China, where M15, M30, M85, and M100 methanol fuel are used (Schröder et al., 2020). Specifications developed for methanol use in automotive engines include ASTM D5797-16, "Standard Specification for Methanol Fuel Blends (M51–M85) for Methanol-Capable Automotive Spark-Ignition Engines". This standard states that components to produce the fuel blends are limited to methanol and gasoline blendstock. Fuel methanol (M99) is defined in the standard as "methanol with small/trace alcohol and hydrocarbon impurities" (ASTM, 2016). Water content (% by mass) of the blends is limited to a maximum of 0.5%. Methanol fuel standards for the automotive sector have also been published in China, India, Israel, and Italy (Schröder et al., 2020). An M100 fuel specification guideline was published in California in the 1990s (California Energy Commission, 1996), to guide transport, retailing, and use of automotive methanol fuel. This specification required a minimum content of methanol of 96% by volume and allowed a maximum water content of 0.3% by mass. Other alcohols and ethers could be present to a maximum of 2% by mass; hydrocarbons derived from gasoline or diesel fuel could also be present to a maximum of 2% by mass. The presence of hydrocarbons was considered possible because it was permitted to transport M100 methanol in tankers previously used for gasoline or diesel, without steam cleaning of the tanks. It was considered that amounts below 2% by mass would not be an issue for automotive engine use.

For marine applications, an ISO standard is under development, as described in Section 2.1.3. The only published marine fuel specification to date is that provided by MAN Energy Solutions for methanol to be used in the MAN B&W ME-LGIM engines (MAN, 2022). This specification includes some of the same parameters as those specified in the IMPCA standard, but allows for lower purity of methanol, and higher maximum values of water and ethanol.

A summary of methanol fuel specifications as described above is shown in Table 1.

Table 1. Summary of Selected Methanol Specifications

Specification	Methanol Purity	Description
IMPCA Reference Specifications	Min. 99.85% w/w on a dry basis	Widely used internationally for market interactions; developed in 1992
ASTM D1152 Standard Specification for Methanol	99.85% grade methanol	Chemical grade methanol standard in wide use prior to 1992, similar to the IMPCA standard
US Federal Specification O-M-232L Grade AA	99.85% grade methanol	Chemical grade methanol standard, similar to the IMPCA standard.
ASTM D5797	Varies from 51% to 85% by volume in the gasoline-methanol fuel blend	Standard Specification for Methanol Fuel Blends (M51-M85) for Methanol-Capable Automotive Spark-Ignition Engines. Developed for fuels to be used in both flexible fuel and dedicated methanol spark-ignition engines.
M100 (1996 California Energy Commission)	Min. 96 Vol %	Developed for automotive methanol fuel, during the methanol fuel trials conducted in the 1980s and 1990s in California.
MAN Fuel Specification (reference)	Min. 95% w/w	For methanol used in MAN B&W ME-LGIM Engines (two-stroke slow speed marine diesel engines). Developed in 2016 – current version dated 2022.

The three chemical industry standards are very similar and specify a methanol purity of 99.85%. The MAN fuel specification allows a lower purity of methanol and higher allowable maximum concentrations of water and ethanol, as shown in Table 2. In addition, not all parameters specified by IMPCA are included in the marine fuel specification. This was because they were not considered of concern for operation of the two-stroke ME-LGIM at the time the specifications were published (pers. comm.).

Table 2. Comparison of IMPCA Reference Specifications (Version 9, 2021) and Guiding Methanol Fuel Specification for MAN B&W ME-LGIM engines (MAN Energy Solutions, Rev. 3, 2022)

Test Parameter	**IMPCA Limit**	**Limit for MAN B&W ME-LGIM Engines**
Purity on a dry basis	Min. 99.85 % W/W	Min. 95 % W/W
Acetone	Max. 30 mg/kg	Max. 30 mg/kg
Ethanol	Max. 50 mg/kg	Max. 5 % W/W
Colour	Max. 5 Pt-co	
Water	Max. 0.100 % W/W	Max. 5 % W/W[1]
Distillation Range at 760 mm Hg	Max. 1 °C	
Specific Gravity 20°C/20°C	0.7910 – 0.7930	
Potassium Permanganate Time Test at 15°C	Min. 60 minutes	
Chloride Cl-	Max. 0.5 mg/kg	Max. 0.5 mg/kg
Sulphur	Max. 0.5 mg/kg	Max. 0.5 mg/kg
Water Miscibility	Pass ASTM D 1722 test	
Carbonizables	Max. 30 Pt-Co	
Acidity as Acetic Acid	Max. 30 mg/kg	Max. 30 mg/kg
Iron in Solution	Max 0.10 mg/kg	
Non Volatile matter	Max. 8 mg/kg	
Appearance	Clear and free from suspended matter	Clear, uncoloured, and free of suspended solids
Lower Calorific Value (LCV)		Min. 19 MJ/kg

Notes:

1. The guiding specifications state that a water content of up to 30% W/W may be accepted under certain conditions and after agreement with MAN ES (MAN ES, 2022)

Regarding the methanol impurities, acetone and ethanol are considered to primarily originate from production of methanol (IMPCA, n.d.). Lower concentrations of ethanol are not considered a concern for a combustion engine burning methanol, generally, as ethanol also combusts well and has similar properties to methanol. The origin of chloride in methanol is considered to be most likely seawater (IMPCA, n.d.).

2.3 Experience with methanol fuel in large dual-fuel marine engines

Methanol has been used as a fuel in commercial shipping since 2015, when the first of four large-bore medium-speed four-stroke Wärtsilä-Sulzer 8-cylinder Z40S engines on the *Stena Germanica* RoPax ferry was converted to methanol/fuel oil dual-fuel operation (Ellis and Tanneberger, 2015). The remaining three main engines were converted to dual-fuel operation in 2015/2016 (Lewenhaupt, 2017). The methanol used as fuel in the engines is commercial grade methanol produced from natural gas, which meets the IMPCA specification (personal communication). In addition, a small batch of methanol produced from steel mill off-gases, as part of the "From Residual Steel Gasses to Methanol" (FReSMe) project was tested. This was distilled to meet IMPCA specification methanol purity.

The first methanol dual-fuel vessel using an MAN two-stroke engine came into service in 2016 (MAN Energy Solutions, 2023), and as of January 2023 there were 23 methanol dual-fuel tankers in service worldwide (MOL, 2023), all using two-stroke MAN engines. Thus, there is considerable operational experience with methanol in large two-stroke engines. Methanol used as fuel on the tankers is produced in conventional plants and meets IMPCA specification. In 2023 a blend of bio-methanol and natural-gas based methanol was used to fuel a methanol product tanker on a "zero emission" voyage (Methanex, 2023). The bio-methanol was produced from renewable natural gas feedstock in a conventional natural gas production facility and was of IMPCA standard. MAN has also developed dual-fuel methanol engines that can achieve Tier III compliance with the addition of water to the methanol fuel (MAN ES, 2021). Running on methanol that is mixed with 25% to 40% water, with 5% diesel pilot fuel, achieves compliance with IMO Tier III NO_x without the need for exhaust gas after treatment (MAN ES, 2021). The technical water for this solution is generated on board and the methanol meets IMPCA specifications.

Wärtsilä has also tested blending methanol with water to reduce NO_x with their four-stroke engine concept. Reportedly 25% water was blended to achieve NO_x Tier III, with a 1-2% increase in fuel consumption, but long-term effects have not been studied yet. Water for NO_x reduction was also tested in a Wärtsilä Vaasa 4L32LNGD in early tests of the feasibility of methanol fuel – a 10% water blend was tested and NO_x reductions were shown (Stenhede, 2013).

3 Methanol Fuel Testing in FASTWATER

The FASTWATER project was initiated to investigate the use of renewable methanol fuel in smaller engines used in inland and coastal shipping. The power range investigated –– 200 kW up to 4 MW – had not been tested previously in continuous vessel operation and thus was an identified gap to be filled by the project.

In FASTWATER, research on methanol combustion is being carried out, and engine types are being developed to demonstrate on the vessels being converted to use methanol as a primary fuel or dual-fuel solution. While the engines developed to demonstrate on the harbour tug and the coast guard vessel have not been evaluated with respect to the impact of varying fuel characteristics, the developers do consider it possible to adapt to future developments in methanol fuel specification. Research conducted at Ghent University and Lund University does, however, elaborate on the impact of water blended with methanol. Moreover, the engine developed by ScandiNAOS has also undergone trials to reduce the amount of ignition improver required, in an effort to reduce fuel cost.

3.1 Methanol water blend testing in FASTWATER

Research conducted by Dierickx et al. (2023) experimented with a high-speed, dual-fuel, port injection engine using various blends of water and methanol. Three objectives were investigated: (1) if water can act as a knock suppressant, the current main limitation to diesel substitution at high load, and ultimately increase diesel substitution, (2) if the cooling effect of water can be a measure to control NO_x, and (3) to test the impact a blend of 90% methanol and 10% water by weight has on brake thermal efficiency. The latter was chosen to mimic crude methanol produced from biomass or methane (e.g., natural gas or biogas) on the basis that it may be a more cost-effective fuel to produce and has been reported as not deteriorating engine performance. Other methanol-water blends with higher water content were chosen to test the NO_x reduction potential due to their resemblance to crude methanol from other production methods.

The converted Volvo Penta D7C-B TA used a custom-built methanol supply system, a multi-point port injection (one at each cylinder intake) and was initially used for testing in the Horizon 2020 project LeanShips. Results from the experiments in FASTWATER showed that:

1. Increasing water content in the fuel reduces the in-cylinder temperature and increases ignition delay. It does however not confirm the hypothesis that water acts as a knock suppressant to increase the diesel substitution rate at high loads where too high temperature is the cause of knock. At all tested loads, pure methanol achieves the highest diesel substitution rate with a peak of 75% of the energy coming from methanol occurring at the highest load. While misfire is the limiting factor for maximum diesel substitution at low loads for all methanol-water blends, for a methanol-water blend of 50% it is also the limiting factor for substituting diesel at the highest load.
2. Water is a highly effective measure to decrease NO_x emissions at low loads. At higher loads, 10% water blended in methanol can remarkably create higher NO_x emissions than pure methanol, well above Tier III limits at peak diesel substitutions. At the highest load, neither pure methanol nor a blend of 10% water in methanol is sufficient to reach Tier III limits. Although, with higher water blends Tier III limits can be met.
3. Blending water in methanol has a positive impact on brake thermal efficiency compared to pure methanol or diesel only operation. With 10% of water blend there is a slight but significant increase. Increasing the water content increases the brake thermal efficiency.

The authors conclude from their experimental research that water in methanol has interesting benefits. The cost of fuel production may be lower while during combustion brake thermal efficiency is increased and NO_x emissions are decreased.

3.2 ScandiNAOS Enmar Engine

The FASTWATER project's first successful demonstrator is described by Pu et al. (2022) and involves the retrofit of the Swedish pilot boat *Pilot 120 SE* to a methanol-powered main propulsion engine. The engine converted to use methanol is a high-speed compression ignited Scania DI16 that uses a single-fuel, direct-injection with an increased compression ratio. It does not require any after treatment of exhaust gases to meet Tier III NO_x requirements. Since its launch in December 2021 the engine has been used without any major issues during both cold winter days at temperatures from -15 °C to warm summer days above +30 °C – still accumulating running hours. The engine is available on the market and provides a solution to other ship owners operating smaller vessels. The retrofit of the pilot boat and engine conversion was performed by ScandiNAOS and builds on previous work conducted in the project GreenPilot, completed in 2018.

For the engine to ignite the single fuel using only compression an ignition improver is added to the methanol. The technique is mature, well-developed and has been used with the recognized fuel standard for ethanol ED95, another alcohol-based fuel, since the 1980s. The additive enables the use of a higher energy fraction from the alcohol than most dual-fuel engines, reducing greenhouse gasses further if a renewable fuel is used.

Compared to the beginning of the project, the engine developed has now been trialed and tested to use a blend of 3% ignition improver (Beraid 3555M) instead of 5% and maintaining the 0.1% of lubrication additive (Armolube 211 or Ethomeen O/12) by mass fraction. There is an incentive to reduce the amount of ignition improver since it is more expensive than methanol and accounts for 10-20% of the total fuel cost. With insufficient amounts the methanol is, however, reluctant to ignite. Two critical situations drive the amount of ignition improver necessary: cold start and step load changes. Extensive testing with blends of ignition improver ranging from 1-3% revealed that as little as 2% is needed for cold starts but 3% is necessary to avoid misfire during step load. Analogous to ED95, the fuel used for ScandiNAOS' engine development is named MD97 as 3% of the mass fraction is from an ignition improving additive while otherwise being IMPCA-quality methanol.

It should be noted that fuel quality specifications traditionally allow for additives such as those used in the engine developed by ScandiNAOS, without needing to add a specific fuel grade to the ISO specification. For petroleum product fuels, the standard states that it is permitted to have additives that improve some aspects of the fuel's characteristics or performance if the material "is not at a concentration that is harmful to personnel, jeopardizes the safety of the ship, or adversely affects the performance of the machinery" (ISO, 2017). It is expected that a similar approach would be taken for methanol. Thus, substances such as ignition improvers and lubricants could be added to the fuel, meeting the requirements of the engine builder, without the need for a specific fuel standard to be developed.

4 Renewable methanol as marine fuel: production, distribution and use perspectives

Renewable methanol production currently accounts for only a small percentage of total worldwide methanol production. In 2021, less than 200,000 tonnes of renewable methanol were produced annually (IRENA, 2021), out of a total worldwide methanol production capacity of 140 million metric tonnes. A large growth is forecast, however, to meet growing demand expected for renewable methanol as a ship fuel. For example, container ship operator Maersk has 19 dual-fuel methanol vessels on order (reported in January 2023); they forecast the need for 750,000 tonnes of green methanol annually to fuel these vessels (Bergman, 2023). Maersk predicts the need for 6 million tonnes of green methanol annually to meet its 2030 fleet emissions target milestone (Bergman, 2023). Other large ship operators such as Hyundai Merchant Marine have also recently placed orders for methanol dual-fuel vessels (Mandra, 2023). If the demand for a fuel grade methanol, with lower purity, develops, there may be the potential for reduced production costs and reduced energy need for this product, as compared to the higher purity. A new product grade on the market, however, will have implications for other parts of the renewable methanol fuel supply and use chain, as illustrated in Figure 4-1.

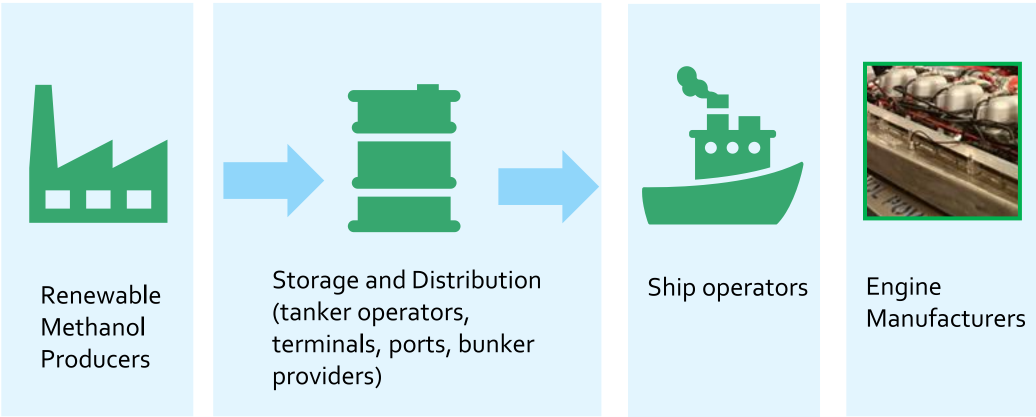

Figure 4-1. Renewable marine methanol supply, distribution, and use chain stakeholders considered in the study.

Impacts could include the need for separate distribution channels and storage, and implications for storage on board the ship. These were investigated within the FASTWATER project through interviews with stakeholders in each part of the chain shown above. Interviews were conducted using a semi-structured approach. Interview findings were supplemented with a literature review to provide supplementary information.

4.1 Renewable Methanol Production Perspective

Renewable methanol producers with operational plants or in the final stages of obtaining financing and permits were identified through contacts with the FASTWATER project consortium, which includes Methanex and the Methanol Institute. The Methanol Institute has compiled a list of more than 80 renewable methanol projects that are under development (Methanol Institute, 2023). Producers were also identified through press releases and news articles. A focus was placed on those operators who were already producing renewable methanol, or who were expected to be producing for the marine fuel market. For example, Maersk has issued press releases where it has identified strategic partners that it has entered into "letters of intent" or other agreements to secure supply of green methanol for the methanol dual-fuel vessels that it has on order (e.g. see Maersk, 2022). Bergman (2023) notes that many of the agreements include a commitment by Maersk to cover the complete offtake of methanol once production has begun.

Renewable methanol can be produced from many different feedstocks. Commercial renewable methanol available on the market today is limited ((IRENA, 2021) and main feedstock and production methods include:

- Methanol produced from biogas – the natural gas feedstock in conventional methanol production plants is substituted with biogas to produce bio-methanol to meet requested demand. Methanex has produced bio-methanol in this manner at its Geismar (Louisiana) plant (Methanex, 2023). OCI's BioMCN plant in the Netherlands has also produced bio-methanol from biogas (IRENA, 2021).
- Methanol from gasification of municipal solid waste: Enerkem in Edmonton, Alberta started producing in 2014 (IRENA, 2021).
- Methanol as a by-product from the wood pulping process: Södra forest products began producing methanol in 2020, with an annual production volume of 5,350 tonnes (Södra, n.d.). Alberta Pacific began production for internal needs in 2014 and for commercial production in 2017 (Alberta Pacific, n.d.). The annual production volume is 2,000 tonnes.

- e-methanol from CO_2 and hydrogen produced by electrolysis of water: Carbon Recycling International (CRI) has been producing methanol in Iceland since 2011 using geothermal CO_2. Annual capacity is 4,000 tonnes (IRENA, 2021).

For each renewable methanol producer contacted, information on feedstock, production method, and approximate annual production capacity was collected. The following questions were asked of the methanol producers in a semi-structured interview:

- What is the main (current or expected) market for your product (fuel, chemical industry, other)?
- What standard/quality of methanol is produced or expected to be produced at your facility? (for example IMPCA (International Methanol Producers and Consumers Association) Reference Specifications with 99.85% purity? Other? Not decided?)
- Have there been requests or interest from customers for methanol that does not meet IMPCA specifications? If so, what other specification or purity is requested?
- Is it possible to produce a lower purity methanol with the process used (or planned) at your plants, and if so what would the desired purity be? What would the non-methanol portion be (e.g. mostly water? anything else?)?
- Do you foresee any challenges and/or opportunities with establishment of a fuel grade methanol specification?

Not all of the renewable methanol producers had started production of methanol and some had not yet finalized plant processes. Information was therefore also collected from technology providers and from the literature on the possibilities for plant configuration and energy savings possible for producing methanol meeting different specifications, primarily with regards to omission of a final distillation step.

4.1.1 Methanol from renewable methane gas

Traditional natural gas-based methanol plants can also produce bio-methanol as has been reported by Methanex (Methanex, 2023). This is currently done on a project basis after requests by customers. Examples of methane feedstock for these projects includes landfill gas or biogas from animal manure. The source of the biogas may depend on the customer requirements. Bio-methanol for use in MTBE and gasoline blending requires certification of the feedstock to ensure sustainability regulations are met.

<u>Expected market and requests for other specifications</u>: The marine fuel market is considered to be a driver for the renewable methanol market. Other markets include the MTBE and gasoline blend-in applications. There may also be some niche markets in the chemical industry for voluntary (non-regulate) applications. Methanex provided ISCC (International Sustainability and Carbon Certification) certified bio-methanol in 2023 for use as ship fuel to demonstrate a net-zero voyage from Geismar, US to Antwerp, Belgium (Methanex, 2023).

No specific requests for other grades of methanol such as fuel grade had been reported.

<u>Standard/Quality of methanol produced</u>: Only IMPCA standard methanol was reported to be produced. The only difference between the bio-methanol and that produced from natural gas is the environmental attributes.

<u>Possibility to produce lower purity methanol</u>: Producing a lower purity methanol at the existing plants is not an option.

Challenges/Opportunities: The need for separate tanks for distribution and storage was considered a challenge for establishing a second methanol grade – which would be a distinct separate product. This could lead to higher costs, and could be difficult with an international market where the product from different producers may be co-mingled during storage.

4.1.2 E-methanol

Renewable electro-methanol (e-methanol) is produced using renewable electricity and a renewable carbon source. The projected production capacity of e-methanol plants by 2027 is approximately 2.7 million tonnes annually, as shown by the Methanol Institute renewable methanol database (Methanol Institute, 2023).

Expected market: For some of the planned e-methanol plants the marine fuel market has been specifically identified as a target. The 50,000 tonnes of e-methanol expected to be produced starting 2025 in Örnsköldsvik, Sweden, will be used in the shipping industry, as announced by project owner Ørsted (Habibic, A., 2023). The e-methanol facility planned by developer Liquid Wind for Sundsvall, Sweden, with an expected annual production of 100,000 tonnes, will also provide fuel to the maritime market (Prevljak, 2022).

Standard/Quality of methanol produced: According to the e-methanol producer interviewed, the standard of methanol produced had not been finalized. They were following the work on development of a methanol marine fuel standard and open to production of a fuel grade, as the marine market is their expected customer.

Possibility to produce lower purity methanol: Producing methanol with a lower purity was considered possible with the process planned by the e-methanol developer interviewed. A purity of about 95% would mean that only one distillation column would be needed, which would result in capital cost savings. Avoiding a final distillation column means less energy during operation and lower environmental impact. The final methanol would likely include more ethanol and butanol than the current specifications, and also additional water, which is not expected to be a concern for the fuel market.

Challenges/Opportunities: A 95% purity methanol would save investment capital costs and also have the benefits of reduced operational costs and production impacts. There was no quantitative information available.

4.1.3 Methanol as a by-product of wood pulping

Bio-methanol is a by-product of the kraft pulping process (Jensen, 2012), created when wood chips are "cooked" with chemicals (Södra, n.d.). Two pulp mills upgrade this methanol to a commercial product, as follows:

- Alberta Pacific, which uses a process whereby methanol rich gas is stripped from the foul condensate which is an off stream from the pulp process. The methanol from this off gas is purified through distillation processes (Jensen, 2012). About 3700 tonnes of methanol is produced annually.
- Södra, located in Mönsterås, Sweden, which uses a patented extraction process to produce methanol from the condensed black liquor that results from the sulphate pulp process (Södra, n.d.). Södra produces 5,250 tonnes of bio-methanol per year, which is certified by the ISCC (International Sustainability and Carbon Certification).

Methanol has also been produced with pulp mill residues via gasification of the black liquor by Chemrec, who ran a pilot plant in Piteå, Sweden (Landälv, 2017). This plant is currently not active for methanol production.

Market: The amount of methanol produced from existing plants is small and marine fuel has not been the target market. Methanol produced by Södra has been used in the FASTWATER project pilot boat demonstrator, however.

Standard/Quality of Methanol Produced: The methanol produced by both Alberta Pacific and Södra is stated to meet a minimum 99.85% methanol purity. The typical values provided for the chemical composition of the Södra methanol show a sulfur content of 3.0 to 4.0 mg/kg (Södra, 2022). This is higher than the IMPCA specification but orders of magnitude lower than the amount required for marine emissions under the IMO's SOx emission control regulations, which is 0.1% m/m (100 g/kg) in sulphur emission control areas. Jensen (2012) states that contaminants produced during the kraft pulping of wood include the ionizable sulphur compounds, hydrogen sulphide, and methyl mercaptan. The extraction and distillation processes to produce the commercial methanol target these compounds, among others.

Challenges/Opportunities: For methanol produced by gasification of black liquor, a study by Carvalho et al. (2018) examines the potential cost savings of producing raw methanol (with 5% water) rather than proceeding with a final process step of a product distillation unit to result in a minimum of 99.85% pure methanol. Results of this modelling study found that a savings of 3-15% could be obtained for the raw methanol production. Part of this savings was due to capital cost savings from forgoing a final distillation column. It was noted, however, that there were more options for use of the 99.85% methanol. The two plants producing bio-methanol from pulp by-products today have customers requiring the higher purity methanol and their production volumes are small. Thus it may not be feasible to produce two methanol grades at these facilities.

4.1.4 Methanol from gasification of waste

Gasification of biomass and solid waste use similar processes, which include initial steps of feedstock pretreatment; gasification; and conditioning and cleaning of the synthesis gas (IRENA, 2021). The syngas that is then processed in the methanol synthesis unit is almost the same regardless of the origin (IRENA, 2021). When a mixed feedstock such as non-recyclable municipal solid waste is used, a percentage of carbon of fossil origin, such as from some plastics, will be present. There are certification schemes that may be followed to determine the portion of the final methanol produced that is of biogenic origin. For example the International Sustainability and Carbon Certification (ISCC) process identifies approaches for calculating bio-yield, such as Carbon-14 measurements carried out according to analytic standards.

Market and requests for other specifications: The producers interviewed mentioned the fuel market – one stated that the portion of the methanol produced from the biogenic carbon present in the feedstock will be sold for fuel industry products (gasoline fuel blending, etc.). The methanol from the non-biogenic carbon in the feedstock goes to the chemical industry. Another noted that the maritime fuel market was seen as a potential for growth but the initial market would be a mixed customer group. The fuel market was expected to be the strongest over time. The potential for a designation of "recycled carbon fuel" for the non-biogenic portion of fuel was mentioned as a possibility.

Standard/Quality of methanol produced: IMPCA quality methanol is produced as it is required for the gasoline/petrol blending market served by the producers. One producer also carried out optional IMPCA testing for TMA (trimethylaminuria, considered as an impurity generating bad odours) for some chemical industry customers. There had been no requests or interest expressed to the respondents for a lower purity methanol.

Possibility to produce lower purity methanol: One respondent stated that it would be possible to skip the final distillation step. They stated that this would only result in operational savings as the distillation equipment would remain within the process train to have the possibility to provide IMPCA quality methanol to customers requesting it. Cost reductions were expected to be only marginal. Another respondent stated that they had no interest in producing a lower purity methanol.

Challenges/Opportunities: One respondent noted there would be market limitations if a lower purity grade was produced. Another noted that if another grade required more water or particular additives, it could be easily produced by blending at bunkering facilities rather than adapting the plant. One respondent noted that it could be a challenge to convince producers to commit to only fuel grade methanol, until the market was large enough.

4.1.5 Methanol Plant Technology Provider Perspective

Several technology providers have developed solutions for e-methanol plants which may be licensed and tailored in collaboration with plant developers. Examples include Carbon Recyling International (CRI, n.d.), thyssenkrupp Uhde (thyssenkrupp Uhde, 2022], and Haldor Topsoe (Haldor Topsoe, 2019). Technology providers develop solutions that can produce IMPCA grade methanol but can also adapt solutions to produce methanol of other specified qualities. For example fuel grade methanol of 95% can be produced with a single distillation column whereas two distillation columns are required for higher grade methanol. The respondents did not foresee any challenge with providing solutions and plant technology for a fuel grade methanol.

4.2 Methanol Distribution and Storage Perspective

Ports with storage facilities, tankers and bunker ships are critical stakeholders in the methanol storage and distribution system. A primary concern raised by these regarding an introduction of a separate fuel grade methanol is that there may be a need for parallel storage and distribution network. It is common for chemical grade methanol to be co-mingled in a large land-based storage tank or on a large tanker discharging at several ports. An owner offers space in a tank and customers can rent the volume they require. This is made possible because the product shares the same specification. The concern with introducing a different specification for fuel is that a parallel storage and to some extent also a parallel distribution network would be required to avoid contaminating the chemical grade methanol. Ultimately, this could lead to a higher total cost of the fuel despite the fuel grade methanol being cheaper to produce.

A tanker or bunker barge may clean its tanks after delivering a batch of fuel grade methanol and be ready to accept a higher grade of methanol with minimum risk of contamination. A storage terminal at a port would be required to keep different grades separated by using separate tanks. Common pipework may be shared by developing operational measures where flushing of the pipes with the higher-grade methanol near completion of a transfer could be utilized.

An overview of the different storage volumes is presented in Figure 4-2 to indicate the different stakeholders' capacities. Given the size of large land-based storage and fuel tanks of large ships it is likely that a fuel specification will be developed primarily with these in mind and not necessarily for the smaller ship types involved in FASTWATER.

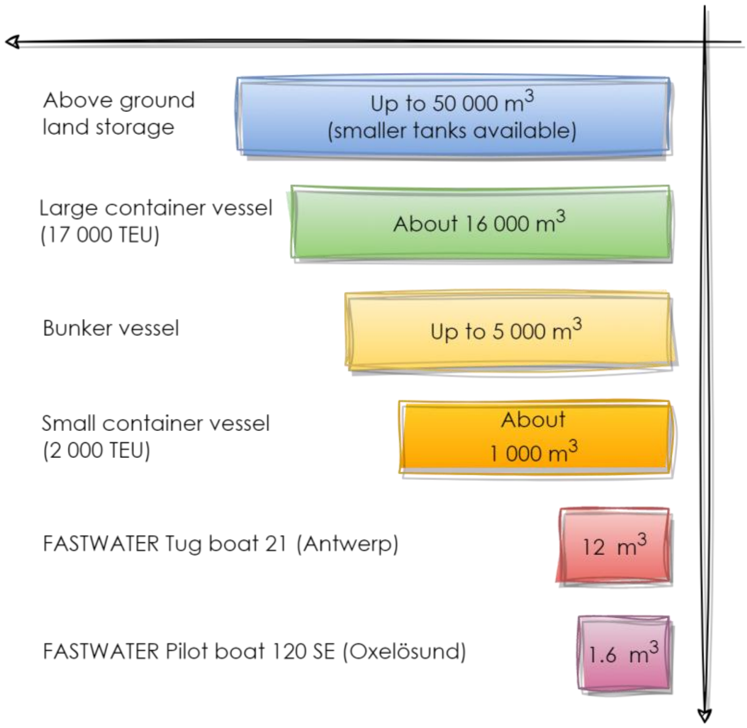

Figure 4-2. Total tank volume capacity of methanol storage infrastructure compared to typical bunker vessel tank size and fuel tank capacity on selected ship types

Ports recognize that methanol will become a piece of the bunkering puzzle, also noting that a port that wishes to serve as a bunkering hub may offer methanol as a fuel to be competitive. Simply offering the fuel may even bring additional cargo volumes because it affects trade patterns. Tank storage operators are sometimes separate from the port and thus, for the port to be able to offer methanol as a fuel, it must convince a tank storage operator to either convert an existing tank or build a new tank to store methanol. Doing so is a business decision but neither is likely without there being enough volumes to capitalize on or the port offering incentives to establish a methanol storage. The future growth of methanol supply is estimated by the ports to be primarily driven by methanol becoming a ship fuel. From their perspective it does not necessarily matter if it is green, gray, blue or any other form of feedstock used to produce the fuel, but accommodating for several grades could be more challenging.

Several flammable liquid feed stocks (benzene, acetone, toluene) and liquid transportation fuels (ethanol and gasoline) essentially share the same guidelines for designing, fabricating, repairing, and safeguarding above-ground storage tanks. Some chemical properties are however unique to methanol and should be considered, among these are various forms of corrosion. Unlike gasoline methanol may cause galvanic corrosion if stored in tanks made of incompatible material, especially if not fitted with cathodic protection. Compatible material is in general stainless steels in the 300-series or a carbon steel tank with a coating and galvanic protection. The former has a high investment cost but low maintenance cost while the latter being the opposite, noting that all coatings and galvanic protections need to be maintained and have a limited life span. A failed coating may result in contamination of the methanol or in the worst case a tank failure. Because methanol is hygroscopic it may extract water from the humidity in air if the tank is open to atmosphere. When excess water is present in methanol it may increase corrosion leading to issues with the tank or the methanol, for example in a carbon steel tank with a defective coating where the solution is in direct contact with the steel (Methanol Institute, 2018).

4.3 Ship Operator Perspective

The large ship operator contacted stated that they have only used IMPCA specification methanol in their dual-fuel engines and have not had any quality issues. The majority of methanol that has been used is commercial grade, but a small volume of methanol produced from steel mill off-gases, through the "From Residual Steel Gasses to Methanol" (FReSMe) project, was used on one occasion as well. This methanol had been distilled to the same purity (99.85%) as IMPCA specification methanol. The vessel was dry-docked in the spring of 2023 and an inspection of the methanol tanks showed them to be in very good condition after eight years of operation (Stena, 2023). The methanol tanks are carbon steel ballast tanks that were treated with a zinc-based coating during the ship conversion.

There was openness towards the use of a fuel grade methanol containing more water, as long as it wouldn't be more corrosive towards the tanks. If stainless steel tanks were required rather than coated carbon steel, this would add to the capital costs of vessel conversion and of new-build vessels.

Other methanol dual-fuel ships in operation currently are all methanol product tankers and thus are using IMPCA specification methanol, which they are also transporting.

The two ship operators in the FASTWATER project, the Swedish Maritime Administration and the Port of Antwerp-Bruges, are still in the process of gaining experience with methanol use. The Swedish Maritime Administration has used bio-methanol produced by Södra in their pilot boat operation as part of the FASTWATER project. They have also used standard IMPCA grade methanol produced from fossil feedstock. The Port of Antwerp-Bruges plans to test some renewable methanol that is produced to IMPCA specification but will also use traditional methanol, for financial reasons (lower cost).

4.4 Engine Manufacturer Perspective

Engine manufacturers are adapting to the needs of the market. In practical terms it means that if a ship owner finds high water-content methanol to be cheaper than chemical grade methanol, engines will develop in that direction. The approximately 20 two-stroke engines in service are onboard methanol tankers using their cargo as fuel: IMPCA specification. Engines from MAN are guaranteed to handle up to 5% of water in the fuel (see

Table 2) but this should not be taken as the upper limit, it is merely what has been tested so far. Put in simple terms MAN is confident under what conditions their engines can be guaranteed but does not specify where the upper limits for operation are without further testing. It is possible some adjustments can be made to accommodate for a higher water content, it is also possible the engine can operate with no or minor adjustments should the water content of the fuel increase or any other specification change.

Moreover, a large two-stroke engine may consume in excess of 500 tonnes of fuel per day and its combustion process and injection strategy is relatively simple compared to a four-stroke engine. Hence, fuel quality requirements are generally higher for smaller, high-speed four-stroke engines than for large low-RPM two-stroke engines. From this perspective it is not unlikely that there may be more than one fuel grade available, as for fossil fuels. This is a stark contrast to the stakeholders who do not see the introduction of any methanol fuel grade as beneficial.

Engine manufacturer partners in the FASTWATER project, Anglo Belgian Corporation (ABC) and ScandiNAOS, have developed and tested their concepts using methanol with a purity of 99.85%. Both have indicated, however, that if such a grade was on the market and preferred by ship operators due to lower cost, then it could be accommodated.

5 Discussion and Conclusions

The marine fuel market for renewable methanol is expected to grow rapidly in the next few years. This is driven by the 19 dual-fuel methanol containerships that are currently on order by Maersk, with the first, a 2,100 TEU container feeder vessel, expected to be delivered in summer 2023 (Maersk, 2023). Other ship owners and operators have followed suit with a total of 58 dual-fuel methanol containerships on order albeit not all have specified whether they will source green methanol (Wilmington et al., 2023). The manufacturer's guiding fuel specification for the two-stroke engines used in these vessels allows for operation of methanol with a minimum concentration of 95% w/w (MAN ES, 2022), lower than the current IMPCA specification value of minimum 99.85% w/w. Although the current production of renewable methanol is low, there is an expected growth in production capacity, with volumes of up to 2.5 million tonnes per year forecast as early as 2024 (Methanol Institute, 2023). More than half of the forecast new production capacity is for e-methanol. If these new e-methanol production facilities targeted 95% w/w methanol as a product they could forgo a second distillation column and save both capital and operating costs. Technology exists to build plants with single distillation column to achieve 95% w/w. Thus there appears to be a good opportunity and match between acceptable methanol quality for a two-stroke engine and plant capital savings for the emerging e-methanol production market.

For the existing renewable methanol producers there were some challenges identified with establishment of a fuel grade methanol. These included:

- the need for duplicate storage and distribution chains
- uncertainty about the marine fuel market and loss of potential customers requiring higher grade renewable methanol.

In addition, the production cost savings would be minimal as the capital costs for the second distillation column had already been incurred. For new methanol producers planning to supply only the marine fuel market, if they have offtake agreements in place as described by Bergman (2023), the uncertainty is much lower. Although this would depend on the terms. Additionally, if only one grade of methanol (fuel grade) is produced at the plant, there would not be the need for duplicate on-site storage and transportation. Until the demand for fuel grade methanol increases there may be limited storage for fuel grade methanol at ports and terminals. Ports, however, have indicated a willingness to provide bunker fuel to meet the needs of customers implementing low-carbon solutions.

From a storage and distribution perspective, there may be the need to clean or flush tanks after a lower grade methanol before a higher grade is loaded.

Ship operators were open to a fuel grade of methanol as long as the water content did not increase corrosion and result in the need for more expensive materials. Coated carbon steel tanks have worked well with the IMPCA specification methanol. If stainless steel tanks were required then investments would be higher. Additionally, a fuel grade methanol should have a price reduction that at least compensates for the slightly lower energy content expected with the lower methanol content.

The engine producers in the FASTWATER project currently only have experience with operating and testing with 99.85% purity methanol but were open to accommodating a fuel grade if it was available and preferred by ship operators due to lower cost.

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